Contribution to the design and control of a hybrid renewable energy generation system based on reuse of electrical and electronics components for rural electrification in developing countries.
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Abstract

While the Cambodia’s government is making effort to increase electricity production for its energy demand, it still remains dependent on the existing or the expansion of the centralized grid lines which have high initial investment cost. The temporally solution is to employ a distributed energy generation system which has lower life cycle cost and provides a diversity of technologies to meet the desired applications.

Minimizing environmental impacts represents a major objective of sustainable development considering resources depletion and the limited capabilities of the environment to adapt. The potential of renewable energy resources has been well understood as the solutions to power rural development and to reduce the environmental impacts of energy generation. Due to advance in technologies and increasing consumer demands, there has been a vast amount of electrical and electronic waste which introduces severe impacts on the environment. The current strategies mainly rely on conventional waste collection and processing techniques for material recovery.

This thesis proposed a solution of reusing discarded components in an isolated hybrid renewable energy system as the solution for electrification of rural Cambodia. This is frugal innovation, local solution with local materials for and with local people. A suitable configuration for the proposed system is a solar-hydro hybrid generation system since solar and water resources are plentiful in rural Cambodia. The components that are reused in the solution after being discarded include computer power supply units (PSUs) for the solar part, uninterruptable power supply units (UPSs) and three phase induction machines for the electro-hydro part. Used auto-mobile batteries will be used for the system storage.

The thesis presents in the first part the evaluation of the environmental impacts of the proposed reuse solution for rural electrification. The study of the environmental impacts is based on Life Cycle Assessment (LCA) methodology which compares the life cycle impacts of the proposed solution to that of a conventional solution. Moreover, a sensitivity analysis is achieved in order to evaluate the impacts of uncertainties of the environmental impacts.

The second part of this work deals with the technological aspects of the reuse solution in both theory and experimentation. The first part of this aspect is focused on the repurposing of used computer power supply units (PSUs), through limited modifications of the circuits in order to increase its range of operation. The PSU which usually contains one of a few types of isolated DC-DC converters is repurposed as charge controller with MPPT control in a cheap micro-controller with very good results.

The last part of this thesis studies a new configuration of generators based on re-used three-phase induction motors. The proposed single-phase generator is based on a three-phase machine in a modified version of the coupling and with a rather uncommon supply. Modelling is highly investigated. An inverter-assisted topology where two windings will be supplied separately by two inverters for excitation and the remaining winding is connected to load. A new modeling of the generator has been studied. The results of simulation were
compared to experimental test results in open loop study. These results have demonstrated the advantages of the new configuration in comparison to the previously proposed inverter-assisted topology in term of efficiency and minimization of torque ripple.

**Keywords:** Frugal Innovation, reuse, Life Cycle Assessment, power supply units, second-life, renewable energy, modelling, induction generator, inverter-assisted induction generator.
Résumé

Bien que le gouvernement cambodgien s’efforce d’augmenter sa production d’électricité pour répondre à sa demande en énergie, il reste toujours dépendant de réseau électrique existant ou de l’extension du réseau dont le coût d’investissement initial est élevé. La solution temporelle consiste à employer un système de production d'énergie distribué qui présente un coût de cycle de vie inférieur et introduit une diversité de technologies pour répondre aux applications.

Minimiser les impacts environnementaux représente un objectif majeur du développement durable, compte tenu de l’épuisement des ressources et des capacités d'adaptation limitées de l'environnement. Les ressources en énergies renouvelables ont été bien comprises comme les solutions pour alimenter le développement rural et réduire les impacts environnementaux de la production d’énergie. Suivant les progrès technologiques et de la demande croissante des consommateurs, de grande quantité de déchets électroniques et électroniques ont entraîné de graves conséquences pour l’environnement. Les stratégies actuelles reposent principalement sur les techniques classiques de collecte et de traitement des déchets.

Ce travail de thèse proposait une solution de réutilisation des composants électroniques dans un système d'énergie renouvelable hybride isolé pour la solution d'électrification pour la zone rurale. Une configuration choisie pour le système proposé est un système de génération hybride solaire-hydroélectrique, car les ressources solaires et hydrauliques sont abondantes dans les zones rurales du Cambodge. Les composants qui sont réutilisés dans la solution comprennent des blocs d’alimentation d’un PC (PSU) pour la partie solaire, des alimentations sans interruption (UPS) et des machines asynchrone triphasées pour la partie hydraulique. Les batteries automobiles usagées sont utilisées pour le stockage d’énergie.

Ce travail de thèse aborde dans une première partie l’évaluation des impacts environnementaux de la solution de réutilisation proposée. Cette étude repose sur la méthodologie de l’Analyse du Cycle de Vie (ACV) qui compare les impacts du cycle de vie de la solution proposée à ceux d’une solution conventionnelle.

La deuxième partie de ce travail traite des aspects technologiques de la solution de réutilisation, à la fois en théorie et en expérimentation. La première partie de cet aspect concerne la reconversion des blocs d’alimentations usagées. Le bloc d'alimentation, qui contient généralement l'un des quelques types de convertisseurs DC-DC isolés, est réutilisé comme contrôleur de charge, qui est le composant principal du système de générateur photovoltaïque.

La dernière partie de cette thèse décrit une nouvelle configuration de générateur basé sur des moteurs asynchrone triphasés. Le générateur monophasé proposé basé sur une machine triphasée est une version modifiée d'une topologie à base de l’onduleur où deux enroulements sont alimentés séparément par sources d'excitation, et l'autre enroulement est connecté à la charge. Une nouvelle modélisation est proposée. Les résultats de simulation sont comparés aux résultats expérimentaux en alimentation sinus. La comparaison met en évidence une
supériorité de la nouvelle configuration par rapport à l'ancienne en termes de rendement et de minimisation de pulsations de couple.

**Mots Clefs:** Réutilisation, Analyse du Cycle de Vie, ACV, blocs d’alimentation de PC, énergies renouvelables, modélisation d’un générateur asynchrone, générateur asynchrone excité par l’onduleur.
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<tr>
<td>ATX</td>
<td>Advanced Technology eXtended motherboard specification.</td>
</tr>
<tr>
<td>BOS</td>
<td>Balance of System.</td>
</tr>
<tr>
<td>CCCSP</td>
<td>Cambodia Climate Change Strategic Plan (2014-2023).</td>
</tr>
<tr>
<td>CCM</td>
<td>Continuous Conduction Mode.</td>
</tr>
<tr>
<td>CMC</td>
<td>Current-Mode Control.</td>
</tr>
<tr>
<td>DOD</td>
<td>Depth of Discharge.</td>
</tr>
<tr>
<td>E-waste</td>
<td>Electronics waste.</td>
</tr>
<tr>
<td>EAC</td>
<td>Electricity Authority of Cambodia.</td>
</tr>
<tr>
<td>EDC</td>
<td>Electricité Du Cambodge.</td>
</tr>
<tr>
<td>EEE</td>
<td>Electrical and Electronic Equipment.</td>
</tr>
<tr>
<td>ELC</td>
<td>Electronic Load Control.</td>
</tr>
<tr>
<td>EoL</td>
<td>End-of-Life.</td>
</tr>
<tr>
<td>EV</td>
<td>Electric vehicle.</td>
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<tr>
<td>GDP</td>
<td>Gross Domestic Product.</td>
</tr>
<tr>
<td>GERES</td>
<td>Groupe Energies Renouvelables, Environnement et Solidarités.</td>
</tr>
<tr>
<td>HDI</td>
<td>Human Development Index.</td>
</tr>
<tr>
<td>HFO</td>
<td>Heavy Fuel Oil.</td>
</tr>
<tr>
<td>HRES</td>
<td>Hybrid Renewable Energy System.</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency.</td>
</tr>
<tr>
<td>IPP</td>
<td>Independent Power Producers.</td>
</tr>
<tr>
<td>LCA</td>
<td>Life Cycle Assessment.</td>
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<tr>
<td>LCI</td>
<td>Life cycle inventory.</td>
</tr>
<tr>
<td>LCIA</td>
<td>Life Cycle Impact Assessment.</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquefied Petroleum Gas.</td>
</tr>
<tr>
<td>MDOD</td>
<td>Maximum Depth of Discharge</td>
</tr>
<tr>
<td>MOEC</td>
<td>Ministry of Environment of Cambodia.</td>
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<td>MPPT</td>
<td>Maximum Power Point Tracking.</td>
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<td>NGO</td>
<td>Non-governmental Organization.</td>
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<td>NOCT</td>
<td>Nominal Operating Cell Temperature.</td>
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<td>OIATI</td>
<td>One-Isolated-And-Two-Isolated-Inputs generator configuration.</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board.</td>
</tr>
<tr>
<td>PFC</td>
<td>Power Factor Correction.</td>
</tr>
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<td>PSU</td>
<td>Power Supply Unit.</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic.</td>
</tr>
<tr>
<td>RCD</td>
<td>Resistor, Capacitor and Diode clamping circuit.</td>
</tr>
<tr>
<td>REE</td>
<td>Rural Electricity Enterprises.</td>
</tr>
<tr>
<td>SCIM</td>
<td>Squirrel Cage Induction Machine.</td>
</tr>
<tr>
<td>SEIG</td>
<td>Self-Excited Induction Generators.</td>
</tr>
<tr>
<td>SETAC</td>
<td>Society of Environmental Toxicology and Chemistry.</td>
</tr>
<tr>
<td>SLI</td>
<td>Starting-Lighting-Ignition (batteries).</td>
</tr>
<tr>
<td>STATCOM</td>
<td>Static Compensator.</td>
</tr>
</tbody>
</table>
SVC: Static VAR Compensator.
TSCAOI: Two-Series-Connected-And-One-Isolated generator configuration.
UEEE: Used Electrical and Electronic Equipment.
UNEP: United Nations Environmental Programme.
UNU: United Nation University.
UPS: Uninterruptable Power Supply Unit.
US-EPA: Environmental Protection Agency of the USA.
VEB: Vented lead-acid Battery.
VMC: Voltage-Mode Control.
VRLAB: Valve-Regulated Lead-Acid Battery.
WEEE: Waste Electrical and Electronic Equipment.
## List of Symbols

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<tr>
<td>$A_{pv}$</td>
<td>PV panels surface area.</td>
</tr>
<tr>
<td>$C_{bat,Ah}$</td>
<td>Batteries capacity in Ah.</td>
</tr>
<tr>
<td>$C_{bat,Wh}$</td>
<td>Batteries capacity in Wh.</td>
</tr>
<tr>
<td>$C$</td>
<td>Excitation capacitor.</td>
</tr>
<tr>
<td>$C_{eff}$</td>
<td>The equivalent excitation capacitor.</td>
</tr>
<tr>
<td>$C_{min}$</td>
<td>The minimum requirement capacitor value for SEIG operation.</td>
</tr>
<tr>
<td>$D$</td>
<td>Duty cycle of PWM signal / viscous friction coefficient.</td>
</tr>
<tr>
<td>$E_{dc}$</td>
<td>Daily energy consumption by batteries.</td>
</tr>
<tr>
<td>$E_{bat}$</td>
<td>Daily energy needed to charge batteries.</td>
</tr>
<tr>
<td>$E_{PV,STC}$</td>
<td>Daily energy generated by PV panels at standard test conditions.</td>
</tr>
<tr>
<td>$[I_r]$</td>
<td>Rotor current vector in ‘abc’ frame, $[i_{ra}, i_{rb}, i_{rc}]^T$.</td>
</tr>
<tr>
<td>$[I_s]$</td>
<td>Stator current vector in ‘abc’ frame, $[i_{sa}, i_{sb}, i_{sc}]^T$.</td>
</tr>
<tr>
<td>$[I_{e,dq0}]$</td>
<td>Rotor current vector in ‘dq0’ frame, $[i_{rd}, i_{rq}, i_{r0}]^T$.</td>
</tr>
<tr>
<td>$[I_{s,dq0}]$</td>
<td>Stator current vector in ‘dq0’ frame, $[i_{sd}, i_{sq}, i_{s0}]^T$.</td>
</tr>
<tr>
<td>$I_{e1}, I_{e2}$</td>
<td>Excitation currents. ($I_{e1} = i_{sa}; I_{e2} = i_{sb}$).</td>
</tr>
<tr>
<td>$i_C$</td>
<td>Capacitor current.</td>
</tr>
<tr>
<td>$i_L$</td>
<td>Load current.</td>
</tr>
<tr>
<td>$J$</td>
<td>Overall system inertia.</td>
</tr>
<tr>
<td>$[L_s], [L_r]$</td>
<td>Stator and rotor inductance matrix.</td>
</tr>
<tr>
<td>$l_{sp}$</td>
<td>Stator phase proper inductance.</td>
</tr>
<tr>
<td>$l_{sl}$</td>
<td>Stator phase leakage inductance.</td>
</tr>
<tr>
<td>$l_{rp}$</td>
<td>Rotor phase proper inductance.</td>
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<tr>
<td>$l_{rl}$</td>
<td>Rotor phase leakage inductance.</td>
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<tr>
<td>$L_s, L_r$</td>
<td>Stator and rotor cyclic inductance.</td>
</tr>
<tr>
<td>$L_{sd}, L_{rd}$</td>
<td>Stator and rotor inductances corresponding to homopolar components.</td>
</tr>
<tr>
<td>$M$</td>
<td>Mutual cyclic inductance.</td>
</tr>
<tr>
<td>$M_{sr}$</td>
<td>Maximal mutual inductance between a stator and a rotor phases.</td>
</tr>
<tr>
<td>$m_{pv}$</td>
<td>PV panels mass.</td>
</tr>
<tr>
<td>$NOCT$</td>
<td>Normal Operating Cell Temperature.</td>
</tr>
<tr>
<td>$N_p$</td>
<td>Number of primary turn of a transformer.</td>
</tr>
<tr>
<td>$N_s$</td>
<td>Number of secondary turn of a transformer.</td>
</tr>
<tr>
<td>$\eta_{inv}$</td>
<td>Inverter efficiency.</td>
</tr>
<tr>
<td>$\eta_{bat}$</td>
<td>Batteries efficiency.</td>
</tr>
<tr>
<td>$\eta_{pv}$</td>
<td>PV generator efficiency.</td>
</tr>
<tr>
<td>$\eta_{conversion}$</td>
<td>PV generator conversion efficiency which include charge controller efficiency ($\eta_{chargecontroller}$), dirt on the PV surface, mismatched modules ($\eta_{dirt,mismatched}$), and module temperature ($\eta_{cellTemp}$).</td>
</tr>
<tr>
<td>$P$</td>
<td>Number of poles.</td>
</tr>
<tr>
<td>$P_{inv}$</td>
<td>Inverter input power.</td>
</tr>
<tr>
<td>$P_{loadpeak}$</td>
<td>Peak load power consumption.</td>
</tr>
<tr>
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General Introduction
General Introduction

In many developing countries including Cambodia, the majority of the population in rural area lacks sufficient access to sustainable, reliable and effective energy systems. Today, the most fundamental energy access is distributed in electricity form which is very easy to be transformed into the desirable types of energy that are useful to our activities. Access to affordable and reliable energy services is fundamental to reducing poverty and improving health, increasing productivity, enhancing competitiveness and promoting economic growth. However, extension of centralized grid electricity lines to rural area in developing countries faces significant challenges including high construction cost of transmission lines, transmission losses and is nearly impossible for utilities to be profitable due in large part to low rural household energy consumption and insufficient population densities. The temporally solution is distributed energy micro-generation system which has lower life cycle cost and provides a diversity of technologies to meet the desired applications in rural communities.

Minimizing environmental impacts represents a major objective of sustainable development considering resources depletion and the limited capabilities of the environment to adapt. The potential of renewable energy technologies to power rural development has been well understood as the solutions to power rural development and to reduce the environmental impacts of energy generation. Because renewable energy is regionally diverse, choosing the appropriate system generally depends on the local availability of renewable energy resources and the characteristics of the local electricity demand. Cambodia is one the Southeast Asia countries having one of the richest countries in hydropower resources due to its river system. While the Cambodia government is making effort to increase electricity production for its energy demand by investment in new hydro and coal power plants, it still remains dependent on the existing or the expansion of the centralized grid line. Although photovoltaic lighting systems have paved the way in some rural village, the solution of providing electricity access using distributed energy generation system based on renewable energies has not been significantly explored for the rural communities in Cambodia. Several barriers might be the obstacles for adoption of such the system including lack of adequate infrastructure and appropriate technology, technical skills, existing knowledge on the management, operation and regulation of RETs and substantial investment costs.

This thesis proposed a novel solution of reusing discarded components in isolated renewable energy systems for electrification for rural Cambodia first. This solution is interesting not only for Cambodia but for any countries or regions which are rich in solar or hydro resources. A suitable configuration for the proposed system is a solar-hydro hybrid generation system since solar and hydro (mostly in highland regions) resources are plentiful in rural Cambodia. The components which can be reused include computer power supply units (PSUs) as DC-DC converters, uninterruptable power supply units (UPSs) as inverters, three phase induction machines as induction generators, and car batteries as an energy storage. Such solution helps to provide an intermediate, affordable and sustainable energy access solution for rural
communities. The cost of the system can be cut due to reuse of discarded components instead of brand new devices.

With the rapid expansion of technological development, innovation and consumer demand, various electronic equipment has been significantly improved, results in the shorter life of electronic products, and higher amounts of waste electrical and electronic equipment. The current strategies mainly rely on conventional waste collection and processing techniques for material recovery. The proposed solution can also provide extra tool to solve the growing e-waste problem and eliminate the impacts due to production of new components for the system.

The objectives of this thesis work were to 1) evaluate the environmental impacts of the proposed reuse solution for rural electrification while making the comparison with the impacts of the same system using newly made components; 2) address the technological aspects of the reuse solution in theory, simulations and experimentation. The comparative study of environmental impacts is based on Life Cycle Assessment (LCA) methodology that encompasses all the potential impacts throughout the product chain. LCA is a holistic and standardized tool that makes comparisons complete and less subjective. Nevertheless, some inventories data were based on assumption and data extrapolation due to the lack of specific information from database and literature. The sensitivity analysis is made to assess the effects of the assumptions and of possible variations in the collected data on the results.

Since the proposed reuse solution is based on a solar-hydro hybrid generation system, the technological study of the system can be divided into two parts: the first part focus on the repurposing of used computer power supply units (PSUs) which is the main component in solar photovoltaic (PV) generator system; the second part studies the generator for ‘pico-hydro’ plant that is based on discarded induction motors and hydro turbines. Power supply units usually contain one of a few types of isolated DC-DC converters. This kind of converter can be repurposed as ‘Electronic Load Controller’ for voltage regulation of induction generator, auto-mobile alternator output controller, and mainly as charge controller in photovoltaic generator system. In order to optimize the energy extraction from the sun in PV generator, the ‘Maximum Power Point Tracking’ (MPPT) control has to be implemented with a cheap easy-to-program microcontroller. This controller can be implemented with the power supply units which are lightly changed by removing or adding a few electronic components.

Though purposed built induction generators are expensive, three-phase induction motors can be used as generator when the drive condition is right. Three-phase induction motors are mass produced and widely used in the factories, power tools, and home appliances. For this reason, it is quite cheap, easily available, and can be found easily at the waste collection site all over the world. Widespread exploitation of stand-alone renewable systems has led to popular use of self-excited induction generators (SEIGs) for supplying electrical energy in rural areas. However, SEIGs suffer from unsatisfactory voltage regulation and frequency variations. Several techniques of voltage and frequency controls using power semiconductor devices and reactive elements have been studied widely by the researchers over the years. In addition to review of these strategies, a novel configuration of single-phase generator based
3-phase induction machine was presented as a new alternative based on the recent two-series-connected and-one-isolated or ‘TSACOI’ configuration.

**Dissertation structure**

This thesis manuscript is divided in four main chapters, following a general introduction and leading to overall conclusions and perspectives. The first chapter presents the current status of rural electrification in Cambodia, its electrification policy, and its renewable energy resources. This chapter also describes the current situation of electronic waste worldwide and in Cambodia. This review provided the justifications for the introduction of the solution for rural electrification by reusing discarded electronic and electrical devices in a hybrid renewable energy system.

The second chapter aims to evaluate the environmental aspect of a proposed stand-alone renewable energy system using LCA methodology. The environmental impact associated with the life cycle conventional renewable system based on newly made components is also evaluated for comparison. The evaluation processes will follow these important steps: defining functional unit and system boundaries, system sizing and defining the life cycle inventories, and impact assessments. The sensitivity analysis of uncertain or assumed parameters is made to verify the reliability of the impact assessments.

The technological aspect of the proposed solution focused on the refurbishing and repurposing processes of the used power supply units is addressed in chapter 3. This chapter introduces the general structure, converter topologies, and type of control systems commonly found in power supply units. The main part of this chapter focuses on the general conception and common techniques to identify the issues and modify the structure of the power supply units to operate as a general purpose DC-DC converter. The power supply unit is successful converted to a MPPT controller providing optional energy transfer from the PV generator to load.

The fourth and last chapter proposes a new variable excitation technique derived from the TSCAOI topology for the induction generator of the pico-hydro plant. The overview of various voltage regulation techniques for three-phase and single-phase loads are first presented to illustrate the different advantages and disadvantages of each technique. The proposed single-phase generator based on three-phase generator is a modified version of an inverter-assisted topology where two winding will be supplied separately by two inverters for excitation, and the remaining winding is connected to load. Mathematical model of the generator is first explored. The performance of the proposed topology is studied in open loop by computer simulation and validated using experiments and a lot of characterization results are provided.
Chapter 1
Reuse for the Solution of Rural Electrification in Developing Countries
Chapter 1: Reuse for the Solution of Rural Electrification in Developing Countries

1.1. Introduction

Energy is considered to be one of the most important key drivers in economic development and human well-being of modern society. Electric energy is the final and most volatile energy form providing the most convenient way to transport and distribute energy to any remote areas. While most advanced economies have required secure access to sufficient sources of energy to drive their development and economic growth, millions of people in poor countries are in urgent need of electricity access.

Having access to modern energy services in rural communities drives economic growth, educational opportunities, and eliminate negative public health and environmental impacts. The first obvious solution is to extend the centralized electricity grid to remote areas. This solution faces several challenges including high initial cost, and low profit in return. An alternative is to rely on isolated energy micro-generation system which could provide communities immediate electricity access with lower investment cost without long delay. In many remote regions, renewable energy resources, such as solar, wind, and hydropower has the potential for a more environmental friendly and lower initial cost generation system.

Today, more and more people around the world rely on electric and electronic devices such as computer, phones, fans (in hot countries) and batteries as an essential part of their everyday lives. However, the rate at which they purchase and discard these devices is having a serious impact on our planet because they are being discarded before their useful lifetime. Reusing the devices for either the same usage or different applications with some repair and refurbishment extends their effective lifetime. Reusing products could be preferable over other end-of-life strategies as this is the least energy and material intensive solution.

Currently, reuse is often practiced by retailers driven by market demands for cheaper second-hand products. Often overlooked, some parts or components of a device can be repurposed for completely different applications. While it is possible to repair the whole devices, some components of the products such as power supplies, batteries, and electric motors have the potential for reuse as components in small renewable energy system for rural area. All these points will be developed in the following chapters, but the first one hereafter will be devoted to rural electrification and e-waste in terms of state of the art in general and in the context of the country in interest (i.e. Cambodia). The importance of providing electricity access to the rural communities is further clarified in the following section. This chapter also introduces a novel solution for rural electrification by reusing discarded electronic and electrical devices in a hybrid renewable energy system. This solution targets not only Cambodia but particularly the countries rich in renewable resources such as solar, hydro and wind energy.
1.2. Importance of Rural Electrification

From daily activities such as cooking, heating, cooling, and lighting to transportation and communication, to professional activities and industries, energy is required in one form or another. Energy is obtained from various conventional sources including fossil fuels (coal, natural gas, wood, nuclear and oil), and new renewable sources including hydroelectric power, solar, wind, sea, geothermal and biomass. It can be transported for use in solid, liquid or gas fuel or transmitted through conducting cables in electricity form. In electric current form, energy can be employed in almost every application with the exception in long distance and heavy transportation where fuels combustion remains the primary source.

While developed countries has secured access to plentiful sources of energy to drive their development, many developing countries lack sufficient and effective energy access. The majority of the people in these countries are still living in remote rural areas, which are not urbanized, with low population density and where most portion of land is devoted to agriculture. Without access to the centralized electricity grid, they rely on solid biomass such as dried wood for cooking, and animal power for agriculture.

According to the International Energy Agency (IEA) [101], in 2016, 1.1 billion people globally are without access to electricity. The majority of these people are in rural area living either in sub-Saharan Africa or developing Asia [102]. An estimated 2.8 billion do not have access to clean cooking facilities. A third of the world’s population, 2.5 billion people rely on the traditional use of solid biomass to cook their meals [101]. Around 120 million people use kerosene and 170 million use coal.

There has been some progress. For instance, since 2000, the number of people in developing countries with access to cleaner cooking, principally liquefied petroleum gas (LPG), natural gas and electricity, has grown by 60%, and the number of people cooking with coal and kerosene has more than halved [101]. However, strong population growth in developing countries, especially sub-Saharan Africa, has meant that the number of people relying on biomass for cooking has grown by 400 million people, despite growing awareness of the associated health risks related to traditional method of cooking.

1.2.1. General characteristics of rural energy use

Energy usage in rural areas can be broken down into the household, agricultural and small-scale rural industry sub-sectors and services [103]. Since the amount of energy use for services (health clinics, schools, street lighting, commerce, transport, etc.) is generally quite small in rural areas, it is often included in the rural industries sector. A few broad patterns in the use of energy in the rural areas can be described.

- Households are the major consumers of energy, their share of gross rural energy consumption averages over 85%. Most of this is consumed in the form of traditional energy sources used for cooking and heating, which constitutes 80 to 90% of the energy used by households.
- Agricultural activities involve energy used to power mechanical equipment and irrigation pump-sets. In general these activities do not include human and animal power that provide the bulk of agricultural energy input for the basic agricultural activities.

- Commercial energy, mainly kerosene and electricity where available, is mainly used for lighting. Small amounts of electricity are used to operate radios, television sets and small appliances in electrified villages. This has important implications for many rural electrification projects. Electricity demand curves in many rural areas are characterized by high peaks in the early evening hours and a low overall consumption.

- The energy consumption of rural industries, including both cottage industries and village level enterprises, amounts to less than 10% of the rural aggregate in most countries. Wood fuel and agricultural residues constitute the principal sources of supply for these activities, with electricity sometimes providing some motive power.

- Religious festivals, celebrations, burials and other occasional functions may also consume large amounts of fuel but may be missed by energy consumption surveys.

1.2.2. Benefits of electricity access in rural communities

Electrical energy is the most desirable form of energy since it is very easy to transform into types of energy that are useful to our lives. In developing countries, access to affordable and reliable energy services is fundamental to reducing poverty and improving health, increasing productivity, enhancing competitiveness and promoting economic growth. A secure and modern energy access can be referred to having reliable and affordable access to clean cooking facilities, a first connection to electricity and then an increasing level of electricity consumption over time to reach the regional average [102]. Access to electricity involves more than a first supply connection to the household; it also involves consumption of a specified minimum level of electricity which amount varies based on whether the household is in a rural or an urban area. In rural areas, this level of consumption could, for example, provide the use of a floor fan, a mobile telephone and two compact fluorescent light bulbs for about five hours per day. In urban areas, consumption might also include an efficient refrigerator, a second mobile telephone per household and another appliance, such as a small television or a computer.

Fig. 1-1: (a) Traditional cook stove; (b) LPG stoves; (c) high-efficiency cook stove. [104]
Modern energy access also includes provision of cooking facilities which can be used without harm to the health of those in the household and which are more environmentally sustainable and energy-efficient than the average biomass cook stoves currently used in developing countries. This refers primarily to biogas systems, liquefied petroleum gas stoves and advanced biomass cook stoves that have considerably lower emissions and higher efficiencies than traditional three-stone fires for cooking.

- Public health

One of the advantages of electrification is decreasing the harmful effects of burning fuels for cooking and lighting on the household’s health. The negative impacts of using kerosene lamps for lighting are well documented, including the release of toxins during combustion, contribution to upper respiratory disease, and safety concerns such as fire hazards and accidental ingestion [103]. The traditional way of cooking in poor communities provoke similar negative health. In 2009, out of 3 billion people who use traditional fuels for household energy, 1.5 million died from the high particulate air pollution created by these fuels in poorly ventilated spaces [105].

Household energy is itself a basic human need and is central to the satisfaction of basic nutrition and health needs. For example, 95% of staple foods in developing communities must first be cooked prior to consumption [106]. Household energy drives activities such as cooking and heating, pumping technologies for irrigation systems, and water and sanitation services. Most food (especially meats) cannot be stored without refrigeration for extended periods of time. As a result, either already scarce food is wasted or people are forced to consume it once it has expired. Thus, access to household energy is a precursor to the provision of all essential infrastructure services.

If health centers are better equipped, the quality of health care rises and hygiene improves. Electrification enables the refrigeration of medication and vaccines, the use of electric medical equipment and focused lighting in the consultation rooms. Hospitals are able to offer 24h emergency services. Hospitals that are unable to refrigerate medicines and vaccines greatly shorten their storage period. Considering that clinics near rural areas are most likely short in medical supply already, refrigeration can dramatically enhance the clinics’ utility.

- Communities development

Energy infrastructure is often a prerequisite for income generating activities, increasing productivity and education. Lack of access to household energy and associated infrastructures inhibits economic growth and development in developing countries [107]. Energy consumption increases with development. Fig. 1-2 demonstrates this by charting annual country per capita energy consumption data [109] against the UN composite index of development [110]: the Human Development Index (HDI). The United Nations Development Programme (UNDP) uses the HDI as a composite index measuring average achievement in three basic dimensions of human development: a long and healthy life, access to knowledge, and a decent standard of living. In Fig. 1-2, each point on the graph represents a single
country. The x-axis is the total energy in gigajoules per capita per year consumed by a country. The y-axis is the HDI ratio (scaled from 0 to 1) for a given country. Expected increases in the quality of life and standards of living in developing countries will likely correspond to increases in total energy consumed per capita.

![Graph showing correlation between energy consumption and HDI](image)

Fig. 1-2: Per capita energy consumption and the Human Development Index (HDI). [108]

- **Education**

Equipping the schools with necessary electrical equipment offers better working conditions to pupils and students. At night, electric lighting helps them to enjoy their self-study without serious health issues. The conventional source of lighting, kerosene lamps, typically producing between 1 to 6 lux [111], is insufficient for the purpose of reading. This light output is well below the recommended lighting requirements for task-specific activities (50 lux) and reading (200 to 500 lux) [112, 113]. Although kerosene is higher on the “energy ladder” than charcoal and wood, it has been shown to be more expensive per unit of light output than electric-based alternatives [111].

![Graph showing correlation between electricity consumption and education index](image)

Fig. 1-3: Correlation of electricity consumption and education index based on 120 countries. [114]
Low-power information technologies are transforming the education landscape in many developing countries. Examples of these technologies include low-cost computers, tablets, and e-readers. These technologies require power, but by design are battery driven and have a low power draw (e.g. 2 watts). Some of these information technology devices are also internet enabled, which decreases the “digital divide” between developed and developing countries or between cities and rural areas. Fig. 1-3 shows a strong correlation with electricity consumption per capita and higher scores on the education index, a proxy for the mean years of schooling a student receives across 120 countries. Indeed, recently access to the internet was declared to be a basic human right by a United Nations Human Rights Council [115].

- **Inequalities**

Like other resources, electrical energy is distributed very evenly among the developed and the developing world. There are large inequities associated with the global distribution of energy. UNDP [116] states, in 2000, that the richest 20% of the world’s population uses 55% of primary energy, while the poorest 20% uses only 5%. In general, the poor in developing communities spend more time and effort to obtain energy services that tend to be of lower quality than the energy services available to the rich. Unsurprisingly, there is unequal access to energy services in rural populations versus urban populations.

Lack of electrification also reinforces inequality among different socio-demographic groups specifically in gender. Women and children often spend more time than men in the living spaces adversely impacted by traditional energy sources, thus disproportionately carrying the health burden, with over half of the deaths occurring among children. Nearly 800,000 children die each year as a result of indoor air smoke from cooking [105].

- **Environment**

The environmental effects of unsustainable energy use in developing countries are well documented [117] and include mass deforestation. Deforestation, which is often illegal, is made to produce charcoal through the inefficient pyrolysis of wood. This kind of environmental degradation disproportionately and negatively affects the poor, who often directly rely on environmental resources for their livelihood. The effects of unsustainable energy use are local, regional, and global.

Energy use patterns can be linked directly to environmental challenges, such as urban and indoor air pollution, acidification, and global warming. Reference [108] argues that unsustainable energy consumption is arguably the single largest contributing factor to global detrimental environmental impacts.

**1.2.3. Sustainable renewable energy solution for rural electrification**

The inevitable increase in population and the economic development that will necessarily occur globally have serious implications for the environment, because energy generation processes (e.g., generation of electricity, heating, cooling, or motive force for transportation vehicles and other uses) are polluting and harmful to the ecosystem. The growing
consumption of fossil fuels and the higher demand for sufficient energy supplies are a major cause of climate change [118]. Climate change, most importantly global warming is a grave concern not only for power sector but for economic and well-being of every country. To address such energy challenges as climate change, the growing demand for energy and energy security, effective renewable technologies are needed. Renewable energy, such as solar, wind, hydropower, and biomass, has the potential to mitigate the negative impacts of climate change and CO₂ emissions which also lead to a reduction in global warming [119].

- **Distributed energy generation systems**

Providing access to households in rural communities with centralized provision faces significant challenges. Extension of centralized grid electricity lines is nearly impossible for utilities to be profitable [120] due in large part to low rural household energy consumption, insufficient population densities, high construction cost of transmission lines, and transmission losses. As these projects require long planning and implementation time-horizons, they are unable to address the present challenges and effects from the use of traditional fuels by rural populations. Further, because of the significant capital costs, investments can be politically motivated or ignore informal settlements. Finally, centralized provision requires lengthy and sometimes complex supply chains, which when broken cause intermittent failure and unreliable service.

In contrast to centralized system, distributed energy micro-generation technologies can contribute significantly to providing energy access to the remote areas. These systems can have lower life cycle cost and provide a diversity of technologies to meet specific energy end-use applications in developing communities more appropriately. Additionally, they are less sensitive to corruption and governance instability and are amenable to the relatively low load densities typical of developing rural communities. There are reasons to suggest that the monthly electricity consumption by households in rural communities in developing countries is relatively low [121]. This makes distributed energy technology ideally suited to meet this demand. Distributed energy technologies also have shorter time-horizons for planning and implementation.

Using distributed renewable energy provision is an opportunity to create a low-carbon energy infrastructure in rural communities from the onset of development. Thus, in some ways, rural communities are able to “leapfrog” historical carbon-intensive energy infrastructures. The concept of technological leapfrogging is that communities with underdeveloped infrastructure or technology can progress more rapidly to adopting current technology without first having to proceed through a sub-optimal historical technology.

- **Hybrid energy generation systems**

Reference [122] argues that providing electricity accesses through decentralized renewable energy, particularly to the rural poor, can positively redirect the ecological and social factors that contribute to climate change. Common drawback with solar or wind energy is their unpredictable nature. Standalone photovoltaic (PV) or wind energy system, do not produce
usable energy for considerable portion of time during the year. Combination of PV and wind or hydro in a hybrid energy system reduces the battery bank and diesel requirements. Hybrid renewable energy system (HRES) is any energy system with more than one type of generator. Most often, HRES consist of a conventional generator powered by diesel, and a renewable energy source such as PV, wind, hydro and a combination of them. Through the hybridation of renewable energy, with combustion generator and battery storage, it is possible to generate electricity in rural or remote areas more competitively as compared to conventional power system or renewable system based on single source.

1.3. Energy Status in Rural Cambodia

The Kingdom of Cambodia is located in the tropical region of Southeast Asia in the Lower Mekong region having a total landmass of 181,035 km$^2$ and a population little over 15 million people. The physical landscape is dominated by the lowland plains around the Mekong River and the Tonle Sap Lake. The climate in Cambodia is tropical and subject to both southeast and northwest monsoons. The southeast monsoon, which coincides with the rainy season, extends from May to October. The northwest monsoon brings a cool but drier period from November to April. The temperatures are fairly uniform in the central basin area with an average of about 27°C [123]. As one the least developed countries in the region and in the world, a large proportion of the population is living in rural areas. The country economic rely mainly on agriculture, then garment sector, foreign aid and tourism. Cambodia has achieved high rates of economic growth over recent decades; the real gross domestic product (GDP) grew on average 8.0 % per annum [124]. Despite its rapid economic development, the country still lacks the infrastructure required for the energy sector to match the pace of development.

1.3.1. Energy situation

Cambodia has made considerable progress in reforming the power sector despite its violent past. Nevertheless, the electrification rate remains low in rural area. Practically all people in urban areas can access electricity from different sources, although price and quality remain crucial concerns. However, only a small fraction of the rural population has been electrified. Moreover, electricity cost remains one of the highest in the region and the world due to its heavy reliance on imported electricity, diesel and coal [124].

Per capita consumption of electricity reached 190 kWh in 2011, increasing almost fourfold from 54 kWh in 2005 [125]. Electricity transmission in 2011 was diffused by fragmented grids. A national grid incorporating 68% of the total energy input would serve only 48.7% of total consumers. This grid covers only a few areas of the country including Phnom Penh, Kandal, Kampong Speu, Takeo, and Kampong Chnang province. Other grids inputted by local electricity generators and imported from neighboring countries supplied electricity to other parts of the country.
- **Producers**

Electric power supplied throughout the country is sourced from three different types of licensees including the state-owned Electricité du Cambodge (EDC), Independent Power Producers (IPPs), and the consolidated licensees including Rural Electricity Enterprises (REEs) [124]. Electricity is supplied to Phnom Penh and some other major cities by EDC and IPPs while most of the rural areas are supplied by different sorts of REEs. More than 98% of total energy is supplied by IPPs in 2015.

- **Energy generation**

According to annual report on power sector by Electricity Authority of Cambodia (EAC) [126], in 2015 there are 4 main power plant types that supply the electricity in Cambodia: 1 - Hydropower Plants, 2 - Diesel power Plants, 3 - Thermal Power Plants using coal and 4 – Plants using wood and other biomass. Total electricity generation in Cambodia during 2015 was 4,489 million kWh, compared to 3,058 million kWh in 2014 which is the increase by 46.79%.

In 2010, 968 million kWh of energy have been generated, 93% coming from diesel/HFO plants. The three initial large Hydropower Plants in operation are: Kirirom1 connected to Phnom Penh power system, Ratanakiri connected to Ratanakiri power system of EDC, and Mondulkiri, supplying electricity to provincial town of Mondulkiri. Between 2011 and 2015, four additional hydropower plants (Kirirom3, Kamchay, Stung Atay, Lower Stung Russei Chrump and Stung Tatay connected to the National Grid) and two additional coal power plants (Coal Power Plant of Cambodia Energy Limited and Coal Power Plant of C.I.I.D.G.Erdos Hongjun Electric Power Co., Ltd in Sihanoukville) were put in operation. In 2015, the majority of energy outputs are generated from hydropower plants and coal power plants as illustrated in Fig. 1-4.

![Fig. 1-4: Electricity generated by types of plants in 2010 and 2015 (million kWh).](image)

Given the limited domestic production, electricity is imported from neighboring countries to satisfy the rising demand. In 2010, 1.547 GWh of energy, more than half of total energy
required, was imported from Vietnam, Thailand and Laos. The demand of imported energy was decreasing since 2013 due to the additions of domestic power plants. In 2015, 1.526 GWh is imported from the 3 neighboring countries, which is around 25% of the total energy needed.

Table 1-1: Data of electricity sector of Cambodia at a glance (EAC annual report). [127]

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Generated</td>
<td>million kWh</td>
<td>968</td>
<td>1,018</td>
<td>1,423</td>
<td>1,769</td>
<td>3,058</td>
<td>4,489</td>
</tr>
<tr>
<td>Imported from Thailand</td>
<td>million kWh</td>
<td>385</td>
<td>430</td>
<td>535</td>
<td>579</td>
<td>523</td>
<td>307</td>
</tr>
<tr>
<td>Imported from Vietnam</td>
<td>million kWh</td>
<td>1,162</td>
<td>1,392</td>
<td>1,560</td>
<td>1,691</td>
<td>1,266</td>
<td>1,200</td>
</tr>
<tr>
<td>Imported from Laos</td>
<td>million kWh</td>
<td>5.7</td>
<td>6.59</td>
<td>9.0</td>
<td>10.73</td>
<td>13.7</td>
<td>18.3</td>
</tr>
<tr>
<td>Total Import</td>
<td>million kWh</td>
<td>1547</td>
<td>1,829</td>
<td>2,104</td>
<td>2,281</td>
<td>1,803</td>
<td>1,526</td>
</tr>
<tr>
<td>Total Energy Available</td>
<td>million kWh</td>
<td>2,515</td>
<td>2,848</td>
<td>3,527</td>
<td>4,051</td>
<td>4,861</td>
<td>6,015</td>
</tr>
<tr>
<td>Generation Capacity</td>
<td>MW</td>
<td>360</td>
<td>569</td>
<td>582</td>
<td>949</td>
<td>1,511</td>
<td>1,657</td>
</tr>
<tr>
<td>Number of Consumers</td>
<td>Thousands</td>
<td>673</td>
<td>811</td>
<td>992</td>
<td>1,199</td>
<td>1,425</td>
<td>1,859</td>
</tr>
</tbody>
</table>

Table 1-2: Number of Villages Covered by licenced areas by end of 2015 (EAC). [127]

<table>
<thead>
<tr>
<th>Name of Province</th>
<th>Total Number of Villages</th>
<th>Villages covered by licenced area</th>
<th>Percent of villages covered by licenced area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phnom Penh</td>
<td>900</td>
<td>863</td>
<td>95.88</td>
</tr>
<tr>
<td>Kandal</td>
<td>912</td>
<td>869</td>
<td>95.29</td>
</tr>
<tr>
<td>Preah Sihanouk</td>
<td>111</td>
<td>101</td>
<td>90.99</td>
</tr>
<tr>
<td>Kampong Speu</td>
<td>1,358</td>
<td>913</td>
<td>67.23</td>
</tr>
<tr>
<td>Siem Reap</td>
<td>924</td>
<td>564</td>
<td>61.04</td>
</tr>
<tr>
<td>Steung Treng</td>
<td>128</td>
<td>34</td>
<td>26.56</td>
</tr>
<tr>
<td>Ratanakiri</td>
<td>240</td>
<td>50</td>
<td>20.83</td>
</tr>
<tr>
<td>Preah Vihear</td>
<td>229</td>
<td>71</td>
<td>31.00</td>
</tr>
<tr>
<td>Total</td>
<td><strong>14,073</strong></td>
<td><strong>9,651</strong></td>
<td><strong>68.57</strong></td>
</tr>
</tbody>
</table>

1.3.2. Rural energy status

The electrification rate is 20.3% in 2007 and 34.1% in 2011 [125]. In 2015, 68% of villages in Cambodia are covered by licensed electricity producers as shown in Table 1-2. According to World Bank [128], 12.4 million people live in rural area in 2016, 49.2% has access to electricity. In urban area, the electricity access is 96.9%.

In rural Cambodia, the REEs are providing electricity services from recharging batteries to distribution to households. System inefficiencies, high fuel costs of imported diesel oil and different electricity suppliers in Cambodia bring serious unfairness on the electricity tariff in rural areas. Average electricity tariff for residential consumers supplied by Electricity Authority of Cambodia is $0.17/kWh while that supplied by REEs is $0.66/kWh [129]. This rate for rural area is much higher than the residential consumer tariff of the national power utility in Phnom Penh.
- **Energy for cooking**

In rural areas, the majority of the people still use wood, charcoal and kerosene for their energy needs. As illustrate in Fig. 1-5, Charcoal is a major source of energy in rural areas of Cambodia, although its production is currently illegal. In 2006, with financial support from the United Nations Development Programme, UNDP, the Ministry of Industry, Mines and Energy (MIME), with technical assistance from the international non-governmental organisation (NGO) Groupe Energies Renouvelables, Environnement et Solidarités (GERES), Cambodia launched “Preparatory Activities for a Rural Energy Development Program” project [130]. The project included a study on rural household energy demands, particularly in Kampong Speu and Svay Rieng provinces. A number of samples were selected among 1,050 households in Kampong Speu and 1,109 in Svay Rieng to survey their energy usage.

![Energy sources used for cooking by percentage of population in urban and rural areas of Kampong Speu.](image)

Fig. 1- 6: Energy sources used for cooking by percentage of population in urban and rural areas of Kampong Speu. [130]
Cooking is the most basic activity need in Cambodia’s households which still rely significantly on biomass fuels. Urban households typically use several energy sources for cooking. The most common are firewood, LPG, charcoal and electricity, the latter mainly used for rice cooking. Household energy consumption in rural areas follows a pattern that is similar to cooking practices in urban areas. Fig. 1-6 and Fig. 1-7 depict energy the mix used for cooking in both urban and rural area in Kampong Speu and Svay Rieng. Though there is difference in usage patterns, in the two provinces the use of electricity, LPG and charcoal is significantly higher in urban areas than in rural areas. The demand for wood in cooking is still high for urban areas despite having access to electricity grid since it is a cheaper alternative compared to electricity and LPG costs.

- **Energy for lighting and appliances**

Urban areas in the two provinces show energy consumption patterns similar to those found in other Asian countries. Besides lighting, a considerable variety of appliances can be found in households ranging from rice cookers to refrigerators, fans, TVs and other electronic equipment including the occasional computer. In both provinces urban electrification rates were high with 98% in Kampong Speu and 97% Svay Rieng. Candles and kerosene were still in widespread use particularly in Svay Rieng where electricity is provided by cross-border connections from Vietnam.

In the absence of grid supply, rural households in both provinces satisfy their lighting needs using lead acid batteries, as depicted in Fig. 1-8, and kerosene lamps. Fig. 1-9 and Fig. 1-10 illustrate that higher electrification rates in rural Kampong Speu, 27% of households connected to EDC, REE or their own generators, reduces the prevalence of batteries and kerosene. While 62% of the Kampong Speu rural households use batteries, the figure climbs to 84% in Svay Rieng where only 7% are supplied by grid electricity. Despite the widespread use of batteries, kerosene is still a very important source for lighting showing user percentages of 62% and 75% respectively for Kampong Speu and Svay Rieng. This demonstrates that rural households maintain a portfolio of energy options, probably in an attempt to satisfy energy service needs at a minimum cost.
1.3.3. Government policies

Limited financing, inadequate policies and weak institutional frameworks are the main problems that have encompassed rural electrification in most developing countries.
Therefore, the Royal Government of Cambodia (RGC), have made various attempts in financing and facilitating the increase in the level of rural electrification in the last two decades.

- **Institutions**

There are three main institutions that have considerable power in the electricity sector in Cambodia: the Ministry of Mines and Energy (MME), the Electricity Authority of Cambodia (EAC) and Electricité du Cambodge (EDC). MME and EAC are two main institutions playing important roles in governing the electric power sector in Cambodia. Whilst MME is mainly responsible for the formulation of policies and strategies, EAC is a legal public entity being granted the right from RGC to be an autonomous agency to regulate the electricity services and to govern the relation between the delivery, receiving, and use of electricity.

- **Ministry of Mines and Energy [131]**

The Ministry of Mines and Energy (MME) is responsible for controlling the whole power sector. The Ministry has the duty to set and administrate: Energy Policies, Electric Power Strategies, Power Development Plan, Technical, Safety and Environmental Standard and other duties in power sector [132].

- **Electricity Authority of Cambodia [132]**

The EAC is a legal public entity, being granted the right from the RGC to be an autonomous agency to regulate electricity services and to govern the relation between the delivery, receiving and use of electricity. The EAC is responsible for controlling the activities of electric power services and uses. The Authority has the duty to issue, revise, revoke or suspend the licenses for electric power services, to approve tariff, to issue the regulations to control, to impose penalty and to revolve the disputes related to the electric power services and uses.

- **Rural electrification policy**

The Government of Cambodia has envisaged the ambitious plan for the rural electrification as below [133]:

(i) By the year 2020, all the villages of the Kingdom of Cambodia will have electricity of some type; and

(ii) By the year 2030, at least 70% of households will have access to grid-quality electricity.

To implement the Rural Electrification Policy, the government has established a Rural Electrification Fund (REF) [134], which is an institution integrated with EDC to promote the equity of access to electricity supplies. The objectives of REF are (1)- to promote equitable rural electrification coverage by facilitating the population’s access to electricity at affordable price for economic, social and household uses, thus contributing to poverty reduction, and (2)- to promote and encourage private sector to participate in providing sustainable rural
elec

trification services; in particular the exploitation of and economic application of technically and commercially well proven new and renewable energy technologies.

At present, Department of REF of EDC has four programs [134] for transferring the benefits resulting from the development of electricity to the population in rural area consisting of (1)- Program for Power to the Poor (P2P), (2)- Program for Solar Home System (SHS), (3)- Program for Providing Assistance to Develop Electricity Infrastructure in Rural Areas, and (4)- Program for implementing the subsidy scheme and providing electricity for pumping for agricultural irrigation for licensees connected to the grid system to reduce the tariff for sale of electricity in provinces and cities.

- Green growth and climate change

In 2010, Cambodia developed ‘The National Green Growth Roadmap’ for furthering development to benefit the people and conserve and restore the natural capital base to continue economic growth within the limits posed by the environmental carrying capacity [135]. The National Green Growth Roadmap focuses on addressing the following seven goals: (1) access to clean water and sanitation, (2) access to renewable energy, (3) access to information and knowledge, (4) access to means for better mobility, (5) access to finance and investments, (6) access to food security (agriculture) and non-chemical products, and (7) access to sustainable land use. The ‘National Strategic Plan on Green Growth’ is approved in 2013 to promote the sustainable long-term economic, social and environmental development of the country [136].

In 2013, the National Climate Change Committee has announced the official promulgation of the Cambodia Climate Change Strategic Plan 2014-2023 (CCCSP) [137]. This is the first ever comprehensive national policy document responding to the climate change issues. It has reflected Cambodia’s political will, firm commitment and readiness for reducing climate change impacts on national development, and contributing to global efforts for mitigating GHG emissions under the United Nations Convention on Climate Change (UNFCCC). In 2015, like most countries, Cambodia signed the historic agreement, ‘Paris Agreement’, in the United Nations Climate Change Conference (COP21). The agreement sets global goals of peaking greenhouse gas (GHG) emissions “as soon as possible” and preventing the increase in global temperature by the end of the century from exceeding 2°C (3.6°F) and ideally no more than 1.5°C (2.7°F) [138].

Whilst Cambodia produces relatively low greenhouse gas emissions, the Paris Agreement is of major significance to the Kingdom as it is one of the countries that are most vulnerable to weather-related disasters and other adverse effects of climate change.

1.3.4. Renewable energies for rural areas

In line with sustainable development path, electrification with the aid of renewable energy resources is a key element for the developing countries. Considering the existing governmental policy of enabling 70% of rural households to reach reliable electricity services by 2030, and following the Cambodia Green Growth Roadmap and the Cambodia Climate
Change Strategic Plan 2014-2023, the renewable energy resources are found as the best option for rural electrification. Furthermore, renewable resource development will help create green investments, jobs, and technologies that are correlated with green growth and environmental sustainability.

- **Hydropower**

Cambodia is one of the richest countries in hydropower resources, having the third largest hydropower potential in the Mekong Basin. The potential of hydropower is estimated at 8,600-15,000 MW of installed capacity, of which 90% is located in the Mekong River basin and its tributaries. The remaining 10% is in the southwestern coastal areas [139]. According to the government, 72% of the prospective hydropower is located in the northeastern region of the country, 27% in the southwestern region, and another 1% in other regions [140].

Currently there are several hydropower plants in operation providing almost half of the total domestic energy production. Recent large scale completed hydropower plants include:

- Kamchay Hydroelectric Project, 190 MW (Fig. 1-11): operation in 2011.
- Kirirom Extension Phase II Hydroelectric Project, 18 MW (Fig. 1-11): operation in 2012.
- Stung Atay Hydroelectric Project, 120 MW (Fig. 1-12): operation in 2013.
- Stung Tatay Hydroelectric Project, 246 MW (Fig. 1-12): operation in 2014.

![Fig. 1-11: (a) Kamchay hydro dam (Kampot); (b) Kirirom 3 dam (Koh Kong).](image)

Hydropower plants’ electricity supply is significantly vulnerable to seasonal variations in hydrology, and climate phenomena. During the dry season, the country is very likely to run short of water for hydropower plants’ operations. The development of large-scale hydropower also causes negative impacts for socio-economic development and environmental sustainability. The alteration of the water flow is anticipated and fisheries production is expected to decline. The extinction of species is anticipated due to accumulative impacts of proposed large-scale hydroelectric dams, particularly on the mainstream of the Mekong River [141].
Fig. 1-12: (a) Stung Atay hydro dam (Pursat); (b) Stung Tatay hydro dam (Koh Kong)

Beside the large-scale hydropower plant, there are also a lot of potential sites for smaller micro or pico-hydropower for a house or a community in the remote area. There is anecdotal evidence to suggest that some villagers in Pailin municipality and Mondulkiri and Ratanakiri provinces near the border of Vietnam in North East Cambodia are operating pico-hydro units in basic run-of-river installations [142]. These units were most likely bought from China or Vietnam, but no data exists on their prevalence or performance.

- **Biomass energy**

Biomass energy includes agricultural residues, fuel wood, animal wastes, municipal wastes and other fuels derived from biological sources. One of the common applications of solid biomass is in direct combustion steam turbine that needs more than 1 MW [143]. Traditional biomass is composed of wood and charcoal which are primarily used for cooking in rural areas and by a small segment of households in urban areas. This has put considerable pressure on forests in Cambodia. Agricultural and forestry residues such as rice husk, rice straw, sugarcane, corn cob, cassava stalk, bagasse, logging residues, mill residues, etc. contribute considerable amount of biomass energy potentials to Cambodia. Livestock wastes (manure) such as cattle waste and pig waste are used for biogas production.

According to the Electricity Authority of Cambodia annual report on energy sector 2014, Angkor Bio Cogen Co. Ltd., Phnom Penh Sugar Co. Ltd., IED Invest (Cambodia) and Cam Chilbo Electric Power Co. Ltd. use wood and agricultural products or waste as fuel to generate electricity in Cambodia. From 2013 to 2014, electricity generated by biomass increased from 6.68 GWh to 16.79 GWh. By 2016 there had been another jump, to 42.44 GWh [144]. Despite this growth the production is comparatively small, producing less than 1 percent of the kingdom’s electricity.

- **Solar energy**

Renewable solar energy options are being pursued by many countries which have high monthly average daily solar radiation level. Average sunshine duration in Cambodia is 6-9 hours per day and solar radiation is estimated at 5kWh/m² per day; as a comparison, the average sun hour is between 3-5 hours in France. This creates a huge potential for solar
Photovoltaic (PV) based system. Up to 2012, only 2 MW of solar power has been installed [145].

Fig. 1-13: Solar resource map of Cambodia. [146]

The country’s solar power is driven mainly by donor projects extending from pilot stages. With the assistance of the World Bank, the Bulk Purchase, and the SHS Installation project implemented by the government’s REF (Rural Electrification Fund) [147], the goal is to install 30W and 50W SHS for 12,000 households in rural areas where mini or the national grid is not anticipated for the next 5-10 years. This subsidized project allows beneficiary households to repay the cost of system installation to the REF in installments of up to four years. As of August 2012, the projects have installed 12,093 SHS units throughout eight provinces (Fig. 1-14). This SHS have provided the beneficiaries to use TV, radio, recharge their phone battery and have lighting at night for 3-4 hours every day.

In April 2017, The Asia Development Bank (ADB) said that it will lend $9.2 million to Singapore company Sunseap Group to build Cambodia’s first large solar farm in Bavet. Sunseap has signed a 20-year power-purchase agreement with Electricité du Cambodge for the planned facility. The 10MW production is anticipated to meet around a quarter of Bavet city’s energy needs. [148]
Despite the emerging market of solar PV products, cost remains the crucial challenge of solar energy system for acceptance by rural households. The upfront costs of solar powered solutions are significantly expensive and rural households are low-income or poor. Moreover, the lifespan of a battery used with a solar system is about 3-4 years, so maintenance cost increases. The uptake of solar power will expand as long as the cost of solar technologies decline to a level that is competitive with the current cost of the electricity tariff or battery charging in rural areas.

- **Wind power**

The Cambodian Research Centre for Development [149] pointed out that wind energy could deliver a total electrical capacity of 3,665 GWh per year. However, World Bank gives a...
theoretical potential wind capacity of 65 GW and a potential production capacity of 154 TWh per year given the land area with sufficient wind speeds [150].

The wind resources of Cambodia are low in most parts of the country, reflecting its topography of basins and lowlands rimmed by mountain ranges. Wind speeds range from 6 to 7 m/s over about 6,155 km² and between 7 and 8 m/s over about 315 km² and would therefore be sufficient for wind turbines; combined, however, these areas represent only 3% of Cambodia’s total land area (shown in Fig. 1-15).

The development of this renewable resource is in the early stages. So far, only one wind project, a single wind turbine installed in Sihanoukville in 2010, has been pilot-tested in Cambodia. The project, costing roughly US 1.74 million, is co-funded by Cambodia’s Sihanoukville port authority (48%), Belgium (28%), the EU (24%), and was inaugurated in January 2010 [119]. The pilot project was to demonstrate that wind power could be an effective energy source in Cambodia as well as in the region. The generated electricity is to supply the Sihanoukville port.

1.4. Status of E-waste

The electronics industry is the world’s largest and fastest growing manufacturing industry, and as a consequence of this growth, combined with rapid product obsolescence, discarded electronics, is now the fastest growing waste stream in the industrialized world. As illustrated in Fig. 1-16, electronic waste (e-waste), or waste electrical and electronic equipment (WEEE) is a term used to cover all items of electrical and electronic equipment (EEE) and its parts that have been discarded by its owner as waste without the intent of re-use.

![Fig. 1- 16: Pile of e-waste in Switzerland (Greenpeace). [152]](image)

E-waste may be categorized in different ways: by product type, product size or even treatment technology. The European Union’s WEEE directive [153] previously had a product-oriented categorization, and in the recent recast, moved to a treatment-oriented categorization, with six main categories:
- Temperature exchange equipment, also commonly referred to as “cooling and freezing equipment”, comprised of refrigerators, freezers, air conditioners, etc.

- Screens including televisions, monitors, laptops, notebooks and tablets.

- Small equipment typically comprised of vacuum cleaners, microwaves, fans, toasters, electric kettles, electric shavers, scales, calculators, radio sets, video cameras, electrical and electronic toys, small electrical and electronic tools, small medical devices, small monitoring and control instruments.

- Lamps, which includes all types of straight fluorescent lamps, compact fluorescent lamps, fluorescent lamps, high intensity discharge lamps and LED lamps.

- Small IT and telecommunication equipment, which includes products such as mobile phones, GPS devices, pocket calculators, routers, printers, telephones, etc.

- Large equipment, which typically includes products such as washing machines, clothes dryers, dish washers, electric stoves, large printing machines, copying equipment and photovoltaic panels.

1.4.1. Quantity of e-waste worldwide

E-waste is hazardous and contains containing many different substances which are toxic, and create serious pollution upon disposal. Rapid product innovation, miniaturization and replacement, especially for information and communication technology (ICT) products and consumer equipment are fuelling the increase of e-waste. The growth is beginning to reach disastrous proportions and industrialized countries all over the world are just now beginning to grapple with the problem.

E-waste produces much higher volumes of waste in comparison to other consumer goods. Once consumers purchased a stereo console or television set with the expectation that it would last for a decade or more, but this rarely happen. Consumers now rarely take broken electronics to a repair shop as replacement is now often easier and not that expensive compared to repair. The average lifespan of a computer has shrunk from four or five years to two years [154]. Part of this rapid obsolescence is the result of a rapidly evolving technology. But it is also clear that such obsolescence and the throw away ethic results in a massive increase in corporate profits, particularly when the electronics industry does not have to bear the financial burden of downstream costs.

Globally, sales of EEE have boomed in the last decades. As shown in Fig. 1-17, the total amount of EEE put on the market has increased from 51.33 million tons in 2007 to 56.56 million tons in 2012, as per United Nations University (UNU) estimates [155]. Asia emerges as the largest consumer of EEE, accounting for nearly half of EEE put on the market, with 20.62 million tons in 2005, increasing to 26.69 million tons in 2012. The increase is particularly striking given the drop in EEE sales in Europe and the Americas in 2012 following the global financial crisis.
According to the UNU global e-waste monitor [155], the global quantity of e-waste generation in 2014 was around 41.8 million tons. The global quantity of e-waste in 2014 is comprised of 1.0 million tons lamps, 3.0 million tons of Small IT, 6.3 million tons of screens and monitors, 7.0 million tons of temperature exchange equipment (cooling and freezing equipment), 11.8 million tons large equipment, and 12.8 million tons of small equipment. The amount of e-waste is expected to grow to 49.8 million tons in 2018, with an annual growth rate of 4 to 5%. The quantities of the collection outside formal take-back systems are not documented systematically. However, they are likely to be the gap between e-waste generated, official collected and the e-waste in the waste bin. Official data for the transboundary movement of e-waste (mostly from developed to developing countries) are unknown.

Most of the e-waste was generated in Asia: 16 million tons in 2014. This was 3.7 kg for each inhabitant. The highest per inhabitant e-waste quantity (15.6 kg/inh.) was generated in Europe. The whole region (including Russia) generated 11.6 million tons. The lowest quantity of e-waste was generated in Oceania, and was 0.6 million tons. However, the per inhabitant amount was nearly as high as Europe’s (15.2 kg/inh.). The lowest amount of e-waste per inhabitant was generated in Africa, where only 1.7 kg/inh. was generated in 2014. The whole continent generated 1.9 million tons of e-waste. The Americas generated 11.7 million tons of e-waste (7.9 million tons for North America, 1.1 million tons for Central America, and 2.7 million tons for South America), which represented 12.2 kg/inh.
1.4.2. Current routes for End-of-Life of EEE

Electronic products at their end-of-life are managed by one of two end-of-life management practices: they are either collected for recycling (they may then be subsequently reused, refurbished, or recycled for materials recovery), or disposed in landfills or waste-to-energy incinertors.

- **Disposal of E-waste**

E-waste from consumers is destined for one of the following:

- Into direct reuse, often through donations and consumer-to-consumer sales (e.g., eBay and Amazon), second-hand EEE provides large sections of the population the opportunity to enjoy the benefits of modern gadgets and appliances at more affordable prices. Products may be reused domestically, or exported, often to lower-income countries.

- For function recovery as source for reusable parts, often through asset recovery programs. Repaired and refurbished gadgets are also in demand, both in the developed and developing world, because of their price competitiveness. In addition, prolonging the lifetime of many products also reduces their ecological footprint by preventing resource-intense production.

- Into recycling for material and energy recovery, following collection either through formal take-back or informal collection systems to reclaim various raw materials and energy. In several countries around the world, including in Asia, formal take-back systems have been set up to channel e-waste towards industrialized material and energy recovery facilities. However, of the estimated 48.1 million tons e-waste generated globally, only 6.5 million tons are collected by official take-back systems [155].

- Disposed into landfill, either following earlier processing or together with municipal solid waste.

- **E-waste management system scenarios**
The e-waste management system can be categorized into one or a mixture of the following scenarios:

- **Official take-back systems:** In this scenario, usually under the requirement of national e-waste legislation, e-waste is collected by designated organizations, producers and/or by the government. This happens via retailers, municipal collection points and/or pick-up services. The final destination of the collected e-waste is state-of-the-art treatment facilities, which recover the valuable materials in an environmentally-sound way and reduce the negative impacts. In the European Union, roughly 40% of the annually generated e-waste is officially reportedly treated in this manner; in the United States and Canada, the level is around 12%, 24 to 30% for Japan and China [155].

- **Disposal of e-waste in mixed residual waste:** In this scenario, consumers directly dispose of e-waste through the normal dustbins together with other types of household waste. As a consequence, the disposed of e-waste is then treated with the regular mixed waste from households. Depending on the region, it can either be sent to landfill or municipal solid waste incineration with a low chance of separation prior to these final destinations. Neither of these two destinations is regarded as an appropriate technique to treat e-waste, because it leads to resource loss and has the potential to negatively impact the environment. The e-waste in a landfill can lead to toxin leaching, and if e-waste is incinerated, emissions into air occur. This disposal scenario exists in both developed and developing countries.

- **Collection of e-waste outside of official take-back system in developed countries:** In developed countries, e-waste is also collected by individual waste dealers or companies and then traded through various channels. Possible destinations for e-waste in this scenario include metal recycling, plastic recycling, specialized e-waste recycling and also export. Usually, e-waste handled in this scenario is not reported as part of the official treatment amount by the established take-back systems. E-waste categories that are typically handled by the informal collection are temperature exchange equipment, large equipment, screens and IT products. The main feature of this scenario is that e-waste is traded freely, and usually, its quantity is not systematically documented or reported to authorities, due to lack of specific reporting framework or requirements. In this scenario, e-waste is often not treated in the state-of-the-art facilities, and there is a potential that e-waste is shipped off to developing countries. There is a substantial amount of e-waste being collected in developed countries and then traded to developing countries. The demand for inexpensive second-hand equipment and raw materials in less-developed regions is the biggest driver for the interregional and global trade of e-waste. Trading of second hand equipment is legal only if it is allowed by both sending and receiving countries. However, the dumping of waste occurs exists in practice, is illegal. If the exporting country has ratified the Basel Convention, exports of hazardous waste must comply with the Basel Convention. The Basel Convention is meant to prevent developed countries from illegally dumping waste in developing countries, where recycling infrastructure is typically absent.

- **Informal collection and recycling in developing countries:** In most developing countries, there are an enormous number of self-employed people engaged in the collection and
recycling of e-waste [155]. They usually work on a door-to-door basis to buy e-waste from consumers at home, and then they sell it to refurbishers and recyclers. These types of informal collection activities provide the basic means necessary for many unskilled workers to pay for their living. After informal collection, when electronic products do not have any reuse value, they are mostly recycled by through “backyard recycling” or substandard methods, which can cause severe damage to the environment and human health. Lacking legislation, treatment standards, environmental protection measures and recycling infrastructure, are the main reasons that e-waste is disposed in a crude manner.

- **Main Actors**

The production, consumption and disposal of EEE engage a number of actors along the forward and reverse supply chain. All actors are at least partially responsible for the functioning of developed e-waste management systems. In different countries, different actors are dominant, as reflected in their level of influence and engagement [156]:

- **Governments**: The main role of the government is to provide the policy and regulatory framework for the management of e-waste.

- **Municipalities**: Operating at the local level, municipalities across all countries have the responsibility for waste management.

- **Producers and Trade Associations**: With most e-waste legislation based on the principle of Extended Producer Responsibility (EPR), producers have a major responsibility to organize, finance and operate an e-waste take-back system, either individually or collectively, through Producer Responsibility Organisation (PROS) (also called Producer Compliance Organisations – PCOs). In some countries, while producers accept the responsibilities mandatorily or voluntarily, they are often criticized for not showing the same responsibility in other countries that lack specific EPR legislation around e-waste.

- **Retailers**: As the consumer touch-point for producers, retailers often also act as collection centres or take-back points.

- **Industrial Recyclers**: Industrial recyclers, more often than not, are capital intensive, operating mechanized shredding and sorting facilities or large-scale material recovery facilities. The number and capacity of such industrial recycling facilities varies greatly by country, linked not only to the volume of e-waste generated, but also the legislative landscape and the presence of an active or inactive informal recycling sector.

- **Informal Recyclers**: The informal sector is also a key actor in e-waste management. This involves players in the collection, pre-processing and first material recycling. A small fraction of the informal sector contributes to the adverse effect in human health and the environment due to unsound treatment practices.
1.5. E-Waste in Cambodia

As in other developing countries, fast economic growth has triggered booming demand for gadgets and appliances in Cambodia, driven by a more affluent and growing middle class. The consumption of EEE has rapidly increased in the urban centers in the country. In the absence of domestic manufacturing, most electronics, both new and used, are imported into Cambodia. In addition to domestically circulated second-hand products, which are sold through the informal sector, a major source of used EEE is the Guangzhou region of China, which has an active repair and refurbished products industry [156].

Currently, Cambodia has no specific laws mandating environmentally safe management of e-waste. Although it ratified the Basel Convention in 2001, it is not yet party to the Ban Amendment. However, it does have an import ban, with Article 21 of the Sub-Decree on Solid Waste Management prohibiting the import of hazardous waste from other countries into the Kingdom. Although e-waste imports are banned, illegal imports continue. The 2015 United Nations report on e-waste in Cambodia found a high level of cross-border, often illegal, movement of e-waste into Cambodia, which after being dismantled was then exported to countries like, China, Thailand and Vietnam.

Based on national inventory on using EEE in Cambodia, the importation of EEE and used EEE (UEEE) has been continuously done into the Kingdom of Cambodia with different amounts responding to internal demands. From 2000 to 2006, imported TVs have 903,334 sets (Colour 271291 sets, and black-white 632,043 sets); air-con 193,391 sets; refrigerator 91,935 sets; PC 14010 sets; MP 343,033; and washing machine 30,941 sets [157, 158]. These combined EEE/UEEE statistics have been recorded by responsible institutions, while importers registered and asked for permission to import these materials/facilities. The inventory has indicated the waste generation by type of UEEE such as: TV sector has great amounts of 40,983.0 kg, while air-con’s wastes have 13,318.8 kg, MP’s wastes 2,016.2 kg, and PC’s wastes 1,310.4 kg.

17,000 tons of e-waste piled up in Cambodia in 2015 according to the recent UNU report which has increased by 70% between 2010 and 2015. This waste was typically retrieved by collectors, who sell it to repair shops where reusable parts are salvaged. The rest is disposed of through municipal waste systems, burned by owners or discarded in dumpsites or landfills. Cambodia had the third-highest e-waste volume growth between 2010 and 2015, behind only China (107%) and Vietnam (90%); however, it recorded the lowest waste per capita when compared to its electronics-manufacturing neighbors [159].

1.5.1. E-waste flow and disposal in Cambodia

Imported new EEE are sold at brand-new shops/centers, and used EEE at normal second-hand shops. Some shops sell both new and UEEE products. On the other hand, most second-hand shops provide multiple services such as selling, repairing, dismantling and refurbishing. UEEE or second-hand products are widely used in Cambodia, even if imported brand new items from China are cheap. This is because consumers often consider that second-hand items
produced by Japan and some developed countries have higher quality responding to their needs and are affordable. The flow of EEE and UEEE in Cambodia can be summarized in Fig. 1-20 and Fig. 1-21.

![Flow of EEE/UEEE in Cambodia](image)

**Fig. 1-20:** Flow of EEE/UEEE in Cambodia. [157]

![End-of-life of WEEE in Phnom Penh at a glance](image)

**Fig. 1-21:** End-of-life of WEEE in Phnom Penh at a glance: (a) second-hand shop, (b) repair shop, (c) waste buyer, (d) informal e-waste transportation, (e) transport of computer parts, (f) dumping site and waste pickers. [158, 160]

Used EEE can be thrown in dustbin, sold to repair shop or to waste buyers. E-waste can be retrieved by waste-pickers or informal waste collectors either from municipal dustbins, or directly from owners at their homes. Waste-pickers and collectors transport e-waste by handcart, bicycle, motorcycle or small trucks and sell it either to repair shops for dismantling or to waste traders. Dismantling and recycling take place largely in the informal sector, mostly manually. No formal e-waste recycling facilities exist. At the moment, retailer’s/producer’s take-back system is non-existent in Cambodia. Further, there is no exclusive municipal collection and transportation system for E-waste while dismantlers in informal sector have their own collection and transportation system [160]. E-waste disposed in municipal dustbin and not collected by wasted-pickers will be transported for disposal at waste dump site.
A repair and recycling shop is a kind of a second-hand shop; they buy used equipment for repair and resale, including components and parts that can be used as spares. However, they do not engage in material recovery activities. The reusable parts are kept for sale, and the recyclable materials are then sold to local scrap yard owners for export. The residues left after the extraction of reusable components, and recyclable materials are then disposed of through municipal waste systems, burned by owners (sometimes illegally) or discarded in dumpsites or landfills.

There is a large lack of awareness regarding safety and environment during e-waste management. There is no mandate on wearing safety gear during dismantling processes, which has led to several accidents. Free discharge of toxic gases into the atmosphere from equipment results in health and environmental hazards. Residues are burned in dumpsites or disposed of in public places, causing extreme ground, water and air pollution.

1.5.2. Regulation and framework

Although Cambodia has not issued any laws or regulations for e-waste management (including recycling), the Ministry of Environment, Cambodia, plans to develop a new sub-decree on e-waste management under Law on Environmental Protection and Natural Resource Management. The relevant laws for ESM management of e-waste currently in place are [156]:

- Law on Environmental Protection and National Resource Management (December 1996) stipulates the “prevention, reduction, control of airspace, water and land pollution, noise and vibration disturbances as well as waste, toxic substances and hazardous substances”.

- Sub-decree on Solid Waste Management (April 1999) covers all activities related to disposal, storage, collection, transport, recycling and dumping of garbage and hazardous waste. In this annex of the sub-decree, hazardous waste includes metal waste and the compounds found in e-waste; waste from used or discarded electric lamps; and PCBs from microwave ovens, air conditioners and TVs. In particular, Articles 15, 20 and 21 are the most relevant for e-waste.

- Article 8 of Sub-decree on Water Pollution Control stipulates that the disposal of solid waste, garbage and hazardous substances into public water areas or drainage systems shall be strictly prohibited. The storage or disposal of solid waste, garbage and hazardous substances that lead to water pollution shall be strictly prohibited.

- Sub-decree on Air Pollution and Noise Disturbance stipulates the strict monitoring of emissions from used electrical and electronic equipment and/or electrical and electronic waste burning.

Recently, a sub-decree, made public and signed in early February 2016, sets guidelines for businesses that buy, break down or dispose of electronics - such as TVs, phones and batteries, which will now be required to submit a request to the ministry before starting their operations.
The sub-decree also prevents the import of electronic waste into the country and sets out penalties for individuals and firms found disposing e-waste into rivers or dumps, ranging from 40,000 riel for individuals to 2 million riel for businesses.

A draft National 3R Strategy on Wastes Management is being developed since 2008, with for objectives to establish an efficient solid waste management system. This should permit to generate jobs and revenues for the population, but also to reduce the quantity of wastes in dumpsites, improve the solid waste treatment and recycling system in order to protect human health and environmental resources in Cambodia [162].

- **Stakeholders**

  - Ministry of Environment; Department of Pollution Control: Involved in the assessment of e-waste inventory, formulation of e-waste legislation, guidance on environmental standards and impact assessment for e-waste treatment. Also includes inspection of recycling facilities, planning of landfills and raising public awareness campaigns.

  - Department of Customs and Excises: Responsible for checking and monitoring flows of new and used electronics and e-waste.

  - Informal e-waste collectors: Provide door-to-door collection services to households and businesses.

  - Repair shops: Small and micro-scale enterprises, often in the informal sector, who repair, refurbish and dismantle electronic products.

  - Informal e-waste recyclers: Often backyard businesses applying crude methods for harvesting some precious from e-waste.

- **International frameworks**

With ever-increasing international trade in waste, the growth of international controversies of these transboundary trades have led to the development of regulations at the national, regional and international levels. The most prominent among these regulations, in the context of transboundary movements of e-waste, is the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (commonly known as the Basel Convention). Enshrined under the auspices of the United Nations Environment Programme (UN Environment), the Basel Convention was adopted in 1989, and it entered into force in May 1992.

Cambodia, Japan, the Philippines, Singapore, Thailand and Vietnam have not ratified the Ban Amendment, and of these countries, only Cambodia prohibits the import of e-waste and only Vietnam prohibits the import of second-hand electronics [156].

- **International cooperation**
In recent years, the Ministry of Environment, Cambodia (MOEC) has worked with multiple international organizations (UN, Japan; JICA, Korea International Cooperation Agency (KOICA)) to fund capacity building programs, inventory programs and pilot projects [156]. The Ministry of Environment, Japan supported projects in collaboration with the Ministry of Environment, Cambodia including:

- Development of national e-waste inventory including identifying imports, consumption and disposal patterns, and current e-waste treatment practices (Cambodia Environmental Association, 2007).
- Development of a draft Sub-decree on E-waste Management in order to achieve the goal of effective, environmentally sound e-waste management in Cambodia. Project duration: December 2012-2014.

UN Environment, International Environmental Technology Centre (IETC) supported projects in collaboration with MOEC and local partners including:

- Training programme on e-waste and demonstration of environmentally sound management of e-waste at the recyclable waste collecting site (Ministry of Environment, Cambodia, 2011).

Korea International Cooperation Agency (KOICA) supported a project in collaboration with UNIDO and Samsung Electronics to build capacity through skill development for repair and refurbishment activities, and support the local economy by creating opportunities for green businesses.

1.6. Second-Life of UEEE

Rapid growth and change in EEE products lead to a constant stream of new products offerings and a wide array of used products to be disposed of. This extreme rate at which we purchase and discard electronics devices is having a serious impact on our planet. There is an increasing demand for greener, longer-lasting electronic products, and effective e-waste management system.

1.6.1. Impacts of EEE/UEEE

EEE production involves energy intensive processes. All stages of production including raw material extraction, components production, components assemble, and distributions contribute to energy footprint of this production. In addition, EEE also contains various valuable and scarce resources [163] and hazardous materials such as heavy metals and
chemicals. The impact of material production is further detrimental as product lifetimes decline in response to demand for continual innovation and upgrade of consumers. Many EEE products also have high energy consumption during their use phase.

The presence of hazardous substances in obsolete electronics devices leads to the release of these substances and their by-products during recycling and disposal. This is even more problematic when e-waste is exported to developing countries where recycling and disposal take place without safe facilities. The extensive use of hazardous chemicals in consumer electronics means that recycling workers are exposed to a cocktail of toxic chemicals and by-products. The presence of polyvinyl chloride (PVC) plastic and brominated flame retardants (BFRs) results in the release of highly toxic dioxins, among other hazardous chemicals, when scrap is burnt. Phthalates, used widely as softeners for PVC, migrate out of plastics over time. Some are classified as “toxic to reproduction” and are known to be hormone disrupters. Other health effects of other substances are skin problems, human carcinogens problems, and incurable and debilitating lung disease [152].

1.6.2. Reuse vs. recycling vs. buying new EEEs

To reduce environment impact and energy footprint of EEE, many electronics companies are moving toward cleaner and greener products by reducing energy consumption during manufacturing, eliminating hazardous substances and increasing the energy efficiency of the devices.

Improving energy efficiency of electrical items is an indirect way to reduce energy footprint of the devices by reducing energy consumption during their use phase. However, this is proven to have miniscule effect accounting for the declining product lifetimes due to frequent replacement of them, which means that production process have been accelerated. This “rebound effect” offsets gains from improved efficiency [164]. Improving material efficiency and ensuring a product reaches its optimal lifespan would minimize energy footprint throughout its life cycle from manufacturing, to disposal [165]. Ways of addressing this are to increase product longevity, either by extending a product’s first life or addressing issues of repair, reuse, and refurbishment used EEE.

Sustainable routes for end-of-life EEE rely on wastes collection, materials recovering, and safe disposal of the remaining materials. Recovery processes include dismantling for recycling and testing and refurbishment for reuse. Reusing products would be preferable to recycling or disposal as this is the least energy intensive solution [163]. Therefore, product life extension through careful use and regular maintenance, repair, refurbishment and remanufacturing of used EEE is generally the best option in terms of environmental benefits. Reuse accounts for the costs of simple refurbishing of some products which is a fraction of the original manufacturing costs.

Nevertheless, in some circumstances, reuse can be a worse solution than recycling. This could happen if there is certain level of technological upgrade of new devices, particularly in energy efficiency [166]. The different of energy consumption of a new product and a refurbished one could be significant enough to offset the effect of manufacturing energy
consumption. In this case, there is a significant shift of technology, for example, the upgrade from tungsten light bulb to LED lamp, or CRT monitor to LCD monitor.

**1.6.3. Reuse of UEEE as a solution for rural electrification**

Reuse solution helps slowing and closing up the resource loops which lead to a more circular business economy. Usually, it is practiced in a formed of trading second-hand products driven by market demands. Often UEEE are shipped to other countries where there are demands for more affordable products. The devices in good functioning condition are sold, and the rest become waste. Often, not all the components of the broken devices are malfunction. Those working parts are often overlooked and discarded as waste because of a few broken parts.

*Fig. 1-22: Proposed renewable energy generation system for rural electrification.*

Some components of the products such as power supplies, batteries, and electric motors have the potential for reuse as components in small renewable energy system for rural area. This system could help reduce the impacts from e-waste that is growing quickly and provide an intermediate and affordable energy access solution for rural communities. As depicted in *Fig. 1-22*, the proposed system may include a “solar” part, composed of solar PV panels, modified power supply units (PSUs), a “hydro” part composed of modified an uninterruptable power supply units (UPSs) and a three phase induction machine turned into a single phase generator and an energy storage using used car batteries (Fig. 1-22). The target is focused generally on the countries or regions which are rich in solar, hydro or wind resources.

To validate this solution, there are some economic, environmental and technological aspects to be considered and evaluated. Economic profit is probably the main driver for the implementation of this solution. The cost of the whole system can be cut due to reduced cost of the used components and the extra cost of adding controllers is relatively low in comparison to the cost of main components. Used devices such as computer power supply, UPSs and electric motors (induction motors) can be bought from waste collectors and electronics junk shops at a fraction of the cost of the new products. For this process, testing of operation conditions and configurations is required for selection of compatible components for the system. Further detail study should be made for some devices including automobile batteries whose percentage of good state of health for reuse can be low. While economics
should be addressed, only technological and environmental aspects are the focus points in this thesis.

The environmental aspects of the solution should be addressed by evaluation the energy and embedded carbon footprint savings with the environmental costs of reduced system energy efficiency and the cost of processing needed for reuse of components. This evaluation is made in Chapter 2 using ‘Life Cycle Assessment’ methodology.

The obvious challenge is the technological aspect of the system. The idea of reusing some components of the devices for different usage is relatively new concept, at least for widespread and large scale application. While electronic companies are making effort to reduce the energy footprint and toxic substance of the devices [152], there is no intervention from the manufacturer for reuse provision. This presents several challenges in refurbishing or repurposing the devices. These technical aspects are discussed in Chapter 3 and Chapter 4 for solar PV and hydro generator part respectively.

1.7. Summary

Having access to reliable energy services is very important for any communities for many reasons including reducing poverty and improving health, increasing productivity, enhancing competitiveness and promoting economic growth. While developed countries has secured access to plentiful sources of energy to drive its development, many developing countries lack sufficient and effective energy access. Most rural communities of the developing world lack access to electricity due to many challenges facing the extension of centralized grid. These obstacles are high construction cost, transmission losses, and low profit due in large part to low energy consumption and insufficient population densities. To tackle this problem, distributed energy micro-generation systems is able to provide an immediate and flexible energy access solution to the rural poor. These systems have lower life cycle cost and provide a diversity of technologies to meet specific energy end-use applications in developing communities more appropriately.

Owing to the rapid technological development, innovation and consumer demand, there has been a vast improvement in various electronic equipment which results in shorter life of electronic products, and higher amounts of waste electrical and electronic equipment. This growth leads to increasing concern with pollution due to the release of hazardous substances in obsolete electronics devices.

Cambodia is one of the developing countries which are in need for rural electrification to drive its development. Though the electricity access in urban area is high, only 49.2% in rural area (12.3 million of rural population) has access to electricity in 2016. While the Cambodia government is making effort to provide enough electricity for its energy demand by investment in new hydro and coal power plants, it is mostly depending on the existing or the expansion of the centralized grid line.
The application of reuse of WEEE in a stand-alone renewable energy system has been proposed as a solution for electrification in rural areas in developing countries. This solution is interesting for Cambodia and, in general, the countries or regions which are rich in solar or hydro resources. A suitable configuration for the proposed system is a solar-hydro hybrid generation system since solar and hydro (mostly in highland region) resources are plentiful in rural Cambodia. The components which can be reused include computer power supply units as DC-DC converters, uninterruptable power supply units as inverters, three phase induction machines as induction generators, and car batteries as energy storage. Such solution helps to provide an intermediate, affordable and sustainable energy access solution for rural communities. Also, it helps to reduce the impacts from e-waste that is growing quickly, and the impacts of greenhouse gas emission due to fossil fuel based generator.

The following chapters will address in details the environmental aspect and technological challenges of the proposed solution based on reuse. While economics could be the main decisive force to implement such a solution, it is out of the scope and field of this thesis.
Chapter 2

Life Cycle Assessment of Reuse Solution
Chapter 2: Life Cycle Assessment of Reuse Solution

2.1. Introduction

With the rapid expansion of technological development, innovation and consumer demand, there has been a vast improvement in various electronic equipments, resulting in the shorter life of electronic products, and higher amounts of WEEE or e-waste. The presence of hazardous substances in obsolete electronics devices leads to the release of these substances and their by-products during recycling and disposal. This is even more problematic when e-waste is exported to developing countries recycling and disposal takes place without safe facilities. To tackle these issues, several solutions have been implemented and suggested. Eco-design is the process that considers environmental impacts into design consideration, which could result in environmentally conscious products. Eco-design is getting popular because the degree of awareness of environmental protection is increasing. Since 2007, it is a mandatory legal requirement for products entering the European market to fulfill the eco-design directive [201]. The major objective of this directive is to reduce overall environmental impacts, and particularly those related to energy use [202]. As a result, more and more manufacturers are moving toward the more energy-efficient products for consumers.

In addition to use phase, the strategies for End-of-Life (EoL) of product include waste management, materials recycling, remanufacturing, and reuse of components. While the current EoL management mainly relies on conventional waste collection and processing techniques for material recovery [203], other EoL options including reuse, refurbishment, and remanufacturing have also proven increasingly relevant for e-products [204] due to the growing discussion on circular economy. For the majority of retired products, materials recycling and remanufacturing provide the most environmentally friendly solution of EoL treatments. Unlike recycling, reuse does not involve breaking down of used items to make raw materials for the manufacture of new products. For some particular cases, retired products can be reused for the same purpose or repurposed for other functionalities. In the same way, reuse helps save energy and resources of new production. In an economic point of view, reuse can make quality products available to people and organizations with limited means, while generating more jobs and business activities.

In the field of energy and electrical engineering, the possible environmental benefits of reusing components have not been studied or exploited in a significant way yet. Recently, there have been a number of works which are interested in the second life application of electric vehicle (EV) batteries. This interest is due the current growth of the electric vehicle industry. This growth will rapidly expand the resource of partially degraded, ‘retired’, but still usable batteries. Reference [205] has investigated the feasibility of reusing Li-ion cells used in electric vehicles using environmental indicators. The results evaluated with Life Cycle Assessment (LCA) method, show a positive effect of the Second Life solution on the environmental impact of the Li-Ion cells. The economic benefits of second life application of
the batteries can also be found in [206-208]. As reported in [207], used EV batteries can provide a cost-effective and lower environmental impact alternative to existing lead-acid storage systems in the decentralized mini- and micro-grids.

Beside batteries, the second-life application of few other components has also been studied. For instance, the feasibility of reusing electric motor in consumer products has been investigated in [209]. A data logger circuit was developed that measures, computes, and records parameters that are strongly correlated with the degradation of a motor during the use stage of the product. The analysis shows that using the data-logger circuit in products as an enabler for motor reuse may be associated with large cost savings. The environmental impact of smartphone repurposing as compared to traditional refurbishing using life cycle assessment has been studied in [210].

Though the positive effect of reuse on both environment and economic has been demonstrated in a handful of literature, this result could be mitigated and very depending on various parameters of the system. The main factor which could lead to the negative benefit of reuse is the deterioration of the system performance, mainly its energy efficiency. The case study of reusing personal computers and its environmental impact has been presented in [211]. Using LCA to assess the environmental impacts, the article shows that computer reuse can both lead to positive and negative effects. On the one hand, as long as the new product is not significantly more efficient in the use phase, reusing turns out to be a relative energy saving strategy. On the other hand, if the new product is more efficient than the used items, reuse could lead to a negative environment impact. For example, reusing desktop computer with CRT (cathode ray tube) screen could consume more energy than using a new computer with LCD (liquid-crystal display) screen.

This chapter aims to evaluate the environmental aspect of a proposed stand-alone renewable energy system based on used EEE using LCA methodology. The general concept of the LCA method will be first introduced. This methodology is later applied for the evaluation of the environmental impact associated with the life cycle of the proposed renewable system in comparison to the impact in the life cycle of a conventional renewable system based on newly made components. The evaluation processes will follow these important steps: defining functional unit and system boundaries, system sizing and defining the life cycle inventories, and impact assessments. Finally, the sensitivity analysis of the results is made to verify the reliability of the impact assessments. The effects of uncertain or assumed parameters on the overall result are addressed and discussed.

### 2.2. Life Cycle Assessment Guidelines

Consumers’ products and equipment are manufactured through many stages and processes which require material and energy. These stages (product life cycle) include raw material production, product manufacturing, usage, and end-of-life stage (Fig. 2-1). Process industries involve chemical substances in significant quantities and the emissions associated with their
use have potential impacts on air, water and soil systems as well as posing health problems for people. There are also impacts associated with the energy required for production processes, transportation and usage of products. Energy production, mainly provided by fossil fuel sources, contributes to global warming and other climate related issues. The disposal after usage (EoL) can produce severe impacts on human health and on the ecosystem when they are not well managed.

![Fig. 2-1: Product life cycle. [212]](image)

The Life Cycle Assessment or LCA is a systematic framework to analyse the environmental impact of products, systems or services on a life cycle basis, from the raw material extraction (the cradle), processing and manufacturing (the gate) to use and disposal (the grave). The term life cycle refers to the notion that LCA requires the assessment of raw-material production, manufacture, distribution, use and disposal including all intervening transportation steps necessary or caused by the product’s existence. The concept of LCA began in the 1960s in the USA, when concerns over the limitations of raw materials and energy resources raise interest in finding ways to cumulatively account for energy use and to project future resource supplies and use [213]. In 1969, researchers initiated an internal study for The Coca-Cola Company that laid the foundation for the current methods of life cycle inventory analysis in the United States. The study compared different beverage containers to determine which had the lowest releases to the environment and least affected the supply of natural resources. It quantified the raw materials and fuels used for each container, along with the environmental loadings from the manufacturing processes. Interest in LCA waned from 1975 through the early 1980’s, because environmental concerns shifted to issues of hazardous and household waste management. But when solid waste became a worldwide issue in 1988, LCA again emerged as a tool for analysing environmental problems.
By 1991, concerns over the inappropriate use by product manufacturers of LCAs to make broad marketing claims made it clear that uniform methods for conducting such assessments were needed. A consensus was also required on how this type of environmental comparison could be advertised non-deceptively. At the same time, pressure was growing from a number of environmental organisations to standardise LCA methodology. This led to the development of the LCA standards in the International Standards Organisation (ISO) 14000 series (1997 through 2006) [213]. The Society of Environmental Toxicology and Chemistry (SETAC) was the first international body to act as an umbrella organisation for the development of LCA. It is a scientific organisation with its roots in academia, industry and government and, as such, has been able to offer a science-based platform for the consistent development of LCA as a tool.

Another important international stakeholder in the field of LCA is UNEP (the United Nations Environmental Programme), represented by its Department of Technology, Industry and Economics in Paris [214]. UNEP’s focus is mainly on the application of LCA, particularly in developing countries. An important contribution was the publication in 1996 of UNEP’s user-friendly and easy-to-read guide to LCA, entitled Life Cycle Assessment: what it is, and what to do about it. A second publication of interest is Towards Global Use of Life Cycle Assessment, published in 1999. Furthermore, a series of international workshops dealing with various aspects of LCA are being organised by the Environmental Protection Agency of the US (US-EPA) and CML in the Netherlands, under the auspices of UNEP. SETAC and UNEP are now co-operating in a major new task, concerning the identification of best available practices in the field of life cycle assessment, on the initiative of a SETAC-Europe working group [214].

The methodology and standardization of procedures for life cycle assessment have developed greatly in recent years. The aim should be a transparent assessment where the depth and details are allowed to vary with the goal and scope. Future developments include application and implementation focused processes for existing methodologies and an extension of the framework to include economic and social concerns [215].

### 2.2.1. Basic steps in LCA

By definition an LCA includes 4 phases as depicted in Fig. 2-2: definition of goal and scope, inventory analysis, impact assessment and interpretation, where the results from the other three phases are summarized and evaluated (ISO 14040:2006).
Goal and scope definition:

In the goal and scope phase, the purpose of the project should be formulated into a detailed goal and scope description. The description should include application of the study, reason for carrying it out and planned audience, methodology and requirements on the results. In reality, a life cycle assessment is an iterative process, hence the scope could change throughout the working process, however considering and making most choices in the beginning is an advantage. A core feature of an LCA is the construction of a flow-chart or inventory model where the technical system is illustrated as a set of process units, intermediary product flows linking them together and entry/exit flows in connection to the natural system. A system boundary defines which process units should be considered as part of the studied system and which should not be considered in the study [216]. Deciding on which data to collect and showing where impacts could occur is the backbone of the whole LCA [217]. The choice of which environmental impacts (climate change, acidification etc.) to assess and hereby which inventory data (CO₂ and SO₂ emissions etc.) to search for is defined in the goal and scope definition. A functional unit is also defined to be used as a reference flow to which all other flows included in the model are later related. The study or comparison of different proposed solutions can be made based on the defined functional unit.

Life cycle inventory analysis (LCI):

As depicted in Fig. 2-3, input and output flows from/to the technical system may include, for example, environmental data on mass and energy for all activities included within the system boundary [218]. In the life cycle inventory analysis, every input (raw material, fuel, water, etc.) and every output (product, emissions to air, water and soil, waste, etc.) of the system life cycle is recorded and quantified. The data must be related to the functional unit defined in the goal and scope definition. The considered environmental flows include resource use and release to air, water or land (ISO 14040:2006). The inventory can gather data for hundreds of flows, depending on the system boundaries. In addition, assumptions are stated and calculations to connect the inventory data to the selected functional unit are made. This requires qualitative and quantitative knowledge of all the related inputs, which must be expressed in a common unit. Then the inventory results have to be calculated based on the data collected, according to the chosen methodologies and assumptions. The inventory data are typically illustrated with a flow chart that includes the activities that are going to be assessed in the relevant supply chain and gives a clear picture of the technical system boundaries. Life cycle inventory data are necessary in order to evaluate, in the next step, the environmental performances of the system.
Fig. 2-3: Products life cycle and flows of materials/energy to the environment from [219].

- **Life cycle impact assessment (LCIA):**

  The phase of impact assessment is aimed at evaluating the significance of potential environmental impacts based on the LCI flow results. While the inventory process models exchange of material and energy of the system, the impact assessment focuses on the potential impacts these exchanges have on the natural environment. The inventory data are then converted into indicators assigned to specific impact categories [216]. The impact assessment includes some mandatory activities, e.g. classification and characterization, but also optional elements to clarify the results including normalization, sorting and ranking or weighting of the indicators based on value-choices [220]. The commonly used impact categories in LCA applications are: climate change, impact of land use, depletion of abiotic resources, stratospheric ozone depletion, human toxicity, eco-toxicity (freshwater and marine aquatic and terrestrial) acidification and eutrophication. More specific or accurate impact categories can be defined for a particular LCA case study, however with this custom impact categories definition, the risk of generating LCA results that do not match with other studies must be properly evaluated in goal and scope definition.

- **Life cycle interpretation:**

  In this continuous phase, results from the LCI and LCIA are summarized and discussed. The focus should be on identifying significant issues, evaluating the completeness, sensitivity and consistency of the results and providing conclusions and possible recommendations on improvements [220].

2.2.2. **Classification and characterization**
- **Classification of life cycle inventory**

All the emitted substances, all the materials and energy flows are gathered in the inventory phase. The stage of evaluation of the impacts is classification during which the emissions and resources are ranked into different groups or impact categories according to their potential impact on the environment. The categories proposed and maintained by SETAC are: resources and land use, stratospheric ozone depletion, photo-oxidant formation, acidification, eutrophication, human toxicity, and eco-toxicity [221]. These categories are often classified as midpoint categories which are located between inventory data and endpoints or damage categories.

![Diagram](image)

**Fig. 2-4:** Classification and characterization of impacts. [222]

- **Characterization**

In the characterisation step of impact assessment, the environmental contributions assigned qualitatively to a particular impact category in classification are quantified in terms of a common unit for that category, allowing aggregation into a single score, i.e. the indicator result. For each impact category the (category) indicator result is calculated by multiplying the relevant contributions by their corresponding characterisation factors (Eq. 2-01) [214]. Together, these results constitute the ‘environmental profile’: a table showing the indicator results for all the predefined impact categories.

\[
\text{Indicator Result}_{\text{cat}} = \sum_{i} m_i \cdot \text{Characterization Factor}_{\text{cat},i} \quad (2-01)
\]

where \( i \) is the type of intervention (substance emission or resource extraction); \( m_i \) is a mass amount of substance \( i \) (kg).

- **Normalisation**
ISO 14042 (2000E) defines normalisation as “the calculation of the magnitude of indicator results relative to reference information”. The reference information may relate to a given community, person or other system, over a given period of time. The main aim of normalising the (category) indicator results is to better understand the relative importance and magnitude of these results for each product system under study. Normalisation can also be used to check for inconsistencies, to provide and communicate information on the relative significance of the (category) indicator results and to prepare for additional procedures such as weighting or Interpretation (ISO 14042, 2000E) [214].

The normalised value for each impact category can be simply calculated by dividing indicator result of the category to the corresponding reference value as shown in Eq. 2-02.

\[
NormalisedIndicatorResult_{cat} = \frac{IndicatorResult_{cat}}{Reference_{cat}}
\]  \hspace{1cm} (2-02)

2.2.3. Limitations and critical review of LCA methodology

The most critical aspect of using LCA methodology is that the results are highly dependent on the availability of data and that the study is performed through an iterative process using a series of approximations and dynamic specifications of data. The issue related to the unreliable scientific verification within databanks and the working process of adopting second hand data to a specific system assessed has been highlighted in [216]. The authors stress the importance of a constant revision of calculations and assumptions to decrease the uncertainties connected to the practitioner. A general solution is to use standardized methodologies ensuring that studies are conducted in similar ways, based on similar basic assumptions and criteria and use common mass units for input and output data [223]. A methodological limitation suggested by Reference [224] is the absence of validation and assurance that the model mimics the real system. Currently, LCA studies are more questioned in terms of methodology and comparison to other models, rather than on how well the results represent reality. Following the modelling rules becomes more important than the result for the practitioner. The LCA model should be validated through comparison to reality and improvements should be made if necessary. In addition to the methodological limitations there are complications concerning data sources. Most LCAs depend on data with questionable reliability from producers and fail to present the underlying process data because of confidentiality [225].

2.3. LCA of a Small-scale Renewable Energy System Based on Used Components

The concept of product reuse is certainly not new, however the study of applying used components in a small scale renewable energy system has not yet been carried out to our knowledge. This section aims to evaluate the environmental aspect of such a system when compared to a conventional system based on newly made components. However, the study in
this paper is limited to only the solar PV generation system whose technological aspects have been studied and tested for its feasibility, as presented in the next chapter. Life cycle assessment methodology is a tool for evaluating the impact scores for both the proposed solution and the conventional one. The sensitivity analysis is made to assess the effects of the assumptions and of possible variations in the collected data on the results.

### 2.3.1. Proposed solar PV system based on reuse

A conventional stand-alone PV generation system suitable for small village consumption may consists of photovoltaic panels; lead-acid batteries, charge controller and an inverter (Fig. 2-5). The electric power converted from sunlight by photovoltaic panel charges the battery via the charge controller. The inverter converts the DC voltage from the battery into an AC voltage needed by the village households.

![Fig. 2-5: PV generation system using conventional solution.](image)

In the proposed reuse solution, the charge controller is replaced by modified PSUs, inverter by modified UPSs and used starting-lighting-ignition (SLI) batteries replacing the conventional storage batteries (Fig. 2-6). Cheap microcontrollers (based on Arduino products) with few interface components are added for control purposes. The PC power supply units (PSU) which replace the charge controller unit are lightly modified to: (1) disable their protection functionality; (2) allow the interface between microcontroller and the DC/DC converter of the power supply; (3) reduce their input voltage range which is more suitable for the output of PV generator. The ‘Maximum Power Point Tracking’ (MPPT) control is implemented in the Arduino microcontroller. This microcontroller can be found easily and cheaply worldwide, and can be easily programmed for simple control applications using its free software downloadable from Arduino website. The UPS units which usually contain a charger for a 12V or 24V battery and an inverter to converter battery energy for AC 220V loads can be readily modified to replace the inverter of the conventional solution. The power of individual UPS and power supply can be limited to a few hundred watts. The association of multiple units is applied to increase the limit to match the power required by the system.
The starting-lighting-ignition batteries used in automobile (SLI batteries) have also been proposed as a replacement of the typical deep cycle lead-acid battery suitable for stationary storage application. According to [226], 15% of spent lead-acid batteries China are in good conditions and are selected for refurbishing and 85% of the refurbished batteries could almost meet the standard for new batteries, according to the basic quality testing by batteries recyclers.

2.3.2. Goal and scope definition

The objective of this LCA work is to investigate the environmental variables of the PV system under study involving used components in comparison to a conventional PV system based on newly made parts.

- Functional unit for LCA study

The first step of LCA study involves the definition of the functional unit for which the impacts of the two solutions are evaluated. The objective of the system is the electrification of a small village, mainly in Cambodia or neighbouring countries. The functional unit is defined by satisfying the daily energy needs of the village for a 20 year period. The load profile of the village from Thailand is chosen for this case study due to the lack of actual data from a Cambodia rural village (Fig. 2-7). The typical electrical devices found in villager households include fluorescent lamps, a television, a tap player, a refrigerator and an electric fan [227]. The system sizing for both solutions will be calculated according to the requirements of the energy demand of the village.

![Village load profile](image)

**Fig. 2-7:** Load profile of a single village in Chiangria, Thailand. [227]

- SimaPro software and Ecoinvent database

The LCA software tool Simapro V.7.3.2 developed by PRé Consultants is used in this study. This software program integrates inventory data for a broad spectrum of industrial and economic sectors. Process-based inventories of many common systems are compiled into modules of information to be assembled by the user into a complete inventory. In this way, a user does not need to determine emissions data for basic inputs, such as electricity use or transportation, but may use available information to simplify an analysis. Users may utilize their own data to build new modules, or to update and supplement the software’s libraries. Both options have been used in this study.
ugn 7.3 includes build-in Ecoinvent database (Version 2.2) [228]. The Ecoinvent database provides access to most of the LCI datasets we need in both unit process and system process levels. It also provides impact assessment tools, including Eco-Indicator 99, CML, and IMPACT 2002+, to be used to correlate inventory data with environmental impacts.

2.3.3. System boundaries

The system boundaries define the stages and processes which are included in LCA study. The objective of this study is to evaluate the cradle-to-grave environmental impacts associated to every component of the system.

In the conventional solution, every phase of the lifecycle of the system components is analysed, including part productions, product assembly, transportation, use and end-of-life (disposal, recycle …) (Fig. 2-8). In the reuse scenario, components can be classified into two categories, new components and used ones. PV panels and Arduino controller are new components which are purchased from the market. The impacts of every phase of their lifecycle are accounted for in the boundary of the study. The used items are repurposed PSUs, repurposed UPSs and SLI batteries.

Fig. 2- 8: System boundary of life cycle assessment for the conventional solution.

Fig. 2- 9: System boundary of life cycle assessment for the reuse solution.

In their second life application, used components are collected and transported to their new location for testing and repurposing. The components are further transported to the location where the system is installed. These processes, seen as the reuse phase, are accounted for in the system boundary (Fig. 2-9). The impacts of production, use, and end-of-life stages of used components are considered outside the boundary of the studied system since they are identical to those in the conventional solution which served for their original applications.
- **Replacements and transportation**

Among all the components of PV system, the PV module itself is proven to be the most reliable component. Standard PV modules have matured greatly and show failure rates down to 0.01 % per year [229]. The survey data on faults, failures and performance of PV plants collected by Ref. [229] shows that in most cases PV modules have reached remarkable lifetimes. A good module can perform without detectable power degradation over 21 years. In contrast, in all reports the inverter was the most troublesome component. It accounts for about 66 % of reported troubles, though the number of troubles decreases continuously over time as a sign of maturing in technology. From the German “Sonne in der Schule” Program [229], between 12 and 8 inverter failures per 100 inverters and year are reported for some 350 inverter-years. This relates to a mean failure rate of about 1 failure in 8 to 13 years. The inverter failure rates from the task 7 survey shows an average of about 10 years between failures.

For these reasons, PV panels will be assumed to operate well over 20 years, thus eliminating the need of panel replacement over system lifetime. The inverter and charge controller are assumed to be replaced after 7 years.

Table 2-1: Number of battery cycles as a function of depth of discharge DOD (manufacturer’s data).

<table>
<thead>
<tr>
<th>DOD%</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>80</th>
<th>90</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Types of batteries</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VRLAB1</td>
<td>4250</td>
<td>2750</td>
<td>2125</td>
<td>-</td>
<td>1375</td>
<td>1000</td>
<td>-</td>
<td>800</td>
</tr>
<tr>
<td>VRLAB2</td>
<td>6250</td>
<td>4200</td>
<td>3200</td>
<td>-</td>
<td>2080</td>
<td>1500</td>
<td>-</td>
<td>1250</td>
</tr>
<tr>
<td>VRLAB3</td>
<td>-</td>
<td>5800</td>
<td>4300</td>
<td>3500</td>
<td>2800</td>
<td>-</td>
<td>1800</td>
<td>1650</td>
</tr>
<tr>
<td>VEB1</td>
<td>4500</td>
<td>3000</td>
<td>2250</td>
<td>-</td>
<td>1500</td>
<td>-</td>
<td>1000</td>
<td>900</td>
</tr>
<tr>
<td>VEB2</td>
<td>8400</td>
<td>5500</td>
<td>4250</td>
<td>-</td>
<td>2800</td>
<td>-</td>
<td>1800</td>
<td>1700</td>
</tr>
<tr>
<td>VEB3</td>
<td>6000</td>
<td>4000</td>
<td>3000</td>
<td>-</td>
<td>2000</td>
<td>1500</td>
<td>-</td>
<td>1200</td>
</tr>
</tbody>
</table>

VRLAB1: Flat plate battery type GEL VRLA SOLAR.  
VRLAB2: Flat plate battery type GEL VRLA SOLAR Block.  
VRLAB3: Tubular plate Battery type GEL VRLA A600 SOLAR.  
VEB1: Vented battery with positive tubular plates and specific separation (OPzS).  
VEB2: Vented battery with positive tubular plates and special separation (OPzS Solar-Cells).  
VEB3: Vented battery with positive tubular plates and specific separation (OPzS Solar-Blocks).

Battery’s lifetime is usually given in number of cycles as listed in its datasheet. The end of the battery lifetime is reached when its remaining capacity is 80% of the nominal capacity. The lifespan of lead-acid batteries is greatly affected by the depth of discharge (DOD), the ratio of the amount of electrical discharge from the rated capacity. When deep electrical discharges occur repeatedly, the battery cycle life is shortened. The type of lead-acid battery typical found in PV system is usually a deep-cycle battery which is designed for repetitive deep discharges and lasts for a significant duration. Deep-cycle battery designs require more storage capacity than SLI designs but the primary goal is repeated recovery from discharges of up to 80% of the rated capacity. In comparison with SLI batteries, deep discharge batteries have thicker plates, which are housed in bigger cases that provide greater space both above
and beneath the plates. Greater space below allows more debris to accumulate without shorting out the plates, and greater space above lets there be more electrolytes in the cell to help keep water losses from exposing the plates. A typical deep-cycle, lead-acid battery can be cycled about 4000 times when discharged by 25% of its rated capacity, which would give it a lifetime of over 10 years. At a daily discharge of 80%, about 1800 cycles could be expected, which suggests a lifetime of around 5 years [230]. The relationship between DOD and the amount of total electrical discharge of various deep cycle batteries based on manufacturer’s data is summarized in Table 2-1.

For this study, the batteries in the conventional solution are assumed to be replaced every 5 years and a half corresponding to 2000 cycles [230]. In reuse solution where SLI batteries are employed instead of solar batteries, their lifespans are significantly reduced due to how the batteries are designed. The most important task of automobile SLI batteries is to start car engine which requires a short burst of very high current. Once the engine has started, its alternator quickly recharges the battery, which means that under normal circumstances the battery is almost always at or near full charge. For these reason, SLI batteries are not designed to withstand deep discharges. As shown in Table 2-2, if SLI battery can be used, as is sometimes the case in Cambodia where they may be the only batteries available, daily discharges of less than about 20% can yield approximately 500 cycles, a year or two of operation.

<table>
<thead>
<tr>
<th>Battery</th>
<th>Max Depth of Discharge</th>
<th>Energy Density (Wh/kg)</th>
<th>Cycle life (cycles)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead-acid, SLI</td>
<td>20%</td>
<td>50</td>
<td>500</td>
<td>90 Ah% 75 Wh%</td>
</tr>
<tr>
<td>Lead-acid, golf cart</td>
<td>80%</td>
<td>45</td>
<td>1000</td>
<td>90 Ah% 75 Wh%</td>
</tr>
<tr>
<td>Lead-acid, deep-cycle</td>
<td>80%</td>
<td>35</td>
<td>2000</td>
<td>90 Ah% 75 Wh%</td>
</tr>
</tbody>
</table>

The lifespan of second life of used PSUs and UPSs would depend on its initial usages. The total hours of usage and the operation power are the main factures to reduce their remaining service time. A lifetime of 5 years is assumed for the second life of UPSs and UPSs. Table 2-3 summarizes components lifetime and its number of replacement over the 20 years of systems service.

<table>
<thead>
<tr>
<th>Component</th>
<th>Life cycles</th>
<th>Lifetime (years)</th>
<th>Number of replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV panel</td>
<td>-</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>Solar Battery</td>
<td>2000 cycles</td>
<td>5.48</td>
<td>3.65</td>
</tr>
<tr>
<td>Inverter/ Charge controller</td>
<td>-</td>
<td>7</td>
<td>2.86</td>
</tr>
<tr>
<td>SLI Battery</td>
<td>500 cycles</td>
<td>1.37</td>
<td>14.6</td>
</tr>
<tr>
<td>PSUs/UPSs</td>
<td>-</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Microcontroller (Arduino)</td>
<td>-</td>
<td>10</td>
<td>2</td>
</tr>
</tbody>
</table>
To estimate the impact due to transportation, it is assumed that manufacturing and recycling are made in China which is usually the case for South-Asian countries. The Ecoinvent database of the corresponding type of vehicle is used to assess the impacts of the transportation processes. The components of the system are assumed to be transported 2500Km by sea followed by 500Km on land (Table 2-4) from production to use and after usage to disposal.

Table 2-4: Transportation mode and distance.

<table>
<thead>
<tr>
<th></th>
<th>By road</th>
<th>By ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production to use</td>
<td>500 Km</td>
<td>2500 Km</td>
</tr>
<tr>
<td>Disposal after use</td>
<td>500 Km</td>
<td>2500 Km</td>
</tr>
<tr>
<td>Ecoinvent database</td>
<td>Truck 16t</td>
<td>Transport, barge/RER</td>
</tr>
</tbody>
</table>

### 2.3.4. System Sizing for Life Cycle Inventory

The sizing of components is calculated for the installation of the energy system in a rural area in south-east Asia based on the load profile consistent with the defined functional unit. The inverter is sized to support the peak power of the village load profile.

- **Conventional solution**

The inverter efficiency varies depending on the load, as suggested in Fig. 2-10. At most loads, it can operate at a constant 90% efficiency. At low load, its efficiency drops significantly.

![Inverter Efficiency vs % Rated Output](image)

**Fig. 2-10:** Inverter efficiency against rated output power. [232]

- **Inverter rating**

Assuming a constant inverter efficiency of 90%, the rated power of inverter is defined:

\[
P_{inv} = P_{LoadPeak} \times \frac{1}{\eta_{inv}} = 3000 \times \frac{1}{0.9} = 3333W
\]

(2-03)

where \( \eta_{inv} \) is the inverter efficiency, peak load is defined in Fig. 2-7.
- **Battery sizing**

Typical values of some of the important characteristics of lead-acid battery technologies are summarized in Table 2-2. Assuming a perfect weather, a battery can be sized to provide enough storage to carry the load through the night and into the next day until the sun rises again. In the real situation, there are periods of time when little or no sunlight is available and the batteries might have to be relied on to carry the load for several days. There is no constant set of rules about how to size battery storage. For instance, sizing a storage system to meet the demand 99% of the time can easily cost a lot more of that of one that meets demand only 95% of the time. In a way, the number of days of storage can be estimated using Fig. 2-11, which is based on the guidebook Stand-Alone Photovoltaic Systems Handbook of Recommended Design Practices (Sandia National Laboratories, 1995).

![Fig. 2-11: Days of battery storage needed for a stand-alone system with 95% and 99% system availability. Peak sun hours are for the worst month of the year.](image)

The daily DC energy can be obtained as followed:

\[
E_{dc} = \int_{0h}^{24h} (P_{load}(t) \times \frac{1}{\eta_{inv}}) dt = 17222 \text{ Wh} \tag{2-04}
\]

(Using values of \(P_{load}\) provided in Fig. 2-7)

The battery capacity in Wh can be defined by:

\[
C_{bat,Wh} = \text{Day of storage} \times \frac{1}{\text{MDOD}} \times E_{dc} \tag{2-05}
\]

Where MDOD is the maximum depth of discharge of the batteries.

Assuming 2 days of storage is used and 80% charging efficiency, we obtain:

\[
C_{bat,Wh} = 2 \times \frac{1}{80\%} \times 17222 = 43056 \text{ Wh} \tag{2-06}
\]

The battery capacity in Ah is:
Due to availability and cheap cost, polycrystalline PV modules are used for this analysis. The efficiency of the module varies between 10% and 15%. The PV module is usually rated using its DC power output under standard test conditions (STC), which is at 1000W/m² of insolation (1-sun), air mass ratio of 1.5 (AM 1.5) and 25°C cell temperature [230].

The rated daily energy of PV panels can be found by:

$$E_{PV, STC} = \frac{E_{bat}}{\eta_{Conversion}}$$  \hspace{1cm} (2-08)

where $E_{bat}$ is the energy needed to charge the battery:

$$E_{bat} = \frac{1}{\eta_{bat}} \cdot E_{dc} = 22963 \text{ Wh}$$  \hspace{1cm} (2-09)

where $\eta_{bat}$ refers to the battery efficiency in Wh and a value of 0.75 has been used based on Table 2-2.

The conversion efficiency accounts for charge controller efficiency, dirt on the PV surface, mismatched modules, and module temperature. It can be expressed as:

$$\eta_{Conversion} = \eta_{chargecontroller} \cdot \eta_{cellTemp} \cdot \eta_{dirt,mismatched}$$  \hspace{1cm} (2-10)

Even in full sun, the impact of these losses can easily degrade the power output by 20–40%. Photovoltaic modules perform better on cold, clear days than hot ones. For crystalline silicon cells, its open-circuit voltage drops by about 0.37% for each degree Celsius increase in temperature and short-circuit current increases by approximately 0.05% [230]. The net result when cells heat up is the maximum power point slides slightly upward and toward the left with a decrease in maximum power available of about 0.5%/°C. Cells vary in temperature not only because ambient temperatures change, but also because insolation on the cells changes. PV manufacturers often provide an indicator called the NOCT, which stands for nominal operating cell temperature, to help system designer account for changes in cell performance with temperature. The NOCT (Normal Operating Cell Temperature) is cell temperature in a module when ambient is 20°C, solar irradiation is 0.8 kW/m², and wind speed is 1m/s. To account for other ambient conditions, the following expression may be used:

$$T_{CELL} = T_{amb} + \frac{NOCT−20°}{0.8} \times S$$  \hspace{1cm} (2-11)

where $T_{cell}$ is cell temperature (°C), $T_{amb}$ is ambient temperature, and $S$ is solar insolation (kW/m²).
Cambodia has a temperature range somewhere from 21 to 35 °C. Using a conservative ambient temperature value of 35 °C, under 1 kW/m² of solar insolation, the cell temperature of a PV module with NOCT of 47 °C can be estimated:

\[ T_{CELL} = 35° + \frac{47°-20°}{0.8} \times 1 = 69° \]  

(2-12)

With maximum power expected to drop about 0.5%/°C above 25 °C, the loss due temperature is:

\[ Loss_{Cell Temperature} = 0.5\% \times (69 - 25) = 22\% \]  

(2-13)

In addition, not all modules coming off the very same production line will have exactly the same rated output. Some 100-W modules may really be 103 W and others 97 W, for example. As these modules are put together in the PV array, the expected rated output of the array is less than the sum of rated output of all the modules. This module mismatch factors can easily drop the array output by a few percent. Finally, the loss due to the charge controller must be taken into account.

Assuming charge controller is 90% efficient, there is a 3% loss due to mismatch and 4% loss due to dirt and ageing, the conversion efficiency is:

\[ \eta_{Conversion} = 0.9 \times 0.78 \times 0.93 = 65.3\% \]  

(2-14)

The rated daily energy of PV is obtained:

\[ E_{PV,STC} = \frac{E_{bat}}{\eta_{Conversion}} = \frac{22963}{0.653} = 35165 \text{ Wh} \]  

(2-15)

The rated power of the PV module can found using the expression:

\[ P_{PV} = \frac{E_{PV,STC}}{\text{Peak Sun hour}} \]  

(2-16)

The “peak sun” hour is an approach to estimate the daily energy delivered by PV array. The insolation of, for example, 5kWh/m² per day can be counted as being the same as 5.6h/day of 1-sun, or 5.6h of “peak sun.” The expression (2-16) is valid based on the assumption that system efficiency remains constant throughout the day. The main justification is that these grid-connected systems have maximum power point trackers that keep the operating point near the knee of the I–V curve all day long. Since power at the maximum point is nearly directly proportional to insolation, system efficiency should be reasonably constant. Cell temperature also plays a role, but it is less important. Efficiency might be a bit higher than average in the morning, when it is cooler and there is less insolation. In fact, the value calculated can be viewed as slightly conservative.

The average solar radiation in Cambodia is 5.3 kWh/m²/day based on NASA satellite data [233]. The maximum fluctuation in solar radiation volume throughout the year is relatively
The lowest solar insolation is in September (around 4.8 kWh/m²) and the highest in April.

Using the worst month value of 4.8 h of peak sun hour, the size of PV panel can be obtained:

\[ P_{PV} = \frac{E_{PV}}{4.8 \, h} = \frac{35165 \, Wh}{4.8 \, h} = 7326 \, Wp \]  \hspace{1cm} (2-17)

The solar panels density has been estimated to be 12Kg/m² using PV module manufacturers’ data. Using a 15% efficiency PV module, the surface and mass of PV can be calculated:

\[ A_{PV} = \frac{P_{PV}}{\eta_{PV}} = \frac{7326 \, kW}{0.15} = 48.84 \, m^2 \; ; \; m_{PV} = 12 \times A_{PV} = 586 \, Kg \] \hspace{1cm} (2-18)

The mass of inverter is extrapolated from the inventory data of a 2500W inverter presented in [234]. Due to lack of data, the mass of charge controller is assumed to be identical to that of the inverter. The parameters of system components are summarized in Table 2-5 and Table 2-6.

Table 2- 5: Parameters of components in the conventional solution.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Efficiency</th>
<th>MDOD</th>
<th>Life cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter</td>
<td>3333 W</td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td>Charge controller</td>
<td>7326 W</td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td>Lead-acid Battery</td>
<td>24 V</td>
<td>75%</td>
<td>80%</td>
</tr>
<tr>
<td>Solar PV panel</td>
<td>Polycrystalline</td>
<td>15% (150 W/m²)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2- 6: Component sizing of the conventional solution.

<table>
<thead>
<tr>
<th>Size</th>
<th>Mass (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter</td>
<td>3333 W</td>
</tr>
<tr>
<td>Charge controller</td>
<td>7326 W</td>
</tr>
<tr>
<td>Solar PV panel</td>
<td>48.84 m²</td>
</tr>
<tr>
<td>Battery</td>
<td>1794 Ah</td>
</tr>
</tbody>
</table>

**Reuse solution and assumption**

The unintended application of used components could lead to the deterioration of system performance. For the purpose of the study, the deterioration of used items is modelled by the decrease of its efficiency and lifetime. The efficiency of the modified power supply unit and modified UPS is assumed to be 10% less compared to the value of new components, due to ageing and unintentional use.

The SLI-type lead-acid battery is optimized to produce the high short-duration currents required to start an internal combustion engine. This type of battery is not intended for a deep-cycle application. The parameters of the battery are also taken from [230]. Its efficiency is assumed to be 5% lower than the typical value.

The power density of the PSUs based on the samples collected is about 500W/Kg and about 120W/Kg for UPSs (excluding the mass of battery). The main components of the Arduino
microcontroller are the microprocessor and a 100x50 mm\(^2\) printed circuit board (PCB). The contribution of other components is less significant and thus assumed to be negligible.

Fig. 2-12: Tear down of a 700VA UPS (battery is not shown).

The assumptions about the parameters and sizing of reuse system are shown in Table 2-7 and Table 2-8. The system parameters of conventional and reuse systems are presented in Table 2-9 based on the aforementioned assumptions.

Table 2-7: Parameters of the components of the reuse solution.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Efficiency</th>
<th>MDOD</th>
<th>Life time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV panel</td>
<td>Poly-crystalline</td>
<td>15 %</td>
<td>20 years</td>
</tr>
<tr>
<td>Car battery [7]</td>
<td>24V</td>
<td>70 %</td>
<td>20 %</td>
</tr>
<tr>
<td>PSU, UPS inverter</td>
<td></td>
<td>80 %</td>
<td>500 cycles</td>
</tr>
<tr>
<td>Arduino controller</td>
<td>100 x 50 mm(^2)</td>
<td></td>
<td>5 years</td>
</tr>
</tbody>
</table>

Table 2-8: Component sizing of the reuse solution.

<table>
<thead>
<tr>
<th>Size</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV panel</td>
<td>66.24 m(^2)</td>
</tr>
<tr>
<td>Car Battery</td>
<td>8073 Ah</td>
</tr>
<tr>
<td>PSUs</td>
<td>9936 W</td>
</tr>
<tr>
<td>UPSs</td>
<td>3750 W</td>
</tr>
<tr>
<td>Arduino board</td>
<td>100x50 mm(^2) PCB</td>
</tr>
</tbody>
</table>

Table 2-9: Component sizing (reuse solution vs. conventional solution).

<table>
<thead>
<tr>
<th>Size</th>
<th>Conventional</th>
<th>Reuse</th>
<th>Conventional</th>
<th>Reuse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar PV panel</td>
<td>48.84 m(^2)</td>
<td>66.24 m(^2)</td>
<td>586 Kg</td>
<td>795 Kg</td>
</tr>
<tr>
<td>Lead-acid Battery</td>
<td>1794 Ah</td>
<td>8073 Ah</td>
<td>1230 Kg</td>
<td>3875 Kg</td>
</tr>
<tr>
<td>Charge controller/PSUs</td>
<td>7326 W</td>
<td>9936 W</td>
<td>24.67 Kg</td>
<td>19.87 Kg</td>
</tr>
<tr>
<td>Inverter/UPSs</td>
<td>3333 W</td>
<td>3750 W</td>
<td>24.67 Kg</td>
<td>31.25 Kg</td>
</tr>
<tr>
<td>Arduino board</td>
<td>-</td>
<td>100x50 mm(^2) PCB</td>
<td>-</td>
<td>45g</td>
</tr>
</tbody>
</table>
2.3.5. Life cycle inventory

Most of the inventory data are taken from Ecoinvent database. Additional inventory data unavailable in the database have been collected from the dedicated literature (for instance, inventories for lead-acid battery). Some additional assumptions have been made for some processes due to the lack of precise data source.

- **PV and BOS components**

The life-cycle stages of photovoltaic involve (1) the production of raw materials, (2) their processing and purification, (3) the manufacture of modules and balance of system (BOS) components, (4) the installation and use of the systems, and (5) their decommissioning and disposal or recycling (see Fig. 2-13).

![Flow of the life-cycle stages, energy, materials, and wastes for PV systems.](image)

The best available data for life cycle inventories of PV modules was available in the EcoInvent database. A typical PV system consists of the PV module and the balance of system (BOS). The BOS components include structures for mounting the PV modules and electric components (Inverter, charge controller, cables) which convert the generated electricity to the proper form for usage. Little attention has been paid to the LCA studies of the balance of system, and so inventory data are scarce. The LCI data of BOS components for year 2006 have been taken from [234]. The authors studied two classes of rooftop mounting systems based on a mc-Si PV system. Two types (500 and 2500 W) of small inverters adequate for rooftop PV design were inventoried, which is available in the EcoInvent database (Table 2-10).

Since a database for inverter is only available in a few power ratings, data extrapolation has been applied to evaluate the impacts of the actual inverter size. Detailed data for charge controller have not been found in literature. Yet, a few articles have used the value 1MJ/W of embodied energy for both inverter and charge controller [236, 237]. Hence, for our case, the environmental impacts of both components are also assumed to be identical as per power unit (system power rating).

Also, other BOS components including structure supports, cable and connectors, will be considered similar for both scenarios, they are not considered in the differential analysis and
excluded from the system boundary. Using the inventories from EcoInvent database (Table 2-11), the impact characterisation at midpoint categories of life cycle of 2500 W inverter and a 1 m² multi-Si PV module is presented in Table 2-12.

Table 2-10: LCI of 2500WAC Inverter (Disassembly of inverter and weighing), based on data collected in 2001, from Mastervolt Sunmaster 2500. [234]

<table>
<thead>
<tr>
<th>Products</th>
<th>Unit</th>
<th>Amount</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter</td>
<td>p</td>
<td>1.00</td>
<td>Nominal output 2500 W AC</td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>Kg</td>
<td>9.8</td>
<td>Casing</td>
</tr>
<tr>
<td>Aluminium</td>
<td>Kg</td>
<td>1.4</td>
<td>Casing</td>
</tr>
<tr>
<td>Transformers, wire-wound</td>
<td>Kg</td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>Printed Circuit Board, with electronic</td>
<td>Kg</td>
<td>1.8</td>
<td></td>
</tr>
</tbody>
</table>

Table 2-11: Inventories data for Inverter, charge controller and PV panels.

<table>
<thead>
<tr>
<th>Products</th>
<th>EcoInvent 2.2 database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter, charge controller</td>
<td>Inverter, 2500W, at plant/RER</td>
</tr>
<tr>
<td>Photovoltaic panel, multi-Si, at plant</td>
<td>Photovoltaic panel, multi-Si, at plant/RER</td>
</tr>
</tbody>
</table>

* (1): European average.

Table 2-12: Impacts of inverter and PV module life cycle (Impact 2002+)

<table>
<thead>
<tr>
<th>Midpoint impact categories</th>
<th>Unit</th>
<th>Inverter, 2500W</th>
<th>Photovoltaic panel, multi-Si, 1 m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcinogens</td>
<td>kg C₃H₃Cl₁₄eq</td>
<td>5.40</td>
<td>2.22</td>
</tr>
<tr>
<td>Non-carcinogens</td>
<td>kg C₃H₃Cl₁₄eq</td>
<td>20.08</td>
<td>2.42</td>
</tr>
<tr>
<td>Respiratory inorganics</td>
<td>kg PM₄,5 eq</td>
<td>0.28</td>
<td>0.10</td>
</tr>
<tr>
<td>Ionizing radiation</td>
<td>Bq C-14, eq</td>
<td>8131.75</td>
<td>4446</td>
</tr>
<tr>
<td>Ozone layer depletion</td>
<td>kg CFC-11, eq</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Respiratory organics</td>
<td>kg C₃H₄,eq</td>
<td>0.18</td>
<td>0.14</td>
</tr>
<tr>
<td>Aquatic ecotoxicity</td>
<td>kg TEG-water</td>
<td>74462</td>
<td>14109</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>kg TEG-soil</td>
<td>20806</td>
<td>3004</td>
</tr>
<tr>
<td>Terrestrial acid/nutri</td>
<td>kg SO₂,eq</td>
<td>4.36</td>
<td>2.22</td>
</tr>
<tr>
<td>Land occupation</td>
<td>M² org. arable</td>
<td>2.46</td>
<td>1.31</td>
</tr>
<tr>
<td>Aquatic acidification</td>
<td>kg SO₂,eq</td>
<td>1.55</td>
<td>0.61</td>
</tr>
<tr>
<td>Aquatic eutrophication</td>
<td>kg PO₄ P-lim</td>
<td>0.58</td>
<td>0.05</td>
</tr>
<tr>
<td>Global warming</td>
<td>kg CO₂,eq</td>
<td>169.57</td>
<td>156</td>
</tr>
<tr>
<td>Non-renewable energy</td>
<td>MJ primary</td>
<td>3003</td>
<td>2605</td>
</tr>
<tr>
<td>Mineral extraction</td>
<td>MJ surplus</td>
<td>59.44</td>
<td>4.71</td>
</tr>
</tbody>
</table>

- **Lead-acid battery inventories**

Lead-acid batteries stored energy in form of chemical reactions. The electrochemical reactions during discharge are described by the following reaction. The opposite reaction happens as battery is recharged.

\[
PbO_2 + 2H_2SO_4 + Pb \rightarrow 2PbSO_4 + 2HO_2
\] (2-19)
The main components of the battery are: a cathode comprised of lead peroxide on a lead lattice for support; an anode made of sponge lead, also on a lead lattice; an electrolyte of water and sulphuric acid; fiberglass matte separators that keep the anode and cathode apart; and a containment case, typically made of polypropylene (PP). Antimony (or calcium) is alloyed with lead to suppress electrolysis of water during recharging.

Table 2-13: Material composition of the lead-acid batteries in percentage of battery mass from different references.

<table>
<thead>
<tr>
<th>Material Compositions</th>
<th>[239] (Industrial)</th>
<th>[239] (EV battery)</th>
<th>[240]</th>
<th>[238] (VRLA)</th>
<th>[242]</th>
<th>[241]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>60(^{(1)})</td>
<td>69(^{(2)})</td>
<td>60.69</td>
<td>71(^{(3)})</td>
<td>61.2</td>
<td>69</td>
</tr>
<tr>
<td>Sulphuric acid</td>
<td>10</td>
<td>11</td>
<td>10.33</td>
<td>6.3</td>
<td>9.6</td>
<td>7.9</td>
</tr>
<tr>
<td>Water (unsalted)</td>
<td>16</td>
<td>18</td>
<td>16.93</td>
<td>10.8</td>
<td>13.3</td>
<td>14.1</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>10</td>
<td>4</td>
<td>6.72</td>
<td>7.5</td>
<td>8.2</td>
<td>6.1</td>
</tr>
<tr>
<td>Polyethylene</td>
<td></td>
<td></td>
<td>1.83</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Antimony (Sb)</td>
<td>1</td>
<td></td>
<td>0.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arsenic</td>
<td></td>
<td></td>
<td>0.03</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td></td>
<td></td>
<td>0.01</td>
<td>0.5</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>2</td>
<td>4</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fiberglass mat separator</td>
<td></td>
<td></td>
<td>2.5</td>
<td>2.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grid alloying additives</td>
<td></td>
<td></td>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative Electrode Additives</td>
<td></td>
<td></td>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balancing and control</td>
<td></td>
<td></td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electronics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sb, Sn, As</td>
<td></td>
<td></td>
<td>2.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyester</td>
<td></td>
<td></td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other (expander and oxygen in PbO2)</td>
<td></td>
<td></td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*\(^{(1)}\): 25 (lead), 35 (lead oxides) \(^{(2)}\): 1/3 ratios of lead to lead oxide. \(^{(3)}\): Lead and oxygen, 69% for pure lead.

The life cycle inventory data for stationary storage application lead-acid batteries have been collected from various literature sources for their material production stages and assembly process (Table 2-13). The material composition of the battery shown in Table 2-14 is the average value in percentage of battery total mass based on literature reviews [238-242]. Some less significant materials are not included due to their small quantity. The EcoInvent database provides the necessary inventories data for the extraction and production stages of each material. The energy amount required for the assembly processes of the battery, which includes grid manufacturing, paste and plate manufacturing, plastic moulding and final assembly, is based on [238] (Table 2-15).

Lead-acid batteries are usually collected and recycled after their useful life time. Lead is always among one of the most recycled materials in terms of recovery rate, since can be remelted infinitely to remove impurities. Recycling of lead contributes to reduce the
environment impact since lead recovery from scrap requires far less energy than smelting from ore. As the quality of the recycled lead is almost identical to primary lead collected directly from mining, its value and demand as a recycled material are very high: more than 50 percent of lead used in the production of new lead products around the world is sourced from recycled lead (secondary production) and recycling of lead contributes to reduce the environment impact since lead recovery from scrap requires far less energy than smelting from ore. Lead-acid batteries are highly recycled. About 97% of secondary lead is recovered at secondary lead smelters and refineries as either soft (unallloyed) or antimonial lead, most of which is recycled directly back into the manufacture of new batteries (EPA Office of Compliance, 1995) [243]. Demand for primary lead is expected to remain relatively constant while the demand for secondary lead is predicted to increase with the growth of lead-acid production [244].

Table 2- 14: Material composition in percentage of mass of lead-acid battery ([238-242]) and the corresponding database of material production.

<table>
<thead>
<tr>
<th>Material composition</th>
<th>Percentage of battery mass</th>
<th>EcoInvent database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>65.3</td>
<td>Lead, primary, at plant/GLO[^1]</td>
</tr>
<tr>
<td>Sulphuric acid</td>
<td>9.2</td>
<td>Sulphuric acid, liquid, at plant/RER</td>
</tr>
<tr>
<td>Water (unsalted)</td>
<td>14.86</td>
<td>Water, deionised, at plant/CH[^2]</td>
</tr>
<tr>
<td>Polypropylene (case)</td>
<td>7.15</td>
<td>Polypropylene, granulate, at plant/RER</td>
</tr>
<tr>
<td>Fiberglass mat separator</td>
<td>2.3</td>
<td>Glass fibre, at plant/RER</td>
</tr>
<tr>
<td>Tin</td>
<td>0.4</td>
<td>Tin, at regional storage/RER</td>
</tr>
</tbody>
</table>

[^1]: Global average.  
[^2]: Swiss average.

Table 2- 15: Energy requirement in battery manufacturing process

<table>
<thead>
<tr>
<th></th>
<th>Electric (MJ/kg)</th>
<th>Gas (MJ/kg)</th>
<th>Oil (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid manufacturing</td>
<td>0.37</td>
<td>3.85</td>
<td>0.43</td>
</tr>
<tr>
<td>Paste manufacturing</td>
<td>0.22</td>
<td>0.65</td>
<td>0.02</td>
</tr>
<tr>
<td>Plate manufacturing</td>
<td>0.23</td>
<td>0.68</td>
<td>0.08</td>
</tr>
<tr>
<td>Plastic molding</td>
<td>0.78</td>
<td>0.20</td>
<td>0.02</td>
</tr>
<tr>
<td>Assembly/formation</td>
<td>2.99</td>
<td>0.93</td>
<td>0.10</td>
</tr>
<tr>
<td>Total</td>
<td>4.59</td>
<td>6.31</td>
<td>0.65</td>
</tr>
</tbody>
</table>

EcoInvent database: Electricity, low voltage, production UCTE, at grid/UCTE  
Heat, natural gas, at boiler modulating >100kW/RER  
Heat, heavy fuel oil, at industrial furnace 1MW/RER

Table 2- 16: Ecoinvent data employed for recycling process of battery.

<table>
<thead>
<tr>
<th></th>
<th>CED (MJ/kg)</th>
<th>GWP (kg CO₂-eq/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead, secondary, at plant/RER U</td>
<td>11.9</td>
<td>0.652</td>
</tr>
</tbody>
</table>

It is estimated more than 90% of lead and lead oxide is recycled [245]. A typical new battery contains between 60% and 80% recycled lead and plastic [239]. A collection rate and recycled rate of 100% was assumed for recovered lead-acid batteries. The recycling process
of the battery is estimated using ‘secondary lead’ datasets of EcoInvent (Table 2-16). A ratio of 20/80 for primary/secondary lead is used for the production lead.

Fig. 2-14: Normalised midpoint categories impacts scores of lead-acid battery production (per 1kg battery).

Fig. 2-15: Normalised midpoint categories impacts of lead-acid battery life cycle at difference ratio of primary to secondary lead. (Per 1kg battery)
The normalised impact scores of battery production, assuming 100% primary lead is used is shown in Fig. 2-14. The effect of primary/secondary lead ratio to the overall life cycle impacts of 1kg lead-acid battery is illustrated in Fig. 2-15.

- Reuse solution and assumptions

The processes of modifying the structure of PSUs and UPSs involve removing some components, some soldering by adding a few components. In the same way, used car batteries need to be tested to determine its state-of-health in the processes of selecting the ones that are still in good condition. Though these processes require energy, some additional components, and in case of battery, some chemical substances, the efforts are presumably less significant in comparison to the production of the new parts.

For these reasons and the lack of the actual measurement, the impact of these refurbishing processed is assumed to be negligible or not significant for the overall results. The collection process, however, will be taken into account. In this case, the impact of reuse components is associated to transportation from waste collection facility to installation. A supposed average distance of 200 km of truck transportation is needed to transport the components from the collection facility in the city to the installation site in the countryside. The transportation for new components was assumed to be identical to that of the conventional solution. The Ecoinvent database used in impact assessment are listed in Table 2-17.

| Table 2-17: Ecoinvent database used for impacts characterisation in reuse solution. |
|---------------------------------|---------------------------------------------------------------|
| Solar panel                     | Photovoltaic panel, multi-Si, at plant/RER                   |
| Arduino controller (PCB +      | Printed wiring board, surface mounted,                       |
| microprocessor IC)              | solder mix, at plant/GLO Integrated circuit,                 |
|                                 | IC, logic type, at plant/GLO                                 |
| Transportation                  | Truck 16t                                                    |

2.3.6. Impact assessment results

The life cycle impact assessment methodology IMPACT 2002+ which proposes a feasible implementation of the combined midpoint/damage-oriented approach is adopted for this study to evaluate the environmental impacts of the resources and releases identified during the LCI phase. This assessment methodology links all types of LCI results via 15 midpoint categories (human toxicity carcinogenic effects, human toxicity non-carcinogenic effects, respiratory effects, ionizing radiation, ozone layer depletion, photochemical oxidation, aquatic eco-toxicity, terrestrial eco-toxicity, aquatic acidification, aquatic eutrophication, terrestrial acidification/nutrification, land occupation, global warming, non-renewable energy consumption, and mineral extraction) to four damage categories (human health, ecosystem quality, climate change, and resources). Studies using the ‘endpoint’ methods can be interpreted easily, but usually exhibit greater uncertainties. The ‘midpoint’ methods, on the other hand, lead to more accurate results [246].
At midpoint level, the unit of impacts indicators can be expressed in “kg equivalent of a reference substance s”, the amount of a reference substance that equals the impact of the considered pollutant within the category studies. For instance, kg CO$_2$-eq unit is used in global warming category. However, to illustrate the relative impacts between different scenarios, the impact assessment has been illustrated with normalized values. The normalization is performed by dividing the impact (at damage categories) by the respective normalization factors. The list of normalization factors for damage categories and midpoint categories for Western Europe is detailed in [247].

The result of impact score for conventional system over its lifetime is represented in Fig. 2-16. For almost every category, lead-acid battery has the worst effect on the impacts. The second most pollutant component is PV module. Charge controller and inverter have contributed less than 10% of the system impacts. Transportation has also a significant impact, most of which is also related to battery.

The assessment result for reuse scenario is illustrated in Fig. 2-17. The result shows PV modules provide the most important impact. The significant associated to PSUs/UPSs and microcontroller kit is almost insignificant. Nevertheless, the impacts of reusing lead-acid battery which only include transportation are still important due to their weight and frequent replacement. Due to its short service life, battery is required to replace almost every year.
This turns out to contribute significantly to the environment burden due to transportation of heavy batteries.

![Graph showing normalized impacts scores in different midpoint categories for reuse solution.](image1)

**Fig. 2-17:** Normalized impacts scores in different midpoint categories for reuse solution.

![Graph showing normalized impacts scores comparison of conventional and reuse solutions.](image2)

**Fig. 2-18:** Normalized impacts scores comparison of conventional and reuse solutions.
The comparison of environmental impacts of both cases is shown in Fig. 2-18. This result has demonstrated the reduction of environmental impact by applying reuse solution. A decrease of about 40% is found for the reuse scenario. This gain is largely due to the absence of battery production impacts in the case of reuse. The gain due to reuse of PSUs and USPs units is very low in comparison to lead-acid battery. The comparison in midpoint characterisation scores for some selected categories is presented in Table 2-18.

Table 2-18: Impacts comparison of the conventional and the reuse solutions for selected midpoint categories.

<table>
<thead>
<tr>
<th>Midpoint impact categories</th>
<th>Unit</th>
<th>Conventional solution</th>
<th>Reuse solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcinogens</td>
<td>kg C₂H₂Cl eq</td>
<td>653</td>
<td>159</td>
</tr>
<tr>
<td>Non-carcinogens</td>
<td>kg C₂H₂Cl eq</td>
<td>3210</td>
<td>212</td>
</tr>
<tr>
<td>Respiratory inorganics</td>
<td>kg PM₂.₅ eq</td>
<td>25.34</td>
<td>15.00</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>kg TEG soil</td>
<td>841573</td>
<td>346980</td>
</tr>
<tr>
<td>Terrestrial acid/nutri</td>
<td>kg SO₂ eq</td>
<td>552</td>
<td>403</td>
</tr>
<tr>
<td>Global warming</td>
<td>kg CO₂ eq</td>
<td>21749</td>
<td>14866</td>
</tr>
<tr>
<td>Non-renewable energy</td>
<td>MJ primary</td>
<td>388652</td>
<td>241627</td>
</tr>
<tr>
<td>Mineral extraction</td>
<td>MJ surplus</td>
<td>13410</td>
<td>390</td>
</tr>
</tbody>
</table>

2.4. Sensitivity Analysis and Discussion

A life cycle assessment study has proven some significant decrease in the environmental impacts in comparison to a conventional solution based on new components. The results, which are based partly on some assumptions, interpolations or extrapolations due to the lack of data, could vary in the actual situation. In order to have reliable results, the assumptions made during the first study have been modified and the consequences on the results were analysed. The sensitivity analysis assessed the effects of the assumptions and of possible variations in the collected data on the results. This analysis is performed by varying the assumed parameters.

In this section, the effects of these parameters were analysed:

- The efficiency of repurposed PSUs and repurposed UPSs in the reuse solution. (-20% & -0%)
- The efficiency of storage battery in reuse solution. (-10% & -0%)
- The life cycle of storage battery in reuse solution.
- Transportation distance in both solution

The effects of some parameters including converter lifetime are not considered. The main reason is their relatively negligible share in the impacts results. Also, most of the parameters are only assessed for reuse solution as they have higher uncertainty.

2.4.1. Influence of PSUs and UPSs efficiency

The efficiencies of repurposed PSUs and repurposed UPSs in the reuse solution were assumed to be 10% less than those in the conventional solution. The effect of the change of
the converter efficiencies by 10% around the initial value to the overall impacts of the reuse solution are illustrated in the Table 2-19. The results are only demonstrated in a few impact categories which are significant in term of normalised impacts. The effects of decreasing the efficiencies by 10% (which correspond to 20% lower than those in the conventional solution) have increased the overall impacts by 22-30%. The opposite effects decrease the impacts by 16-20%.

Table 2- 19: Influence of PSUs and UPSs efficiency on the impact result of reuse solution.

<table>
<thead>
<tr>
<th>Impact categories</th>
<th>-10% Efficiency Effect</th>
<th>+10% Efficiency Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcinogens</td>
<td>+29.52 %</td>
<td>-20.33 %</td>
</tr>
<tr>
<td>Non-carcinogens</td>
<td>+26.90 %</td>
<td>-18.73 %</td>
</tr>
<tr>
<td>Respiratory inorganics</td>
<td>+22.69 %</td>
<td>-16.2 %</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>+24.15 %</td>
<td>-17.08 %</td>
</tr>
<tr>
<td>Global warming</td>
<td>+26.12 %</td>
<td>-18.27 %</td>
</tr>
<tr>
<td>Non-renewable energy</td>
<td>+26.40 %</td>
<td>-18.44 %</td>
</tr>
</tbody>
</table>

2.4.2. Influence of battery efficiency

The efficiencies of lead-acid batteries are subjected to various system and environment conditions. Table 2-20 summarises the effects of the change of 10% around the initial value 70% of battery efficiency on the impacts results of the reuse solution in the chosen impacts categories. The increase of 10-15% of impacts is observed at the efficiency of 60%. As the batteries efficiency is increased to 80%, the impacts are reduced by 6-11%.

Table 2- 20: Influence of storage batteries efficiencies on the impact result of reuse solution.

<table>
<thead>
<tr>
<th>Impact categories</th>
<th>-10% Efficiency Effect</th>
<th>+10% Efficiency Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcinogens</td>
<td>+15.57 %</td>
<td>-11.68 %</td>
</tr>
<tr>
<td>Non-carcinogens</td>
<td>+12.93 %</td>
<td>-9.70 %</td>
</tr>
<tr>
<td>Respiratory inorganics</td>
<td>+8.6 %</td>
<td>-6.45 %</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>+10.11 %</td>
<td>-7.58 %</td>
</tr>
<tr>
<td>Global warming</td>
<td>+12.09 %</td>
<td>-9.07 %</td>
</tr>
<tr>
<td>Non-renewable energy</td>
<td>+12.38 %</td>
<td>-9.29 %</td>
</tr>
</tbody>
</table>

2.4.3. Influence of battery life cycle

In storage application in the PV system, the batteries will be continually charged and discharged. The life span of a battery which is normally counted as the number of cycles that it can be expected to perform, a cycle being a discharge followed by recharging, is heavily depending on depth of discharge during the cycle. The effect of batteries life cycle to the overall impacts of the reuse solution is presented in Table 2-21.

2.4.4. Influence of transportation distance

The distances using in transportation are estimated values assuming all new components are manufactured in China and the systems are installed in Cambodia. The effects of transportation distance variations were studied. The effect of about 1.5% on the overall impacts is found in the conventional solution and 3.9% in the reuse solution with the
variation of 10% of distance. This effect is less significant relative to the other presented parameters. This effect is more significant in reuse scenario as transportation directly determine the impacts associated to used components of the system.

Table 2-21: The influence of batteries life time on the impacts result of reuse solution

<table>
<thead>
<tr>
<th>Impact categories</th>
<th>-10% cycle Effect</th>
<th>+10% cycle Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcinogens</td>
<td>+ 0.72 %</td>
<td>-0.59 %</td>
</tr>
<tr>
<td>Non-carcinogens</td>
<td>+ 2.45 %</td>
<td>-2.00 %</td>
</tr>
<tr>
<td>Respiratory inorganics</td>
<td>+ 5.36 %</td>
<td>-4.38 %</td>
</tr>
<tr>
<td>Terrestrial eco-toxicity</td>
<td>+ 4.33 %</td>
<td>-3.55 %</td>
</tr>
<tr>
<td>Global warming</td>
<td>+ 3.03 %</td>
<td>-2.48 %</td>
</tr>
<tr>
<td>Non-renewable energy</td>
<td>+ 2.84 %</td>
<td>-2.32 %</td>
</tr>
</tbody>
</table>

Table 2-22: The influence of batteries life time on the impacts result of both solutions

<table>
<thead>
<tr>
<th>Impact categories</th>
<th>Effect of -10% distance in convention solution</th>
<th>Effect of +10% distance in convention solution</th>
<th>Effect of -10% distance in reuse solution</th>
<th>Effect of +10% distance in reuse solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carcinogens</td>
<td>-0.17 %</td>
<td>+0.17 %</td>
<td>-0.76 %</td>
<td>+0.76 %</td>
</tr>
<tr>
<td>Non-carcinogens</td>
<td>-0.09 %</td>
<td>+0.09 %</td>
<td>-2.42 %</td>
<td>+2.42 %</td>
</tr>
<tr>
<td>Respiratory inorganics</td>
<td>-2.17 %</td>
<td>+2.17 %</td>
<td>-5.40 %</td>
<td>+5.40 %</td>
</tr>
<tr>
<td>Terrestrial eco-toxicity</td>
<td>-0.88 %</td>
<td>+0.88 %</td>
<td>-4.24 %</td>
<td>+4.24 %</td>
</tr>
<tr>
<td>Global warming</td>
<td>-1.41 %</td>
<td>+1.41 %</td>
<td>-3.05 %</td>
<td>+3.05 %</td>
</tr>
<tr>
<td>Non-renewable energy</td>
<td>-1.17 %</td>
<td>+1.17 %</td>
<td>-2.85 %</td>
<td>+2.85 %</td>
</tr>
</tbody>
</table>

2.4.5. Results discussion

Fig. 2-19 summarises the sensitivity analysis of all parameters on the overall normalized environmental impacts. It demonstrates that the assumptions did have some noticeable impact on the results. Nevertheless, it also demonstrates that the results of this study are reliable in the sense that the conclusions which prefer reuse over conventional system remain the same.

The efficiencies of power converter and batteries are the most sensitive parameters. The distance in transportation can dramatically change according to location or countries of producers and location of installation. While the impact of transportation distance and batteries life cycle has little impact on the result, these parameters could vary widely depending on many factors.

Batteries lifetime could greatly affect the result as batteries share the significant impacts potion. The life cycle of batteries, for instance, could change greatly according to technology and usage condition. The operation temperature could greatly decrease its useful lifetime. Although its capacity increases at high temperature, its lifespan can be estimated to shorten by 50% for every 10°C above the optimum 25°C operating temperature [230]. This shortened life time effect increases the impacts of both case, but most significantly the conventional solution, which involve production of new batteries.
Fig. 2- 19: Comparison of influence of parameters to the impact results.

Fig. 2- 20: Comparison of normalised impacts scores by doubling battery lifetime in conventional solution.

In SLI application, wet lead-acid batteries rather than VRLA batteries are commonly used. Gel cell VRLA batteries have too high an internal impedance to deliver the high peak current required by most SLI applications. Absorbed glass mat (AGM) VRLA batteries can provide high current but at considerably higher cost. Despite the cost, these types of batteries are more tolerant of deep discharge, thus providing more life cycles in comparison to the classic flooded lead-acid batteries. The increase of SLI batteries lifespan due to change technology
helps to further decreasing the effect of the reuse scenario. In both presented cases, our results are still justified, and in fact, more conservative.

The result, however, could be different if the technology of storage batteries supposedly increased significantly as that of SLI batteries remains constant overtime. This situation can be demonstrated in Fig. 2-20, by doubling the lifespan of battery in the conventional solution, the impacts results became very comparable. Though this situation is quite unlikely, the result remains positive for reuse solution.

2.5. Summary

The concept of Life Cycle Assessment methodology has been described in this chapter which is used to evaluate the environmental impacts of the proposed renewable energy system based on reuse. This system consist of a solar PV panel, refurbished power supply units (PSUs) as charge controller, refurbished uninterruptable power supply units (UPSs) as inverter, and used car batteries as storage batteries. Cheap microcontrollers (based on Arduino products) with few interface components are added for control purposes.

The objective of this LCA study is to compare the life cycle impacts of the proposed solution and the conventional solution based on newly made components. This comparison has been made based on a functional unit which define a goal that the dimensions of both solutions are determined. The functional unit is defined by satisfying the daily energy needs of a rural village over a period of 20 years. The system boundaries define the stages and processes included in the LCA study.

Most of the inventories data are available in EcoInvent database. For some components, such as inverter, charge controller and lead-acid batteries, the inventories data is supplemented by the data from literature. Due to lack of precise information, some data and parameters are based on estimation and conservative assumption. For instance, the efficiencies of the used components are assumed to be slightly less than those of the new components.

The assessment result clearly shows a decrease of about 40% of impacts for reuse scenario. To illustrate the reliability of this impacts assessment, the assumptions made during the first assessment have been modified and the consequences on the results were analysed. This sensitivity analysis seeks to find the relative influences of different assumed parameters. The result demonstrates that the environmental impacts of reuse solution remain lower even at the most conservative assumption.
Chapter 3
Second-life Application of Power Supply Units
Chapter 3: Second-life Application of Power Supply Units

3.1. Introduction

In the current world, it is rather difficult to imagine our everyday activities without computers. They have become an electronic device of almost every day use for individuals or organisations, and are essential for most businesses or operations in some ways. Due to the rapid technological development, innovation and consumer demand, computers’ lifespan has been significantly cut resulting in increased e-waste. Hundreds of millions of desktop and laptop computers and their accessories are, or will soon become, obsolete globally. Only a marginal portion of these are being recycled through collection and take-back schemes. According to the ‘United States Environmental Protection Agency’ (US-EPA) [301], some 14 to 20 billion of PC were thrown away in 2006 and the developing countries were supposed to triple their output of e-waste by 2010. Almost 52 million computers have been trashed or recycled in US, in 2010. Only 40% of them are recycled. This rate is expected to be lower in the most part of the world. Many developing countries and countries with economies in transition are confronted with the challenge of properly managing an increasing volume of electronic and electrical wastes.

Amount the conventional end-of-life management which includes disposal, recycling, remanufacturing, reuse has not been a commonly used option even if it is always considered superior to materials recovery in recycling or remanufacturing [302]. Usually reuse is a second-life use of whole products from a ‘second hand’ market or in the form donation to organizations or countries in needs. More specifically, reuse of UEEE or its components is to continue to use it (for the same purpose for which it was conceived) beyond the point at which its specifications fail to meet the requirements of the current owner and the owner has ceased use of the product. The idea of reusing or refurbishing some components of the devices for different usage is a relatively new concept. This process not only requires a technical study of the specific components but also need a dedicated group or enterprise to implement the project.

Despite the huge number of PC’s worldwide, very few works investigate a possible second-life of their power supplies. One alternative to dismantling and recycling in an optimistic way has been proposed successively in [303-305] by the same group of researchers. The basic idea undertaken in these works is to transform some parts of an ATX compliant power supply, the active PFC front-end stage, into a new converter dedicated to MPPT control for photovoltaic generation. Reference [306] presented a smart battery conditioner based on PC power supplies and microcontroller. The power supply is modified to allow an interface between microcontroller and its PWM controller. The power supply has been converted to a constant-current converter which is programed with the microcontroller for batteries
charging. The solutions proposed in these works are particularly suitable for the developing countries. The reduced cost of this kind of equipment is the main interest. Besides, rich countries have often organized collection and recycling process for electronic waste while old materials are thrown away and end up in the fields or on river banks in poor countries. Consequently, this reuse concept could contribute to local waste reduction.

Nevertheless, the possibility of reusing power supply units in a renewable system has not yet been fully explored from those previous works. While the active PFC front-end stage of the power supply can converted to MPPT controller in a PV generation system, the rating of the controller will be limited due to the rating of the switching transistor. To operate at the original rating of the PFC, the system must operate at high voltage which is not suitable for batteries storage system. Since power supply units usually contain step-down DC-DC converters, they can be used in a system where batteries storage is required or with low voltage DC loads. For instance, in a solar photovoltaic system, the PV arrays should be rearranged to match the required input voltage of the power supply’s main converter, i.e. usually more than 150V. The power supply's converter can be programmed as MPPT charge controller for batteries using a microcontroller interface. The example of the proposed PV generation system based on repurposed power supply unit (PSU) is depicted in Fig. 3-1.

![Fig. 3-1: Proposed PV generation system based on repurposed power supply units (and used batteries and UPS units).](image)

This chapter addresses one aspect of the technological part of the reuse solution which is the refurbishing and repurposing processes of the used power supply units. The first section introduces the general properties of a power supply units in a desktop personal computer, more specifically the ATX power supplies. The basic of switch-mode power supplies is presented in the next section. This part introduces the general structure, converter topologies, and type of control systems commonly found in power supply units. The main part of this chapter focuses on the general conception and common techniques to identify the issues and modify the structure of the power supply units to operate as a general purpose DC-DC converter. The application of the refurbished power supply in a PV system is presented in the last section. In this experiment, the power supply unit is successful converted to a MPPT controller which helps to deliver optional energy transfer from the PV generator to load.
3.2. Computer Power Supply Units (PSUs)

In the early stage, computers were invented to compute or to solve complex mathematical problems. Before the advent of electronics, mechanical computers, like the Analytical Engine in 1837, were designed to provide routine mathematical calculation and simple decision-making capabilities. The first electronic computers based on vacuum tubes, including the Z3, the Atanasoff–Berry Computer, Colossus computer, and ENIAC are developed just before or during World War II [307]. Early computer owners in the 1960s, invariably institutions or corporates, had to write their own programs to do any useful work with the machines.

Today, computers become an electronic device of almost every day use, whether in workplaces, for communication, study and research, factory operations or personal entertainment. The word ‘computer’ is often associated with the phrase ‘personal computer’ or PC. Computer however is the general term which can be classified by size and power from a ‘Personal computer’, a small, single-user computer based on a microprocessor, to ‘Mainframe’, a powerful multi-user computer capable of supporting many hundreds or thousands of users simultaneously, to a ‘Supercomputer’, an extremely fast and powerful computer that can perform hundreds of millions of instructions per second [308].

3.2.1. Computer hardware

A personal computer (PC) is a multi-purpose electronic computer whose size, capabilities, and price make it feasible for individual use. A desktop computer is a stationary personal computer which is employed in a fixed workplace. Laptops are generally very similar, but portable and they also use lower-power or reduced size components, thus with lower performance. Despite the disadvantages in size and portability, desktop computers are still very common due to their advantages in performance, safety and reliability.

![Open computer case.](image)

Computers are constituted of several components, or ‘hardware’ such as: such as monitor, keyboard, motherboard, data storage device, graphic card, sound card, and power supply units. A power supply unit (PSU) converts alternating voltage and current (AC) to low-voltage and current (DC) which are necessary for the internal components of the computer. In case of Laptops, an ‘AC-DC adapter’ is used to power the components while charging its
battery. For desktop computer, most of the main components including the power supply unit are enclosed together in a computer ‘case’ (Fig. 3-2). It provides mechanical support, protection for internal elements, and protection against electromagnetic interference and electrostatic discharge.

Cases can come in many different sizes (known as form factors). The size and shape of a computer case is usually determined by the form ‘factor of the motherboard’, since it is the largest component of most computers. Currently, the most popular form factor for desktop computers is ATX [309], although microATX and small form factors have also become very popular for a variety of uses. In the high-end segment, we have the unofficial and loosely defined XL-ATX specification.

3.2.2. Power supply units

In a standard desktop computer, the power supply unit converts AC line voltage into DC, providing several carefully regulated low voltages at high currents. Power supplies can be built in a variety of ways, but mainly, they can be classified as linear or switching power supplies. A typical linear power supply converts the high AC voltage into a lower DC voltage using a bulky power transformer and a diode bridge, and then uses a linear regulator to drop the voltage to the desired level. The linear regulators use simple transistor-based circuit and are inexpensive. The main disadvantage however, is they typically waste a significant power as heat from the excess voltage [310]. Another disadvantage is they are large and heavy due to transformer and heat sink. On the plus side, the output is very stable and noise-free.

A switching power supply works by rapidly turning the power on and off, rather than turning excess power into heat. In a switching power supply, by carefully controlling the time of the switching, the output voltage averages out to the desired value. Theoretically, if the components are perfect, no power gets wasted. Switching power supplies are much more efficient, give off much less heat, and thus are much smaller and lighter than linear power supplies.

Switching power supplies became popular products for power supply manufacturers starting in the late 1960s. By 1975, switching power supplies were 8% of the power supply market and growing rapidly, driven by improved components and the desire for smaller power supplies for products such as microcomputers [311]. In 1981, the IBM PC was launched, which would have lasting impact on computer power supply designs. The power supply for the original IBM 5150 PC, produced by Astec and Zenith, is a 63.5W power supply with a flyback design controlled by a NE5560 power supply controller IC. The IBM PC AT power supply became a ‘de facto’ standard for computer power supplies [312]. In 1995, Intel introduced the ATX motherboard specification, and the ATX power supply has become the standard for desktop computer power supplies.

3.2.3. ATX motherboard and power supply

Advanced Technology eXtended or ATX is a motherboard configuration specification developed by Intel in 1995. The specification defines the key mechanical dimensions,
mounting point, I/O panel, power and connector interfaces between a computer case, a motherboard and a power supply [313]. ATX is the most common motherboard design.

Fig. 3-3: Summary of ATX chassis features. [313]

Fig. 3-4: The 4-pin 12V auxiliary power connector on a motherboard provided by ATX12V power supply. [309]

The ATX specification requires the power supply to produce three main outputs, +3.3 V, +5 V and +12 V. Low-power −12 V and +5 VSB (standby) supplies are also required for some particular components. The 5 VSB supply is used to produce trickle power to provide the soft-power feature of ATX when a PC is turned off, as well as powering the real-time clock to conserve the charge of the CMOS battery. As processors become faster and more highly integrated, more current is required. To reduce power distribution loss, board manufacturers are moving towards 12V power distribution. For processors that have been designed for 12V input, an additional 12V power connector must be added (Fig. 3-4). ATX power supplies with the required 12V current and associated connector are designated "ATX12V" [313].

3.3. Switching Power Supply
Computer power supply is in general a type of AC-DC converter, also called ‘off-line power supplies’ which runs off the AC line input. In modern switched-mode power supplies, isolated DC-DC converters are the main switching converters. Fig. 3-5 shows the simplified block diagram of common off-line switch-mode power supplies. The AC input is first converted to DC voltage (high voltage DC rail or HVDC rail) by rectifiers. The DC voltage is then applied to the input of isolated DC-DC converter stage which converts the unregulated input to lower usable regulated output voltages. Modern computers power supplies may contain a collection of switching power supplies and regulators such as: a switching PFC circuit, a switching converter for standby power, a switching forward converter to generate 12V and 5V, and a switching DC-DC converter to generate 3.3 volts.

![Simplified block diagram of off-line AC/DC switched-mode power supplies.](image)

**3.3.1. Power factor correction**

Power supplies can use the input power more efficiently through the technique of power factor correction (PFC). Power Factor (PF) is the ratio of real power to apparent power. A power factor of unity indicates that 100% of the current is contributing to power in the load while a power factor of zero indicates that none of the current contributes to power in the load.

Having a power factor as close as possible to unity is beneficial since none of the delivered power is reflected back to the source or wasted. The reflected power will generate heat according to the total current being carried, the real part plus the reflected part and the harmonics. The reflected power not wasted in the resistance of the power cord may also generate unnecessary heat in the source (the local step—down transformer), contributing to premature failure and constituting a fire hazard [315].

The rectifier stage of power supplies is typically a diode bridge followed by a large input filter capacitor. During the time when the bridge diodes conduct, the AC line is driving an electrolytic capacitor, a nearly reactive load. This circuit will only draw current from the input lines when the input’s voltage exceeds the voltage of the filter capacitor. This leads to very high currents near the peaks of the input AC voltage waveform. A PFC circuit can be found before or after the rectifier to shape the current waveform according to voltage waveform. Passive PFC is usually a line-frequency inductor which smooths the input current, reducing harmonics. Common passive PFC can be implemented in Fig. 3-6. PFC inductor often contains a center-tap pin which can be connected or disconnected to the center point of the series output capacitors using a toggle switch. If the switch is ON, the right side of the bridge rectifier functions as a half-wave doubler enabling the power supply to work with 115Vac input.
An active PFC circuit is a switching power converter, essentially a boost converter that precisely controls its input current on an instantaneous basis to match the wave-shape and phase of the input voltage (see Fig. 3-8). This represents a zero degree or 100 percent power factor and mimics a purely resistive load. Short term energy excesses and deficits caused by sudden changes in the load are supplemented by a “bulk energy storage capacitor”, the boost converter’s output filter. Active PFC converter is able to work in a very wide input range without using the technique of Fig. 3-6.

Though passive PFC is simple and cheap, its inductor is heavy and less effective compare to active PFC. In high end application, active PFC is often preferred over passive PFC.

3.3.2. Isolated DC-DC converter topologies
Switched-mode power supplies may use a number of isolated DC-DC converters topologies including ‘flyback’, ‘forward’, ‘push-pull’, ‘half bridge’, and ‘full bridge’. Isolated DC-DC converters are derived from the standard DC-DC converter by adding transformers which provide input/output isolation. The flyback topology is really a buck-boost converter, with its usual inductor replaced by a transformer, an inductor with multiple windings. Similarly, the forward converter is a buck-derived topology, with the usual inductor supplemented by a transformer. The transformer, besides providing the necessary mains isolation, also provides a fixed-ratio down-conversion step, determined by the “turns ratio” of the transformer, which is usually necessary to down-convert from a high input voltage to a much lower output.

The circuit topology selection depends on many parameters such as output power, input voltage, output/input voltage ratio, cost and regulations. The selected circuit topology is also compromised in size, price, and efficiency [316]. For example, the flyback topology is popular for low-power applications (typically lower than 150 W), and forward converter is often found in medium to high power application.

- **Flyback converter:**

The flyback converter is normally used at power levels below 150W [317]. It is a transformer type converter using the demagnetizing effect. The circuit diagram of flyback converter is shown in Fig. 3-9. Like buck-boost converter, a flyback converter operates by first storing energy from an input source into the transformer while the primary power switch is on. When the switch turns off, the transformer voltage reverses, forward-biasing the output diode and energy is delivered to the output.

The output voltage and the transistor’s drain voltage are found by the expressions:

- Input-output relationship (continuous conduction mode or CCM) (D is duty cycle):
  \[ V_o = \left( \frac{N_s}{N_p} \right) \cdot \left( D \cdot \frac{1}{1-D} \right) \cdot V_{in} \]  
  \[ (3-01) \]

- Switch rating (if proper snubber is employed): \[ V_{ds} = V_{in} + V_o \left( \frac{N_s}{N_p} \right) \]
  \[ (3-02) \]

Flyback converter has a high switch rating due to the reflected output voltage appearing across the switch in addition to the applied input voltage. Beside off-line power supplies, flyback converters are widely used for high voltage applications.
• **Forward converter:**

Forward converters are commonly used for medium power step-down applications due to their circuit simplicity, high efficiency and high reliability [318]. The circuit of forward converter in Fig. 3-10 is basically a buck converter with the addition of a transformer for output voltage isolation and scaling.

![Forward converter topology](image)

Fig. 3-10: Forward converter topology.

The output voltage of a single-switch forward converter in CCM is:

\[ V_o = \left(\frac{N_s}{N_p}\right) \cdot D \cdot V_{in} \]  

(3-03)

Single-switch forward converter is the most elementary form of forward converter. When compared to fly-back converter, it is generally more energy efficient and is used for applications requiring little higher power output. It is typically used in off-line applications in the 150 W – 400 W region [317].

• **Push-pull converter:**

The push-pull converter is derived from two forward converters working in anti-phase, which effectively avoids the iron core saturation. The voltage across the transformer and, hence, the peak drain voltage of the switching transistors is subjected to twice the input voltage. Its circuit diagram is shown in Fig. 3-11. Since there are two switches, which work alternately, the output voltage is doubled.

- Input-output relationship (CCM): \[ V_o = 2 \cdot \left(\frac{N_s}{N_p}\right) \cdot D \cdot V_{in} \]  

(3-04)

- Switch rating: \[ V_{ds} = 2 \cdot V_{in} \]  

(3-05)

Since power is not stored in the transformer, more power can be handled at a greater efficiency and with a better regulation than that of the forward converter. The maximum duty cycle attainable cannot pass 50% due to the push-pull operation. Push-pull converter is used when there is a wide variation in the input and when the output voltage is lesser than the input voltage. It can be used at power levels in the range of few hundred watts to 1 kW.
Half bridge converter:

Half-bridge converter is used at medium power levels in the range of 200-700 W for step down applications. Its switching transistors are not subjected to twice the input supply voltage as it is the case in forward and push-pull converters. However, a half-bridge converter requires a more complex control circuitry. Its major advantage is that the transformer can be smaller, since it transfers energy on both half-cycles. The full-wave output of the half-bridge converter also results in the use of smaller output inductor and capacitor when compared to the forward converter. Maximum voltage on each switch is the dc bus voltage, and the leakage inductance spikes are clamped to the input supply bus.

Full bridge converter:

Compared to a half-bridge converter, a full-bridge converter has more part count, but the switches will handle half the current. The output power of the full-bridge converter is double than that of the half-bridge converter. The power handling capability is therefore higher in full bridge than in half bridge. However, just like half bridge, it requires a complex driver circuitry that is capable of driving high-side and low-side switching switches. A full-bridge
converter is used at high power levels in the range of a kW and is normally not used at lower power levels due to its higher part count.

- Input-output relationship (CCM): \( V_o = \left( \frac{N_o}{N_p} \right) \cdot D \cdot V_{in} \) (3-08)
- Switch rating: \( V_{ds} = V_{in} \) (3-09)

**3.3.3. Types of forward converter based on core reset technique**

Transformer core saturation is a major problem in designing a forward converter. Whenever a core is driven in a unidirectional fashion, the core must be reset. Magnetization energy which serves only to reorient the magnetic domains within the core must be emptied otherwise the core will “walk-up” to saturation after a few cycles. In order to avoid saturation, many flux reset techniques have been used in forward converter design.

The technique of the classic forward converter is to reset the core flux by returning the magnetizing energy to the input source via a tertiary transformer winding in series with a diode [319], as shown in Fig. 3-14. Since the magnetizing energy is recycled to the input source, the efficiency can be improved by this mechanism. Any winding can provide the reset function, but the higher the voltage on the winding, the quicker the core will reset. The maximum voltage of transistor switch and the maximum duty ratio are given by:

\[
V_{ds,max} = \left( 1 + \frac{N_p}{N_r} \right) \cdot V_{in}
\] (3-10)
\[ D_{max} \leq \frac{N_p}{N_p + N_r} \] (3-11)

As can be seen in equations in (3-10) and (3-11), the maximum voltage on the MOSFET can be reduced by decreasing \( D_{max} \). However, decreasing \( D_{max} \) results in increased voltage stress on the secondary side. Therefore, it is common to set \( D_{max} = 0.5 \) and \( N_p = N_r \) for universal input.

An RCD clamping reset, shown in Fig. 3-15 (A), uses a network of resistor, capacitor and diode, to develop a varying clamp voltage into which the magnetizing energy is discharged. This reset circuit is favorable because of its simplicity and cost-effectiveness. Another advantage of RCD reset method is that it is possible to set the maximum duty ratio larger than 50% with relatively low voltage stress on the transistor switch compared to auxiliary winding reset method. One disadvantage of this scheme is that the energy stored in the magnetizing inductor is dissipated in the RCD snubber, unlike in the tertiary winding method.

![Fig. 3-15: Clamp reset forward converter: (A) RCD clamp; (B) active clamp.](image)

The newest adaptation of the common RCD type reset technique is to replace the diode with an active MOSFET switch, called ‘Active clamp’ technique (Fig. 3-15 (B)). Its first purpose is to clamp the primary coil to the reset capacitor, just as a diode would. A second function, which a standard rectifier is unable to provide, is to allow a controlled (switched) transfer of energy back from the reset capacitor to the primary side power stage of the converter. The active clamp is inactive during the normal power transfer portion of the switching cycle, and only operates during the main switch's off-time. For the most part, conventional square wave power conversion waveforms apply to system voltages and currents during the on-time of the main switch. However, significant improvements and differences take place during the low loss clamp, reset and soft alignment of the power switch. Two benefits are obtained with this active clamp approach: higher efficiency and zero voltage "soft" switching transitions.

In higher input voltage applications, a two-switch forward converter is often applied in order to use lower voltage rating of power switches. A two-switch forward converter can be used at higher power levels and does not have an additional reset winding. When the two main switches are turned off, the transformer is reset by returning the magnetizing energy stored to the input source through the two added diodes. Due to the scheme needs, an additional switch and a high side driver, the cost of added elements is increased. The voltage stress on the switches is less in this case when compared to a single switch forward converter. Because of transformer reset requirements, the maximum duty cycle is limited by 0.5.
3.3.4. Resonant converter

The demand for increasing power density of switched-mode converter pushes engineers to use a higher switching frequency. The challenge is a significant increase in the switching losses due to the high switching frequency. A resonant topology is designed to reduce or eliminate the frequency-dependent switching losses within the power switches and rectifiers. Schematically, resonant topologies are minor modifications of the standard switch-mode topologies. A resonant tank circuit is added to the power switch section to make either the current or the voltage ‘ring’ or resonate through a half a sinusoid waveform. Since the sinusoid starts at zero and ends at zero, the product of the voltage and current at the starting and ending points is zero, thus eliminating the switching loss. The switching at zero voltage or current switching condition is the so-called ‘soft-switching’.

In resonant converters, the switching network generates a square wave voltage output with a 50% duty cycle. This voltage pattern feeds the resonant tank. The resonant tank consists of a serial or a parallel combination of L and C passive components. There are several combinations of two or three L and C passive components used in the resonant tank. The most common known resonant topologies are a serial resonant converter (SRC), parallel resonant converter (PRC), and LLC resonant converter. SCR and PRC both use resonant tanks with two reactive elements (one inductor and one capacitor).

LLC converter is one of the configurations of resonant converter with 3 reactive elements in resonant tank. The half bridge LLC resonant converter topology is gaining popularity in
many performance-driven applications because it offers high efficiency and low EMI, regulates the output over wide line and load variations with a relatively small variation of switching frequency [320]. It can achieve zero voltage switching (ZVS) over the entire operating range.

The resonant tank gain can be derived by analyzing the equivalent resonant circuit. Since the resonant tank gain is frequency modulated, the converter can operate in three modes depending on input voltage and load current conditions: at resonant frequency operation ($F_{sw} = F_r$), above resonant frequency operation ($F_{sw} > F_r$), and below resonant frequency operation, ($F_{sw} < F_r$). For LLC converter, the resonant tank has unity gain at resonant frequency operation, and the converter is optimized. For this reason, transformer turns ratio is designed such that the converter operates at nominal input and output voltages at resonant frequency.

### 3.3.5. Control types

While each switching converter topology has different advantage and disadvantage, it requires feedback signal and control circuit to maintain its output voltage. A control circuit is used in all power converters to constantly monitor and compare the output voltage with an internal ‘reference voltage.’ There are two major methods for controlling a switching power supply output(s).

- **Voltage-mode control (VMC)**

In voltage-mode control, only the output voltage is monitored. A typical voltage-mode controlled converter is shown in Fig. 3-19. The key feature of this control is the presence of a feedback loop which keeps track of the output voltage variation with respect to a reference voltage and adjusts the duty cycle accordingly. Precisely, the difference between the output voltage, $v_C$, and a reference signal, $V_{ref}$, is processed by a compensation network which generates a control signal, $v_{con}$. The comparator converts the voltage error signal into the PWM drive signal to the power switch. Since the only control parameter is the output voltage, and there is inherent delay through the power circuit, voltage-mode control tends to respond slowly to input variations. Moreover, the current in the switch is not controlled and can reach too high levels during transients. VMC is commonly implemented in controller chips such as the TL494, NE5560 and SG3524, which were popular in early PCs [321].
Fig. 3-19: Voltage-mode control principle in a Buck converter.

- **Current-mode control (CMC)**

In current-mode control, an inner current loop is used in addition to the voltage feedback loop. The aim of this inner loop is to force the inductor current to follow some reference signal provided by the output voltage feedback loop. Current-mode control has a very rapid input and output response time, and has an inherent overcurrent protection. A simplified schematic of CMC is shown in Fig. 3-20.

The circuit operation of the inner loop can be described as follows. Suppose the switch is first turned on by a clock pulse. The inductor current thus rises up, and as soon as it reaches the value of the reference current $I_{ref}$, the comparator output goes momentarily high and turns off the switch. The inductor current then ramps down. The process repeats as the next clock pulse turns the switch back on. An output voltage loop is needed to achieve output voltage regulation. This loop senses the output voltage error and adjusts the value of $I_{ref}$ accordingly. In practice, the inner current loop is a much faster loop compared to the output voltage loop.

Fig. 3-20: Current-mode control principle in a boost converter.
CMC was popularized in the use of the Flyback controller UC1842 chip, the world first current-mode control chip, from Unitrode [322]. The UC1842 was later improved to UC3842, which, shortly thereafter, became popular in power supplies based on forward converter topology. The push for higher efficiency with forward converter and power factor correction has also made the CM6800 controller chip very popular, since the chip covers both functionalities.

From a collection of discarded PSUs, shown in Table 3-01, half-bridge converter, and single-switch forward converters are the most common. The UC3842 or UC3843 PWM controllers are usually used for single-switch forward converters for current-mode control. The next section will focus on more detail about the power supply units based on forward converters and current-mode control.

### 3.4. Modification Processes of PSU circuit board

The main function of a PSU is to generate regulated DC voltages needed by the computer hardware. It is well suited for supplying a fix source of voltage from an input source of a few hundred volts. In renewable energy generation systems, the main functions of the converters are not only to regulate voltage or current, but also to optimize the power conversion from sources to loads or storage devices. For instance, in addition to control the state of charge of batteries, a MPPT controller is also programmed to maximize the power conversion of photovoltaic arrays. Such converter requires both output current control and input power control.

It is possible to tweak the built-in controller of PSU to allow a variable controlled output, which is an original way to turn it into a “PV converter”. The issue is that the response of the built-in control may be too slow. In addition, the PSU’s built-in controller mostly cannot handle all the controls and functionalities necessary in the second-life application. Most often, an external controller is required. It is also more flexible to implement all the necessary control strategies in the external controller without depending on the built-in controller.

The challenge of refurbishing a PSU can be described in technical difficulties, extra cost, and structures limit of the PSU. The technical issue concerns the converter topologies and the control type. The type of hardware might also be the burden. For instance, multilayer PCB with surface-mount components is harder to work with compared to a single layer PCB with through-hole components. The cost of the refurbished PSU includes the modification process and the cost of external controller and some extra components. If the structures and functionalities of PSU are well known and studied, the tweaking can be done by removing a few components, and connecting a very limited number of new components.

Because of the type of loads included in a PC, the power supplies are strictly limited to step-down converter applications. This kind of converters can be suitable where there is demand for batteries storage or when there are low voltage dc loads.
3.4.1. General structure of PSU

Since most of them are compliant to ATX motherboard design, many common features can be found throughout different models and manufacturers, which is a great advantage. Total power requirements for a personal computer may range from 150 W to more than 700 W for a high-performance computer with multiple graphics cards. Nevertheless, PSUs are commonly found with power rating between 300W to 500W [323].

The outputs of ATX power supplies and its wire colour coding are illustrated in Fig. 3-21. The main outputs are: +12VDC, +5VDC, and +3.3VDC. The low power -12V output was used primarily to provide the negative supply voltage to the RS-232 serial ports. A −5 V output was originally required because it was needed on the ISA bus, but it became obsolete with the removal of the ISA bus in modern PCs and has been removed in later versions of the ATX standard. The +5Vsb (standby) pin provides a small amount of standby power when the computer and the supply wire lines are off. This can be used to power the circuitry that controls the power-on signal. The other three wires are:

- **PS-ON (power on)** is a signal from the motherboard to the power supply. When the line is connected to ground (by the motherboard), the power supply turns on. It is internally pulled up to +5 V inside the power supply.
- **PWR-OK ("power good")** is an output from the power supply that indicates that its output has stabilized and is ready for use. It remains low for a brief time after the PS_ON signal is pulled low.
- **+3.3Vsense** should be connected to the +3.3 V on the motherboard or its power connector. This connection allows remote sensing of the voltage drop in the power-supply wiring.

![Fig. 3-21: Wire color coding of ATX power supplies.](image)

Most power supplies follow the general block diagram shown in Fig. 3-22. There are two main sections. The primary section, comprising the power line input filter, the rectifier, the active or passive PFC, the high voltage part of the main converter, and the PWM controller, deals with high voltage. The secondary section, electrically isolated from the primary section through power transformers and optocouplers, consists of output rectifiers and filters as well as regulation feedback circuits, and voltage/current monitoring circuits.
The two sections are easily recognised as they are located at the opposite half of the circuit board and identified by the location the power transformers and optocouplers. In addition to the main converter stage, most PSUs have auxiliary (standby) power supply that supplies low power to PWM controllers and provide power for computer during its standby mode. The adjustable shunt regulator TL431 is commonly used as error amplifier which generates a feedback signal for the PWM controller.

From a sample of recently discarded PSUs, shown in Table 3-1, three converter topologies are often employed: half-bridge converter, single-switch forward and two-switch forward converters. Alongside these topologies, some of the most common PWM controllers include: UC3843, UC3845, TL494, KA7500, and CM6800. UC3843 and UC3845 are usually used for single-switch forward and two-switch forward converters respectively, which are based on current-mode control. The CM6800 incorporates both current-mode and power factor correction control in the same chip. TL494 and KA7500 are often found with half-bridge topology where voltage-mode control is employed.

<table>
<thead>
<tr>
<th>Model</th>
<th>Rated power</th>
<th>Converter topologies</th>
<th>Controllers</th>
<th>Monitor IC</th>
<th>Power factor correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>H305P-00</td>
<td>305W</td>
<td>Single-switch forward (RCD clamp)</td>
<td>UC3843</td>
<td>WT7517</td>
<td>Passive</td>
</tr>
<tr>
<td>EPAP-420</td>
<td>420W</td>
<td>Two-switches forward</td>
<td>UC3845</td>
<td>WT7515</td>
<td>Active (UCC3818)</td>
</tr>
<tr>
<td>7MOJ-RXV</td>
<td>380W</td>
<td>Two-switches forward</td>
<td>CM6800</td>
<td>HY510N</td>
<td>Active (CM6800)</td>
</tr>
<tr>
<td>H750P-00</td>
<td>750W</td>
<td>Two-switches forward (Synchronous rectifier output)</td>
<td>NCP5425</td>
<td></td>
<td>Active (ICE1PCS02)</td>
</tr>
<tr>
<td>WT-200PC</td>
<td>250W</td>
<td>Half-bridge</td>
<td>TL494 CN</td>
<td>-</td>
<td>Passive</td>
</tr>
<tr>
<td>PSX-A830</td>
<td>480W</td>
<td>Half-bridge</td>
<td>-</td>
<td>-</td>
<td>Passive</td>
</tr>
<tr>
<td>ADV-300PTF</td>
<td>300W</td>
<td>Half-bridge</td>
<td>KA7500B</td>
<td>-</td>
<td>Passive</td>
</tr>
<tr>
<td>LC-250ATX</td>
<td>250W</td>
<td>Half-bridge</td>
<td>TL494</td>
<td>-</td>
<td>Passive</td>
</tr>
</tbody>
</table>
3.4.2. Structure of HP305P-00 power supply

The 305W ATX power supplies, Dell H305P-00, which are found discarded in the collection bin in significant numbers, has been selected for the study of its modification and transformation processes for the second-life usage in a photovoltaic generation system. Fig. 3-24 shows the internal circuit board of the power supply. The power supply’s full simplified block diagram is featured in Fig. 3-25.

The primary input section comprises a power line filter, and a few thermal protection components including a fuse and a thermistor. The filtered current is then fed to a full-wave rectifier to produce a dc voltage of around 320V. This power supply also employs a passive PFC, using a bulky line transformer between the line filter and rectifier stage.

Fig. 3-23: Dell HP305P-00 power supplies.

Fig. 3-24: HP305P-00 internal circuit board.

The main power stage is a single-switch forward converter with RCD reset scheme, as described in Fig. 3-15(A). The dc high input voltage of the forward converter it converted into lower dc voltage by a switching transistor and a power transformer. The PWM controller of the forward converter is the UC3843 current-mode IC. The secondary side of the power
The transformer consists of multiple coils of different number of turns. The turn ratios between the primary and secondary coils are 40/7 for the 12V output and 40/4 for the 5V output. The outputs are rectified and smoothed by LC networks. The block diagram of main power conversion stage is detailed in Fig. 3-26.

At the secondary side, the cross regulation between the 12V and 5V outputs is managed by the use of coupled inductor. The output feedback is processed by the adjustable shunt regulator TL431, and the error signal is sent to the UC3843 controller through the optocoupler (PS2561). The regulation of the 3.3V output is assured by its own post-regulation at the secondary side independent of the UC3843 controller. With a relatively negligible power share, the -12V output uses linear regulator LM7912 to regulate its voltage. The quality of the main output voltages (12V, 5V, 3.3V) is checked by the integrated circuit WT7517.

Fig. 3- 25: HP305P-00 functional block diagram.

Fig. 3- 26: Main power conversion stage in HP305P-00.

The dc voltage rail of the primary side also is also the input of an auxiliary power supply which provides secondary power source (around 12V) to supply the PWM controller of the main converter and generate +5Vsb output. This +5Vsb also provides power supply to bias control circuit of the secondary side including WT7517. The auxiliary power supply is
smaller, flyback converter consisting of independent integrated controller and a small high-frequency transformer.

The magnetizing current of main transformer is reset with a RCD clamp circuit. It is composed of a fast diode with a high reverse breakdown voltage, in series with a parallel resistor and capacitor. A TVS diode is also used in parallel with the resistor and capacitor for voltage surge protection. The power supply can work with both 230VAC and 115VAC line inputs by manual switching operation. The detail of H305P-00 circuit diagram can be found in Appendix A1.

3.4.3. Removing power monitoring functionalities

For ATX compatibility, PSU usually employs some monitoring circuits to monitor the power output and to communicate with the computer mainboard. This part of PSU should be first identified to allow the converter to be tested freely.

The functional block diagram of the monitoring circuit of H305P-00 is shown in Fig. 3-27. In the secondary side, the integrated circuit WT7517 monitors the output power and communicates with motherboard through PWR-OK and PS-ON pins. When all outputs have stabilized and have reached predefined threshold values, the WT7514 outputs a 'good power' signal back to the motherboard by turning PWR-OK pin HIGH. The PS-ON pin from the PC motherboard is an input for the WT7514. This signal will activate the power supply if held LOW (or connected to ground). WT7514 is able to activate or deactivate the main converter using its Fault Protection Output (FPO) pin [324]. The auxiliary power supply which supplies the UC3843 controller can be cut off by turning pin FPO high, and turned ON by turning pin FPO low. By removing WT7517, and keeping FPO pin low, the controller is permanently enabled.

![Fig. 3-27: Fault protection and power monitor circuits.](image)

In the primary side, a LM393 dual comparator is used along with UC3843 controller for under-voltage and overcurrent protection. This part can be modified easily, if needed to allow testing in lower input voltage or higher current conditions. Though, it is recommended to keep the overcurrent function.

The main control UC3843, and monitor control WT7514 are all biased by the auxiliary flyback converter. Since WT7514 is not required, and if the UC3845 is also not used, the
flyback converter could be removed to eliminate the unnecessary power lost. If UC3845 is needed, it is also possible to be supplied from other external sources.

3.4.4. RCD demagnetisation circuit and sub-harmonic oscillation issue

When the dc input voltage of the main power supply is under the predefined voltage threshold, which is about 120V, the UC3843 is shut off. This prevents the power supply to run at critical value of duty cycle. Above a certain threshold of duty cycle, the forward converter that uses peak current-mode control becomes instable. In addition to unwanted output, this instability can cause irreversible damage to the power supply. This issue are related to two factors, clamp voltage of RCD reset scheme, and sub-harmonic oscillation.

Forward converter requires a proper reset technique to prevent core saturation. Without a reset scheme, when voltage step is applied over the transformer primary at ON-state, it forces a linear flux increase inside the transformer. If the flux density does not return to its initial intensity, the next cycle further increase the flux on top of previous one and eventually the transformer saturation will occur (see Fig. 3-28). This completely cancels the power transfer to the secondary and causes short-circuit of the primary coil which could damage the switching components without overcurrent protection.

![Transformer core magnetization: (A) without core reset; (B) with core reset.][325]

To avoid this saturation problem, the flux density needs to be brought back to its initial position at the beginning of each switching cycle. To achieve this, one can apply a reset voltage of opposite polarity across the primary coil during off time to ramp down the core flux. To guarantee a complete reset, the following expression must be justified:

\[ V_{reset} \times t_{OFF} \geq V_{dc} \times t_{ON} \] (3-12)

where: \( V_{dc} \) is the input voltage (ON time), \( V_{reset} \) is the voltage applied over the magnetizing inductor during the OFF time.

- **RCD reset scheme**

The RCD clamped forward converter is a popular topology for low to medium power applications which is also found in H305P-00. RCD circuit provides power transformer reset with a constant clamp voltage during the main switch off time. The reset circuit is composed of a diode and the parallel connection of a resistor and capacitor, which in turn are parallel with the transformer. In H305P-00, a TVS diode is also used in parallel with the resistor and
capacitor. The diode provides a transient surge voltage protection and has a reversed cut-off voltage of 350V.

During OFF time, the diode in the clamp circuit begins to conduct. A negative reset voltage is applied across the clamp capacitor. This built-up voltage resets the transformer magnetization. The maximum voltage stress is the sum of the input voltage and the fixed reset voltage ($V_C$).

$$V_{ds} = V_{in} + V_C$$  \hspace{1cm} (3-13)

In modification processes, reset or clamped voltage is another important issue to resolve in order to prevent the switching components damage and destruction of the power supply. The complete analysis of a clamped voltage ($V_{reset}$) is given in [326]. The RCD clamp network regulates the clamp voltage using an energy balance principle. For the clamp voltage to remain constant, the resistor must dissipate the same amount of energy that is put into the capacitor in a switching cycle. To find the clamp voltage, one have to find the energy that is put into the clamp during a switching cycle.

Let’s consider the circuit model of a RCD clamp forward converter in Fig. 3-29. The transformer is modeled with a magnetizing inductance $L_m$, a leakage inductance $L_{lk}$, and parallel resistance $R_p$. $R_p$ is used to model the of the core transformer core losses.

![Fig. 3-29: RCD clamp forward converter.](image)

The waveform of the voltage across the switching transistor and transformer magnetizing current is shown in Fig. 3-30. The operation of the reset scheme can be described during:

- $t_0$-$t_1$: At $t_0$, Q is turned on. With the input voltage applied across the transformer, the magnetizing current increases at a rate of $V_{in}/L_m$. The time interval ends when the drain-source voltage reaches $V_{in}$.
- $t_1$-$t_2$: When the drain voltage reaches $V_{in}$ at $t_1$, $D_r$ starts to conduct the output inductor current as the current in $D_f$ decreases. On the primary side, the voltage across the transformer is clamped to zero due to both $D_f$ and $D_r$ conducting. The active circuit elements are the leakage inductance and the primary side capacitances, $C_q$, $C_{XFMR}$ and C. The current transfer from $D_f$ to $D_r$ is resonant, determined by the leakage inductance and primary side capacitances.
Fig. 3-30: Operating waveforms: transistor drain voltage and transformer magnetizing current. [326]

- **t₂-t₃**: At $t₂$, the entire inductor current has been moved to $D_r$, and $D_f$ is OFF. With the current moved out of the transformer secondary, primary current drops to $I_{mpk}$. The peak magnetizing current drives the resonant tank formed by $L_m$ and $C_R$ for this period. $C_R$ is an equivalent resonant capacitor formed by the sum of all capacitors and parasites capacitors:

$$C_R = C + C_q + C_{XFMR} + C_D + \frac{C_{Dr} + C_{Df}}{N^2} \quad (3-14)$$

- **t₃-t₄**: At $t₃$ the clamp diode turns on, placing $V_C$ across the series combination of $L_{lk}$ and $L_m$. The magnetizing current is diverted into the clamp network and ramps down at a rate of $V_C/L_m$.

- **t₄-t₅**: When the magnetizing current reaches zero at $t₄$, the clamp diode switches to a blocking state, and $V_C$ drives the resonant tank formed between $L_m$ and $C_R$. The drain voltage resonates down to $V_{in}$, where $D_f$ turns on.

- **t₅-t₆**: The magnetizing current flows through $D_f$, which effectively clamps the transformer voltage to zero due to both $D_f$ and $D_r$ conducting. With zero volts forced across the transformer, the magnetizing current continues to circulate at the negative value of $I_{mng}$.

At the beginning, $t₀$, the negative value of the magnetizing current can be found using energy balance [326]:

$$I_{mng} = \frac{-V_C}{Z_M} e^{-\frac{\alpha}{\omega_d} \tan(\frac{\omega_d}{\alpha})} \quad (3-15)$$

where:

$$Z_M = \frac{I_m}{\sqrt{C_R}}; \quad \alpha = \frac{1}{2.0.8_R.p}; \quad \omega_d = \sqrt{\frac{1}{L_m.C_R} - \alpha^2}$$

The change in magnetizing current during $t₀-t₁$ is:
\[ \Delta I_{lm} = N \frac{V_{in} + V_D}{I_m F_{sw}} \]  

(3-16)

Where \( V_D \) is the forward drop of the output rectifiers and \( F_{sw} \) is the switching frequency. The peak magnetizing current at \( t_1-t_2 \) will be approximately:

\[ I_{mpk} = I_{mng} + \Delta I_{lm} \]  

(3-17)

After \( Q \) is turned off at \( t_1 \), the transistor voltage will resonate according to the equation:

\[ V_Q = V_{in} + e^{-\alpha(t-t_1)} \frac{I_{mpk}}{C_R \omega_d} \sin[\omega_d(t- t_1)] \]  

(3-18)

The magnetizing current is:

\[ I_{lm} = I_{mpk} \frac{e^{-\alpha(t-t_1)}}{C_R \omega_d} \left[ \frac{\alpha}{\omega_d} \sin[\omega_d(t-t_1)] + \cos[\omega_d(t-t_1)] \right] \]  

(3-19)

At time \( t_3 \), the transistor voltage will reach the input voltage \((V_{in})\) plus the clamp voltage \((V_C)\), forward biasing the clamp diode. \( t_3-t_1 \) will be called \( \Delta t \), the clamp voltage is:

\[ V_C = e^{-\alpha \Delta t} \frac{I_{mpk}}{C_R \omega_d} \sin[\omega_d \Delta t] \]  

(3-20)

The magnetizing current at this time is:

\[ I_{MCL} = I_{mpk} \frac{e^{-\alpha \Delta t}}{C_R \omega_d} \left[ \frac{\alpha}{\omega_d} \sin[\omega_d \Delta t] + \cos[\omega_d \Delta t] \right] \]  

(3-21)

By energy balance:

\[ P_C = \frac{V^2_C}{R} = \frac{1}{2} I_m F_{sw} I_{MCL}^2 \]  

(3-22)

From (3-21) and (3-22), we obtain:

\[ V_C = I_{mpk} \frac{e^{-\alpha \Delta t}}{\sqrt{\frac{L_m F_{sw} R}{2}}} \left[ \frac{\alpha}{\omega_d} \sin[\omega_d \Delta t] + \cos[\omega_d \Delta t] \right] \]  

(3-23)

To calculate the clamp voltage \((V_C)\), the system of non-linear equations formed by (3-15), (3-17), (3-20) and (3-23), with two variables, \( \Delta t \) and \( V_C \) needs to be solved. There are no analytical solutions for these equations. Fortunately, the system of equations can be solved using numerical method, which can be implemented with the embedded calculation software such as Matlab.

From equation (3-20) and (3-23), it can be noticed that the \( V_C \) is independent of the input voltage and load current. Nevertheless, there is a partial agreement with [327-328], where clamp voltage was found to be independent of input voltage, but dependent on the output current. Clamp capacitor value can be varied greatly with little effect on the power supply performance.
Equation (3-20) and (3-23) indicate a clear influence of the magnetizing inductance and the parasite capacitor on the clamp voltage. In fact, the maximum allowable for magnetizing inductance can be estimated from the following expression:

\[ L_{m,\text{max}} = \frac{(1-D_{\text{max}})^2}{\pi^2 \cdot F_{\text{sw}}^2 \cdot C_R} \]  

(3-24)

- **Sub-harmonic oscillation issue**

The main control scheme in the studied power supply is the current mode control which transforms the inductor into a controlled current source. This control introduces another limitation on the maximum duty cycle allowable of the forward converter. This limitation is caused by the phenomena of sub-harmonic oscillation, which occurs when the inductor ripple current does not return to its initial value by the start of next switching cycle. Sub-harmonic oscillation is normally characterized by observing alternating wide and narrow pulses at the switch node [329], which is shown in Fig. 3-31. This phenomenon also causes increased input current and audible noise from the transformer.

The response of the output inductor current to disturbance is shown in Fig. 3-32. It can be seen that when \( D<0.5 \) (\(|m2|<|m1|\)), \( \Delta I_L \) gets smaller and smaller with the next switching cycle and the system will get back to stable state after a few switching periods. When \( D>0.5 \) (\(|m2|>|m1|\)), \( \Delta I_L \) gets larger causing the system to go into unstable state. This instability is called sub-harmonic oscillation because it occurs at half the switching frequency. Sub-harmonic oscillation will not only cause output instability, for RCD clamp forward converter, it will instantly cause the increase of clamp voltage. When it happen, most often it can burn and destroy the MOSFET and the diodes in the RCD clamp circuit due to over-voltage or over-current.

![Fig. 3-31: PWM signal at input voltage of: (a) 140V; (b) less than 120V (sub-harmonic oscillation).](image-url)
In order to make the system stable above the limit of 50% of duty cycle, the slope compensation is usually employed. By adding a compensating ramp equal to the down-slope of the inductor current, any tendency toward sub-harmonic oscillation is damped within one switching cycle. This technique can be implemented by two methods, as illustrated in Fig. 3-35: (1) adding the compensating ramp to the control voltage then compared to inductor current; (2) adding the compensating ramp to current sense then compared to control voltage. For UC3843 current-mode controller, the implementation of slope compensation is shown in Fig. 3-36.

Fig. 3-33: Clamp voltage $V_{sn}$ at $V_{in} > 120V$; (50V/div)
Fig. 3-34: Clamp voltage $V_{sn}$ at: (a) $Vin < 120V$; (b) $Vin < 110V$. (50V/div)

Fig. 3-35: Slope compensation methods: (a) No compensation; (b) compensation added to control voltage; (c) compensation added to current sense. [331]

Slope compensation can eliminate the instability for duty cycles above 50% to a certain extent. Too much slope compensation is akin to making the system more and more like voltage mode control, especially at light loads, the double LC pole of voltage mode control will re-appear potentially causing instability of its own [322]. In H305P-00, the slope compensation of Fig. 3-36 (b) is employed. The maximum duty cycle allowable is raised to around 65%. Above this limit, the instability will occur causing the increased clamp voltage, which usually instantly burn out the clamp diode and sometime the MOSFET transistor due to voltage surge.
3.4.5. Reducing input voltage range by using primary side center tap

The high step-down ratio of PSU’s main converter presents a potential challenge in the reuse applications. In normal usage, the dc input of the power supply may range from 250V to 350V. The output is limited to less than 16V due to the rating of the filter capacitors. Without capacitor, the output will be bound by the reverse break down voltage of the Schottky diodes which is also rather low. Nevertheless, increasing the output range further increases the range of input which is itself subjected to the rating of certain components.

Due to its low output voltage, a modified PSU is limited to low voltage load such as 12V rechargeable batteries. The input sources can be designed for the required rating of the PSU. For instance, in PV solar systems, the PV arrays can be selected and arranged for the desired nominal output voltage and power.

If lower input voltage is required, there are some possible solutions which can be proposed for PSU’s components. The first solution is to modify the secondary coils of the power transformer. One way to do this is to physically add extra turns for a coil. We can also alter the connection between each coil to get a new coil of higher total number of turns. The burden with this solution is that the transformer would have to be taken apart.

Another solution is to alter the transformer primary coil if it has a center-tap pin. This solution requires the center-tap pin to be accessible, though not being used, such in the case of H305P-00. By using center-tap pin to replace of one of the other pins, the primary winding is cut to half its initial turns, reducing the turn ratio by half. This allows the converter to work with a lower input voltage. In H305P-00 the turn ratio of the transformer’s primary can be reduced from 40 to 20 by using this method. However, this change will have the effect on the power rating of the power supply since the input voltage is reduced. By reducing the voltage by half, with the same output power, the input current have to be increased by 2 times. The modified power rating will be defined by the current rating of the power supply’s components.
For the transformer core saturation, the relationship between current and the magnetic flux density can be expressed as:

\[
I_{\text{sat}} = \frac{L_{mp}}{\mu N_p} B_{\text{sat}}
\]  
(3-25)

Where \(L_{mp}\) is magnetic path length, \(\mu\) core permeability and \(N_p\) number of primary turns. Since \(N_p\) is reduced in half, the current for saturation is allowed to be doubled. Hence this modification has no effect on the saturation of the transformer’s core.

This change of primary coil also requires reevaluation of the effect of magnetizing current to RCD clamp circuit to ensure proper transformer demagnetization and prevent damage to RCD components. The relation (3-24), presented in the previous section, reassured the possibility of using the center-tap of primary coil, without effect on the clamp circuit, since the new magnetizing inductance is reduced instead of being increased.

![Graph](image)

Fig. 3-37: Power supply’s output load regulation characteristic at different input levels when center-tap pin of the transformer is used.

Experimental result with the center tap pin shown in Fig. 3-37 and Fig. 3-38 confirms that input voltage can be as low as 60V before sub-harmonic oscillation occurs. However, at 60V of input, the duty cycle is close to its limit. Sub-harmonic oscillation occurs around the output current of 7A. Though the oscillation will not occur when the input is higher than 70V, the voltage regulation has failed at lower output current in comparison. This might be due to the fact that the input current has surpassed the value which allows the controller to work correctly. Though even if the regulation still works at higher output current, there will be problem of overheated of the components.
3.4.6. **Variable output control using built-in controller**

Between the three most significant outputs, the +12V provides the most significant output power and more importantly has the usable voltage level. In H305P-00, the maximum output power of the +12V output is rated at 264W which is about 86% of the total maximum power (305W). Hence, the modification will be focused only on the +12V output. To remove the power loss and influence from the other outputs, some minimal amount of components were removed. For minimal effort, removing the right key components will disable all irrelevant components.

The complete representation of the control system of the power supply is shown in Fig. 3-39. The cross regulation between the 12V and 5V outputs is managed by the use of coupled inductor. The output feedback is processed by the adjustable shunt regulator TL431 with its internal error amplifier [332]. The error signal is fed back to UC3843 controller through the optocoupler.

- **Voltage control**

The initial feedback circuit of the +5V and +12V outputs is shown in Fig. 3-40(a), and its equivalent circuit in Fig. 3-40(b). The TL431’s internal functional blocks consist of a 2.5V reference connected to an op-amp’s negative input, with the op-amp output used to drive an open collector transistor’s base. The optocoupler can be modelled as a current-controlled current-source, with the CTR defining the gain. The network of R416, R417 and R418 resistors and the TL431’s 2.5V reference set the converter’s dc output voltage. Without physically modifying the value of the resistors, the output voltage can’t be controlled since the reference is set by the internally by TL431.

![Duty cycle of the power converter at different output current](image)

Fig. 3- 38: Duty cycle of the power converter at different output current (For \( V_{\text{in}} = 60V \), the sub-harmonic oscillation occurs at around the output current of 7A)
One of the solutions to control the output voltage is to indirectly change the reference from an external signal. In the modified circuit (Fig. 3-41), the +5V output is disconnected from the feedback circuit. The +12V output (represented as $V_o$), which is now used to biased the optocoupler and TL431, is fed through a new resistor $R_1$ to the error amplifier. By the action of the controller without input $V_1$, we get in steady state relationship (3-26):

$$V_o = \frac{R_1 + R_{418}}{R_{418}} V_{ref}$$  \hspace{1cm} (3-26)

where $V_{ref}=2.5V$ is the reference voltage. $R_1$ can be set to obtain the desired output voltage.

Fig. 3- 40: (a) The initial feedback circuit; (b) Equivalent circuit.
To control the output voltage, an input signal $V_1$ is applied to reference pin of TL431 through $R_2$. This signal will effectively change the reference voltage of the voltage loop. The equation is obtained in steady state is changed into (3-27):

$$\left(1 + \frac{R_{418}}{R_1} + \frac{R_{418}}{R_2}\right)V_{\text{ref}} = \frac{R_{418}}{R_1}V_o + \frac{R_{418}}{R_2}V_1$$

(3-27)

If $R_1=R_2=10\,\text{K}\Omega$, this relationship becomes $V_o = 15.42 - V_1$ (3-28). Hence, the value of output $V_o$ is changed linearly by the change of the injected signal $V_1$. The value of output $V_1$ should be carefully set so that $V_o$ cannot exceed 16V, the voltage rating of its filter capacitor.

The performance of this solution has been validated by simulation and experimental test. The PSIM simulation model of the power supply unit is given in Appendix A2. The primary winding of the main transformer has been modified to reduce the number of turns using center-tap pin. The power monitor circuit, the auxiliary power supply and all the outputs except the 12V, were disabled. The main controller is supplied by a +12Vdc source. The input voltage is now 70V to cope with supply voltages which could be on the output of PV panels and lower than the AC common grid once rectified. The steady state test result is plotted in Fig. 3-43. The transient responses of the output voltage to change of control input $V_1$ and change of load are shown in Fig. 3-44 by simulation and Fig. 3-45 by experiment.
It can be noticed, from the result of Fig. 3-43 that at $V_I > 12V$, $V_O$ reaches a minimum value (3.3V) at which further action has no effect. This is due to the minimum voltage required to bias the optocoupler emitter diode (about 0.8-1.1V) [332] and TL431. TL431 requires a biased voltage greater than the 2.5V, and minimum sink current of 1mA for its operation [333].

![Graph](image1)

**Fig. 3-43:** Steady state relationship between $V_O$ and $V_I$ (at 6Ω load).

![Graphs](image2)

**Fig. 3-44:** Simulated transient responses of $V_O$ to: (A) change in $(V_I)$ with 3Ω load; (B) load transition, 12Ω-3Ω.

![Graphs](image3)

**Fig. 3-45:** Experimental transient responses of $V_O$ to: (A) change in $(V_I)$ with 3Ω load; (B) load transition, 12Ω-3Ω.

- **Current control**
Since current mode controller is employed, the control of output current can be implemented with the existing current loop. A reference signal can be applied to current loop of UC3843 through its feedback pin (pin 2) (Fig. 3-46). Despite its simplicity, this method cannot correctly control the output current. This output can be affected by the change of load characteristics since there is no direct feedback of the actual output current, only the peak value of MOSFET current at high voltage side of the converter is sensed. However, in the application of renewable energy generation, the technique might be useful by the addition of outer control loop which might serve for energy optimization or other energy management purposes. The error of current control loop will be compensated by an outer control loop.

The same method applied for output voltage control is also possible for output current control as shown in Fig. 3-47. In this case, the output current is converted to a feedback voltage signal by using a series shunt resistor Rs. The sensed output current is fed to the voltage loop through a resistor R3. The input signal Vi will serve to modify the control reference value. The set output current will be defined by Rs, R3, R4 and R418.

![Fig. 3-46: Using current loop for output current control.](image1)

![Fig. 3-47: (A) Feedback modification for current control; (B) an additional circuit to supply the feedback circuit.](image2)

Due to the absence of any embedded voltage source, an additional voltage source is needed to supply the feedback network (Vb). The constant voltage source Vb needs to be high enough, i.e. 5V, to deliver enough current for the operation of opto-coupler. The external voltage sources which supply other parts the system can be shared for this purpose. However, it can also be implemented in the same forward converter by adding a few more components as
shown in Fig. 3-47(B). This circuit can easily guarantee a 5V constant voltage even at small duty cycle since the feedback circuit requires relatively small biased current.

- **Application in automobile generator**

The stability and performance of the proposed method are tested in both simulation and experimental tests. The experimental setup for inductive load is depicted in Fig. 3-48. The input for the modified PSU is 80V. The inductive load in the tests is the rotor field coil of an automobile alternator (model: BOLK BOL B051099) driven at low speed by a DC motor. More detail about the alternator characteristic is given in Appendix A3. The output of this alternator is connected to a 20Ω load. The relation of the output voltage and the rotor field current of the alternator are illustrated in Fig. 3-49.

![Test bench: Control of alternator field current using the modified PSU.](image)

**Fig. 3-49:** Alternator output voltage characteristics.

The results of experimentations with resistive load (3Ω) and inductive load are illustrated in Fig. 3-50 for steady state, Fig. 3-52 for transient response. The simulated transient response is shown in Fig. 3-51. For inductive load, the current ripple is insignificant as shown in experimental result of Fig. 3-53. It can also be noted that the output current has slower response for inductive load when compared to resistive load. Significant overshoot can be
noticed for resistive load. This problem can be eliminated by removing the output filter capacitor of the PSU.

Fig. 3- 50: Relationship between output current ($I_o$) and input voltage $V_i$ in steady state for resistive load and inductive load.

Fig. 3- 51: Simulated step response of output current ($I_o$) for (A) resistive load (3 $\Omega$) and (B) inductive load (3$\Omega$, 13mH).

Fig. 3- 52: Experimental step response of output current ($I_o$) for (a) resistive load and (b) inductive load (alternator’s rotor).

These results have proven that it is possible to modify the built-in controller of the PSUs from voltage regulation functionality to voltage or current control functionality by changing and/or adding a few electronic components. These processes might depend on converter topologies and type of controllers. For most PSUs which are based on forward converter and current-
mode control, the processes will be similar. For some PSUs which employ TL494 or similar controllers, the modifying processes is in fact less complex for voltage control since the input reference signal can be directly accessed from one pin of the controller.

![PWM signal and output current waveform](image)

Fig. 3-53: PWM signal and output current waveform for (a) resistive load and (b) inductive load.

These modifications of the PSUs’ functionalities can be applied in induction generator’s voltage controller, auto-mobile alternator output controller, and PV charge controller. For a stand-alone operation of induction generator, the voltage control PSUs can be programmed to keep the output power constant to regulate the output voltage and speed of the generator. In this case, it functions as an ‘Electronic Load Controller’. This process of voltage regulation of induction generator will be discussed further in the next chapter. Nevertheless, in practice, the built-in controllers are not necessarily needed and the modification process will be much simpler. Since additional controller is always required in addition to the built-in controller, there is no added cost due to the external controller. This process will be discussed in detailed in section 3-5 where the modified PSU is employed in a PV generation system as Maximum Power Point Tracker (MPPT) controller.

### 3.4.7. Parallel and series combinations of PSUs

Since PSUs are designed for supplying a personal computer which consumes power at the range of few hundred watts, the combination of several units is usually required to increase its power rating according to the size of the system. Parallel combination also provides fault-tolerance for the system in the event of certain module failure, increasing reliability owing to redundancy [334]. In this way the power distribution of the system becomes more reliable. However, in general, even the PSUs of the same model are not identical due to factors such as: component tolerances, non-identical conductors from the converters to the load, and others. This causes unbalanced currents drawn from their outputs which shorten the life-time of the units delivering heavy current and degrade system reliability [335]. For this reason, it is necessary to design a control scheme that keeps accomplishes the main task while keeping the power distribution of the converters.

- **Input connection**

  Like the output, the input of each PSU can be connected in parallel or in series to the same power source. However, since PSUs require high voltage input, around 200 to 350V, in the application of PV generation system, the optimal solution is to employ parallel connection
which is a configuration for minimal input voltage as shown in Fig. 3-54a. The output of a single PV panel is generally low while adding more panels in series reduces to the efficiency of the overall efficiency of the array due to shading and module mismatch [336].

![Diagram](image)

**Fig. 3-54:** (a) Parallel-input connection; (b) Converter-per-panel approach.

Another feasible configuration, ‘converter-per-panel’ approach, is described in [336]. In this approach, each panel is connected to input of separate converter, while the output power is combined by parallel or series connection of the outputs as depicted in Fig. 3-54b. In this configuration, each converter module can independently control and so optimize the power flow to or from its source. It offers the advantage of allowing panels to be given different orientations and so open up new possibilities in architectural applications. Also, the other advantage is the greater tolerance to localized shading of panels. In our case, each panel may have to be replaced by a string of panels and the converter can be a collection of $N_p$ parallel connected PSUs. Nevertheless, since the number of series connected PV panels are the same in both converter-per-panel and parallel-input approach, there is no apparent advantage between the two configurations regarding the losses due to shading and modules mismatch.

- **Output connection**

The outputs of PSUs are ready for parallel and series connection to increase the system power and output voltage. The number of parallel strings depends on the required output current. Each string may be a single PSU or multiple PSUs in series-output connection. In a solar power system where PSUs serve as charge controllers, the output voltage is defined by the storage batteries. If system has no batteries storage, the outputs can be connected in series to obtain high DC voltage level, which permits the system use transformer-free inverter.

To prevent non-uniform share of power amount converters, a current (voltage) distribution control is required for parallel (series) connection of the outputs as shown in Fig. 3-55 [334, 337-339]. A few current distribution control techniques are presented in References [334, 337-338], including master-slave control, the central-limit control and sliding-mode control. Basically, the output voltage is regulated by an outer voltage loop, while the equalization of the load current is normally attained by adding an inner current loop which compares the current supplied by each module with a reference current. However, this is not the same
control in the proposed application of repurposed PSUs. Furthermore, this control presents extra cost due to increased complexity in controller and feedback systems.

In the application of MPPT controller, if the PSUs are of the same model and design and each unit is driven by identical switching signal (as shown in Fig. 3-56), the unbalance effect could be minimal and the current/voltage distribution control may or may not be required. This is one the main issues to be addressed because there is a potential of reduced complexity and implementation cost.

![Fig. 3- 55: (a) Current distribution control of parallel-input-parallel-output connection of PSUs [337]; (b) voltage distribution control of parallel-input-series-output connection of PSUs [339].](image)

![Fig. 3- 56: Association of identical PSUs using the same switching signal without current or voltage distribution control.](image)

### 3.5. Second-life Application as MPPT Charge Controller

In the countries where natural water systems and the sun are plentiful, a solar-hydro hybrid generation system which is illustrated in Fig. 3-57 offers an alternative solution to energy need while grid power is not available. With our proposed re-use solution, some second-life
components can be employed in the system. The wasted induction motor or automobile alternator is used for the hydro power generator. The transformed PC power supplies can effectively replace the power converters between the DC sources and the DC loads. In this case and the additional control unit (generally a cheap microcontroller), it will replace the MPPT charge controller which is found between solar PV panels and batteries. To resolve the issue with high input requirement of the power supply, the PV modules can be configured to have enough series strings as to increase the input voltage and to match the input range of PSUs.

![Diagram of solar-pico-hydro hybrid energy generation system.](image)

If the automobile alternator is used, the DC-DC converter driving the inductor of the alternator can be replaced by the modified PSU and once again with an additional microcontroller which will control the output current. Then, with some light modifications of the converter structure as described in previous sections, the output current of the PSU can be controlled by an additional input signal. This allows the PSU to be used as DC-DC converter to charge batteries or to drive the inductor of the alternator as tested in Fig. 3-48. The 12V output of PSU is well suited for batteries charging and alternator field current control. Additionally, the PSU can draw its input from the AC output of an inverter.

### 3.5.1. Repurposing PSUs as MPPT charge controller

As a case study and for demonstration of the feasibility, the PSU is modified and transformed into a MPPT charge controller. For simplicity, a small 120W solar system is implemented. The MPPT control is implemented in the transformed PSU to ensure an optional power conversion to charge the batteries. A resistive load is connected the batteries terminals.

- **MPPT converter**

MPPT control is used to allow the maximum PV power to be delivered to battery and electrical load. The two most common MPPT techniques in PV generation have been selected for this experiment. The basic algorithm flowchart of the Perturb and Observe (P&O) and Incremental Conductance (INC) technique is depicted in Fig. 3-58. In P&O, method a perturbation of the operation point of the system is introduced, in this case, by an increment or decrement of the duty cycle of the converter (Δα). This perturbation causes the change of output power and output voltage of PV generator. By observing these changes and the $P=f(V)$ characteristic of the PV generator, MPPT controller introduces a new perturbation through an
increment or a decrement of the duty cycle by $\Delta \alpha$ to move the operation point closer to the Maximum Power Point (MPP). The process is repeated every sampling period $T_a$.

The INC method has the same goal, but uses a different method of finding the direction of the perturbation. MPP is tracked by comparing the instantaneous conductance ($I/V$) to the incremental conductance ($\Delta I/\Delta V$). From the P-V characteristic of PV generator, we obtain: $\Delta I/\Delta V = 1/V$ at the MPP, $\Delta I/\Delta V > 1/V$ on the left hand side of MPP, and $\Delta I/\Delta V < 1/V$ on the right hand side of MPP. Similar to P&O, the INC algorithm has the ability to track the MPP under disturbances, such as sudden changes in climatic conditions or temperature, but unlike P&O, INC has less or no oscillations at steady state.

As illustrated in Fig. 3-59, MPPT is usually implemented with non-isolated DC-DC converter including buck converter and boost converter. The input voltage and input current signals are required as feedback of the controller. The MPPT algorithm can be easily implemented in a programmable controller. The controller can either output direct PWM signal to control the switching transistor or output reference signal for and additional current or voltage loop.

- **Implementation of MPPT controller with Arduino Due microcontroller**
Both common MPPT methods use different algorithms to find the maximum power point by incrementing or decrementing the converter duty cycle according to the result of voltage and current feedbacks. The built-in controller in PSU isn’t implemented for such purpose which requires a programmable controller. Consequently, this control algorithm is implemented in an additional external controller. Arduino Due microcontroller board is the suitable the proposed control for its suitable cost, availability, and simplicity of implementation. Moreover, it could be found worldwide and its software could be found open source for free. It matches all the requirements.

This microcontroller has a built-in PWM module which can be easily programmed for a MPPT control algorithm (Appendix A5). In this case, the native controller IC of the PSU is no longer needed. The main switching transistor of PSU converter can be then controlled directly by the Arduino output. Some components are removed to isolate the transistor’s gate from UC3843. A UC3709 MOSFET driver is employed to shift the PWM output of Arduino to match the voltage level needed for the transistor drive (Fig. 3-60).

To sense the input current, a shunt resistor $R_s$ is used. The networks of resistors and Zener diodes serve as sensing circuits which convert input voltage and input current into voltage signals that can be read by analog input pins of Arduino. The complete Arduino programming script for P&O and INC control can be found in Appendix A6.

3.5.2. Experimental tests

The solar array consists of twelve FVG 10P solar panels (10W) (Appendix A4). The panels have been connected in two parallel strings of six panels to match the input voltage range of

![Fig. 3-60: Arduino programmed MPPT control: voltage and current sensing network and driver interface for PSU.](image-url)
PSU. In this configuration, the PV’s output voltage at maximum power point is at $V_{pv} = 105\text{V}$ for standard test condition (STC). The output of the PSU is connected to a 12V, 44Ah lead-acid battery which is sized for daily energy storage compliant with on day needs of a typical rural village in such rural areas. A resistive load is connected the batteries terminals.

The performance of the modified PSU in MPPT control has been tested for load step changes and change of sun light intensity. The parameters used for P&O and INC methods in this test are: $T_a = 0.02\text{s}$, $\Delta \alpha = 0.01$. Smaller $T_a$ results in faster response. However, this time should be long enough so that the outputs of the PV generator reach steady state. The choice of $T_a$ is based on the experimental results of Fig. 3-61 and Fig. 3-62.

![Fig. 3-61: PV generator output voltage response to step transition of duty cycle.](image)

![Fig. 3-62: PV generator output current response to step transition of duty cycle.](image)

The experimental P-V curve of the solar panel given in Fig. 3-63 shows the maximum power points for the voltages at between 75 to 80V. The experimental results using INC algorithm with the modified PSU are presented in Fig. 3-64. Both P&O and INC algorithms have given similar performance.
Fig. 3-63: Solar panels P-V curve at two different irradiance level.

Fig. 3-64: Performance of PSU with MPPT control in load change and incident light change (INC algorithm).

Fig. 3-65: Steca’s Solarix MPPT 2010 module.

The performance of the system has also been tested with a charge controller product bought from the market. The Steca’s Solarix MPPT 2010 module, shown in Fig. 3-65, is used for this comparison. The PV array has been rearranged in six parallel strings of two PV panels to match the input voltage range of this commercial MPPT module. In this configuration, the Steca’s module functions at lower input voltage than that of the modified PSU.
The efficiency is calculated by the ratio of the output consumed by load over the solar insolation power. The solar insolation power is estimated using the known surface area of the PV arrays and the solar insolation power density measured by pyrometer placed at the angle of the PV. The comparison, illustrated in Fig. 3-66, shows the efficiency of both systems which have been measured for different light intensities. Surprisingly, the Steca’s module is only partly more efficient at high solar radiation intensity. Since the insulation profile varies a lot during a day, due to sunrise, sunset and clouds, rain, etc, the MPPT modules will not always work at their nominal power. This is an optimistic condition for our re-use converter. As an illustration, a simulation can be made with those two characteristic curves of Fig 3-66 on the insulation profile locally measured in Phnom Penh, in order to calculate the expected output power at the output of both converters.

![Fig. 3-66: System efficiency (ratio of output power and solar insolation power) of Steca MPPT module and modified PSU with MPPT control.](image1)

To show the efficiency in an actual daily usage, the daily energy outputs can be made using the efficiency curves and the daily solar radiation profile measured directly from local area. The solar insolation of a normal day in August of 2014 in Phnom Penh city is shown in Fig. 3-67. Using the insolation data and the efficiency graph in Fig. 3-66, the total daily energy transferred to load is 911kJ using Steca’s Solarix module and 891kJ using the modified PSU.

![Fig. 3-67: Solar radiation profile in Phnom Penh, measured in a day time in August, 2014 (local time)](image2)
Overall, the efficiency of the PSU is slightly lower than the commercial module. In practice, the PV panels in reuse solution are required to be bigger in comparison to the conventional solution.

### 3.6. Summary

While some papers have presented the study of repurposing a computer power supply units as MPPT controller and batteries chargers, this reuse concept has not yet been fully explored for application in a renewable system. This concept has been studied and tested in this chapter. Computer power supply is in general a type of off-line AC-DC converter which runs off the AC line input and consists of a rectifier stage, passive or active PFC stage, and a main isolated DC-DC converter. The DC-DC converter is usually one of a number of topologies including ‘fly-back’, ‘forward’, ‘push-pull’, ‘half bridge’, and ‘full bridge’. Two major controller types, current-mode control and voltage-mode control, are usually employed for controlling the power supply outputs.

The first process of repurposing PSUs is to isolate the main isolate DC-DC converter from any limitation imposed by their original functionalities. This limitation is usually implemented with power monitoring circuits which sense the output voltage of the power supply and communicate with computer’s motherboard. For some topologies, snubber or core reset circuit may not function normally after repurposing of the converter usage. This factor should be considered to prevent damage or instability caused by overvoltage or overcurrent in the snubber. Due to the high input-to-output voltage ratio of the DC-DC converter, only the 12V output should be used since the other outputs are at too low level for useful application. Based on design, the input voltage is range from 200V-300V for its power rating. If lower input voltage is required, there are some possible solutions to reduce the input-to-output voltage ratio of the converter. The most practical solution requires the center-tap pin of the power transformer to be accessible.

To increase the power rating of the PSU unit, the combination of several units is necessary to increase the current or voltage capability of the converters. If different types of PSU unit are combined, current or voltage distribution control is required to prevent the unbalance effect which will cause damage or shorten the life-time of the unit that deliver the most current or voltage. On the other hand, if identical PSU units are used and controlled by the same switching signal, the distribution controls may not be necessary since it increases system’s complexity and cost and the unbalance effect is minimal.

The PSUs has been repurposed as for voltage or current control DC-DC converter using the same controllers which is employed for voltage regulation. If the PSUs use current-mode controller and error amplifier with internal reference voltage, an external signal can be applied to indirectly to control the output voltage. Similar method can also be applied for current control by adding shunt resistor for current sensor. In practice, the built-in controllers are not necessarily needed; a direct control from external controller is enough and provides
faster dynamic response. The modification process will be much simpler and since additional controller is always required in addition to the built-in controller, there is no added cost. In experimental test, the selected PSU is modified as Maximum Power Point Tracker (MPPT) controller in a PV generation system. The performance of the repurposed PSU is compared with that of a commercial MPPT converter which is shown to have comparable conversion efficiency.
Chapter 4

Chapter 4: Novel Structure of a Stand-alone Three-phase Induction Machine Feeding Single-phase Loads

4.1. Introduction

In the remote rural areas in many developing countries where centralized grid system still faces many challenges, isolated or distributed energy generation system can contribute significantly to providing energy access for the communities. A small-scale distributed generation system developed for supplying local households provides reduced cost compared to the more expensive distribution lines as the central grid is far enough from the location. Generation of power through stand-alone generating units utilizing various natural resources is a viable option and even recommended by statutory bodies [401]. The usage of natural resources is advantageous because fossil fuel fired plants pollutes the environment and add up to the global warming issues. Further, these plants can meet the scarcity of fossil fuels. Also, the renewable resources are often abundantly available even in hard to access regions.

Depending on the geographic location, renewable sources such as hydroelectric, wind and solar are viable solutions for rural electrification. For instance, pico-hydro schemes, which have an output of less than 5 kW, are usually installed in remote area located in the regions covered by mountains and water channels. This pico-hydro system has a great potential to provide rural electrification to remote regions in Cambodia and some other neighboring countries. By using appropriate designs, local skills and local manufacture, these schemes can be more cost-effective than national grid or large hydro projects [402].

Traditionally, synchronous generators have been used for power generation. However, in recent years induction generators have gained significant attraction, because of their relative advantageous features over conventional synchronous generators in wind energy and hydrogenation systems in isolated and hilly areas. They are simpler and cheaper in construction with low maintenance cost when compared with synchronous generators. Squirrel cage induction machine (SCIM) is an attractive choice for autonomous generation systems for its brushless rugged construction, less maintenance, simple operation, and self-protection against faults, good dynamic response and capability to generate power at varying speed [403]. Though purposed-built induction generators are expensive, three-phase induction motors can be used as generator when the drive condition is right. These motors are mass produced and so are quite cheap and easily available.

Widespread exploitation of stand-alone renewable systems has led to popular use of self-excited induction generators (SEIGs) for supplying electrical energy in rural areas [404]. However, SEIGs suffer from unsatisfactory voltage regulation and frequency variations, and thus are only suitable for fixed speed application [405]. For optimal operation under varying
wind speed conditions, an intermediate dc-power conversion stage is usually needed between generators and grid or loads [406]. The addition of power converter stages for voltage and frequency control increases system complexity and introduces extra cost which could offset the advantages of using stand-alone induction generators.

Most autonomous power systems and loads are based on single-phase distribution schemes, which give rise to the development of single-phase induction generators. Single-phase induction machines can be operated as SEIGs with appropriate modification in the winding or circuit configuration, but in general these machines are limited to relatively small power outputs. At power ratings above 3kW, three-phase induction generators are preferred over single-phase generators due to their advantages of lower weight, lower cost, and higher availability [407]. The operation of three-phase induction machines as stand-alone, single-phase generator with fixed excitation source has been widely studied. These schemes are based on configurations with extra capacitors or unbalanced loads on the stator terminals of the generator.

Since fixed excitation sources are used in these schemes, they are not suitable for dynamic loads and with varying rotation speeds. Recently, a new configuration which a 3-phase induction machine can be used as a single-phase generator under variable speed conditions without an intermediate inverter stage has been proposed in [408, 409]. This technique uses a Two-Series-Connected-And-One-Isolated (TSCAOI) phase winding configuration where one of the three windings is for excitation. The two remaining windings, which are connected in series, serve as power winding for the single-phase electricity generation. A new idea based on the TSCAOI configuration and reuse has been presented in [410], where disposal components such as induction motor and Uninterrupted Power Supply (UPS) are utilized instead of brand new components.

This chapter proposes and studies a new variable excitation technique which is derived from the TSCAOI topology. The next part introduces the concepts and principles of induction generator in stand-alone mode. The overview of various voltage regulation techniques for three-phase and single-phase loads are also presented in the same section. The study of the proposed single-phase generator based on three-phase generator is presented in the next section. This topology is a modified version of TSCAOI topology where two winding will be supplied separately by two inverters for excitation, and the remaining winding is connected to load. This technique will be called One-Isolated-And-Two-Isolated-Inputs or OIATI configuration by using the same naming convention. Mathematical model of the generator is first explored. The performance of the proposed OIATI topology in comparison to the TSCAOI topology is also accessed by computer simulation. The last part is the validation of the results using experiments.

4.2. Stand-alone Induction Generators

Induction generators had been used from the beginning of the twentieth century until they were abandoned and almost disappeared in the 1960s [411]. In the 1990s, ideas such as distributed generation began to be discussed more intensively in the media and in research
centers due to the general consciousness of finite and limited sources of energy on the earth. Induction generator, with its lower maintenance demands and simplified controls, appears to be a good solution for such applications. For its simplicity, robustness, and small size per generated kilowatt, the induction generator is favored for small hydro and wind power plants. More recently, with the widespread use of power electronics, computers, and electronic microcontrollers, it has become easier to administer the use of these generators and to guarantee their use for the desired applications. The induction generator is always associated with alternative sources of energy.

Induction generator has great economic appeal for small power plants. In standing alone mode, it usually reaches maximum of 15kW [411]. On the other hand, if an induction generator is connected to the grid or to other sources, it can easily approach 100kW. Very specialized and custom-made wound-rotor schemes, for example, double fed induction generator, enable even higher power.

### 4.2.1. Three-phase self-excited induction generator (SEIG)

An induction generator is mechanically and electrically similar to an induction motor. It can be operated in either grid-interactive or stand-alone mode. In grid-interactive mode, the generator is directly connected to the grid that imposes its voltage and frequency and supplies the required reactive power. Induction generators produce electrical power when their shaft is rotated faster than the synchronous speed of the equivalent induction motor. If the shaft rotates slower than the synchronous speed, the machine acts like an induction motor. The analysis of a grid-connected induction generator does not differ much from that of an induction motor.

![Fig. 4-1: Self-excited IG with capacitor banks.](image)

In stand-alone systems, it is necessary to have an external source of reactive power permanently connected to the terminals to enable self-excitation and further voltage build-up. Self-excitation can be achieved by the connection of suitable capacitors at the machine’s stator terminals, as shown in Fig. 4-1. The lagging reactive power (VAR) supplied by the capacitors is consumed by the machine’s excitation, leakage reactance and the reactance of the inductive load. Such a generator is called self-excited induction generator (SEIG) and its voltage and frequency are not fixed but depends on many factors such as, rotation speed,
load, excitation capacitor, generator parameters, etc. The analysis of a SEIG is thus much more difficult than that of a grid connected induction generator.

Self-excitation process enables induction machine to work as autonomous generator, provided: (1) the rotor is driven to a speed higher than that of the stator magnetic field, (2) rotor core has sufficient residual magnetism, and (3) capacitor connected across stator of induction machine has sufficient charge to provide necessary initial magnetizing current [412, 413].

- **The self-excitation phenomenon**

If an appropriate capacitor bank is connected across the stator terminals of an externally driven induction machine and rotor has sufficient residual magnetism, an e.m.f is induced in the machine windings due to the excitation provided by the capacitor. If the e.m.f is sufficient then it would circulate a leading current in the capacitor. Then the flux produced due to these currents would assist the residual magnetism. This would increase the machine flux and larger e.m.f will be induced. This in turn increases the currents and flux, the induced voltage and the current will continue to increase until the VAR supplied by the capacitor is balanced by the machine and which is decided by the saturation of the magnetic circuit [414, 415].

Once the machine is self-excited and loaded, the magnitude of the steady-state voltage generated by the SEIG is determined by the nonlinearity of the magnetizing curves, the value of the self-excitation capacitance, speed, machine parameters and terminal loads. As the load and speed of the SEIG changes, the demand for lagging VARs to maintain a constant AC voltage across the machine terminals also changes.

- **Magnetizing curves and calculation of capacitor bank**

The magnetizing curve, or saturation or excitation curve, which is related directly to the quality of the iron, core dimensions, overall geometry, and coil windings can be determined by the characteristic of terminal voltage for a given magnetizing current through the windings at a given frequency as shown in Fig. 4-3. The curve can be found from operating the induction machine as motor at no load and measuring the current \( I_m \) in Fig. 4-2 at different voltage levels \( V_1 \). This curve starts at the value of the residual magnetism (zero current) existing before the beginning of the test in the iron hysteresis curve of the machine.

For operation as a stand-alone generator, the SEIG should be connected to a three-phase bank of capacitors. Like the excitation curve, the capacitive reactance (Fig. 4-3) will be a straight line passing through zero whose slope is:

\[
X_c = \frac{1}{\omega C} \quad (4.1)
\]

The magnetizing current lags behind the terminal voltage by about 90°, depending on the losses of the motor in a no-load condition while the current through the capacitor is approximately 90° ahead. The reactive power produced by the capacitor bank is given by Eq. 4.2.
\[ Q = VI = \frac{v^2}{X_c} = \omega CV^2 \]  

(4.2)

The value of \( C \) can be chosen for a given rotation in such a way that the straight line of the capacitive reactance intercepts the magnetizing curve at the point of the desired rated voltage (\( V_{\text{rated}} \)). This means that the intersection of these two lines is the point at which the necessary reactive power of the generator is supplied only by capacitors (the resonant point). Therefore, to have the excitation process, this value should be between the straight-line slope passing through the origin and the tangent to the most sloped part of the excitation curve (the air gap line), also passing through the origin. The current corresponding to the interception point should not be much above the rated current of the machine. If the capacitance line is close to the excitation line of the generator, there may not always be excitation when the generator is started. The excitation process is also dependent on the speed that rotates the generator. Choosing a high enough value of capacitance and providing sufficient build-up speed will increase the probability of achieving excitation [416, 417].
**Load influence**

If resistive loads are connected, the generator will require higher reactive power due to increased active power consumption. When the load increases, the generator requires a higher amount of reactive power to maintain the voltage level. If there is no increase in reactive power supply, the magnetizing current provided by the capacitor bank will be lower than the current needed to maintain rated terminal voltage. The result will be a reduction in voltage. However, this does not take into account the speed variations that will occur in a micro-hydro system. If the load increases to a level where the voltage drops too low, the reactive power produced falls and it can result in de-magnetizing of the system and total voltage collapse. 

When inductive loads are connected to the generator, they will consume reactive power. This means that some of the current from the capacitors will go to the load instead of the generator. This will reduce the reactive power supply to the generator, and the generator voltage will drop. An inductive load is influencing the total capacitance by decreasing the effective value. This is shown in the Eq. 4.3, where the parallel connection of the capacitor bank and the inductive load is represented as a new and reduced actual capacitance value.

\[ C_{eff} = C - \frac{L}{\frac{R_l^2}{\omega_n^2} + L^2} \]  

(4.3)

Where \( L \) and \( R_l \) represent inductive load, \( C \) is the capacitor bank value, and \( C_{eff} \) the equivalent capacitor bank. At small value of inductance \( L \), it will not have much influence on the capacitance value. If the value of \( L \) is high enough, the resulting \( C_{eff} \) may become smaller than the defined \( C_{min} \) for the system and the voltage will collapse. The inductive loads will also influence the frequency in the system due to increase of speed caused by voltage drop.

### 4.2.2. Voltage regulation themes for SEIG (review)

If the voltage and frequency are not kept at the right level, the user loads connected to the generator can be damaged. Most appliances have reduced performance or fail to operate at low voltage. If it is too high, most devices will be damaged or have reduced lifetime. On the other hand, most devices are less sensitive to frequency level. Most consumer loads are tolerant with higher frequency except speed dependent motor loads. Lower frequency can cause internal circuits to overheat and fail in radio, TV and motor.

In spite of numerous advantages offered by SEIGs over other conventional generating machines, they are known to suffer from an extremely restrictive voltage and frequency regulation due to reactive power consumption [420]. This imposes technical barriers on their suitability for practical applications, especially when feeding inductive loads.

In hydropower systems, two main different scenarios referent to the prime mover can be considered: constant-speed/constant-frequency, and variable-speed/constant-frequency [421]. The first case considers the continuous adjustment of the turbine speed, and consequently of the generated power, by means of speed governors, in accordance to the load applied. This
scenario is found in fuel injection generation systems and large hydropower generation stations. The second case, on the other hand, considers the generation of constant power independently of the power demand by loads. The prime mover imposes a constant speed and the frequency regulation, in this case, must be done by the control of the consumed load, by means of auxiliary loads that are controlled to consume all the power generated, well known in the literature by electronic load control (ELC) [422]. For example, if the generator produces 1000 Watts and the total load connected by the consumers is only 600W then the ELC will control the switching on and off of the ballast so that the remaining 400W is also dissipated. If the consumer load changes at any time, the IGC will automatically adjust the power diverted to the ballast so that the voltage and frequency are kept constant. This technique is preferable in SEIG-based micro-hydro power generation (<100 kW), because there is no reservoir and the water flow is constant. Moreover, the speed governor is an expensive option and its large mechanical time constant limits a quick reaction to the transients [422].

While the frequency of generated voltages is associated with the balance of the active power of the system, which depends on the relation between the mechanical power delivered on the generator’s shaft and the electrical power consumed by the electrical system, the amplitude of the generated voltages is associated with the balance of the reactive power of the system, being strictly dependent of the power and power factor of the load applied [422]. This way, the control of voltages and frequency can be done by the control of reactive and active powers, such an independent way of each other. In the literature, several types of voltage and frequency controls strategies using power semiconductor devices and reactive elements have been studied widely by the researchers over the years.

a. Series capacitor scheme

Series compensation is made by adding series capacitors, in addition to the parallel connected capacitor bank as depicted in Fig. 4-4. Series compensation is a less complex solution since there is no power converter involved, thus does not have the operational problems associated with harmonics and switching transients [423]. The combination of series and shunt capacitance can be done either by short shunt or long shunt connection. Short shunt means connection of the series capacitors at the load side of the shunt capacitance, and long shunt means connection at the generator. The short shunt solution requires lower capacitance values, gives a better voltage regulation compared to the long shunt configuration and thus has better performance. [423, 424]

With a correct combination of the capacitors in the short-shunt configuration, it is supposed to be possible to have an almost flat load characteristics and the need for additional reactive compensation will be eliminated [423]. When choosing the size of the shunt and the series capacitance, the shunt is first determined, and used as a base of choosing the series capacitance. The factor which is defined by the ratio of series capacitive reactance to shunt capacitive reactance has been suggested between 1 and 0.4 in various literatures ([423, 425-428]). The main disadvantage of this solution is the possible occurrence of sub-synchronous resonance (SSR) in the system while supplying inductive loads and dynamic loads [424].
Fig. 4- 4: Series compensation with short shunt connection [423, 424].

b. Switched capacitor scheme

One or more switched capacitors can be connected in parallel with the existing capacitor bank, used to provide the varying need for reactive power at different loading conditions. With this solution, the shunt capacitance value can be dimensioned for full resistive load, and the system can be designed to switch in one or several capacitors when the voltage level decreases below a certain value due to shortage of reactive supply in the system. This provides voltage regulation in discrete steps, given that the capacitor can only be switched logically on or off. This method may not be able to provide the correct amount of reactive power and hence the voltage level at varying input and loading conditions [424]. If the amount of capacitors needed in the system is high, this is an expensive solution for reactive compensation. Addition of an extra capacitor also includes an extra switch, which is costly and that might provide disturbing transients.

c. Electronic load controller (ELC)

Electronic Load Controller is relatively simple, robust and cheap to manufacture and maintain in operation. It is designed for a run-of-river pico-hydro system which operates at near constant power at constant head and discharge of water [429]. ELC regulates the voltage and frequency of the generator through monitoring of consumer load and adding an additional controllable load called dump load, so that, the total output power of SEIG remains equal to its rated power.

Three main techniques can be used to control the ballast load. A binary weighted load controller (BWLC) consists of dump load resistors divided in the ratio of 1:2:4:8 of total per phase dump load [430]. BWLC in three-phase system require large number of resistive elements for binary switching and their associated switching circuits.

The thyristor-controlled bridge converter based ELC and rectifier/chopper based ELC are represented in Fig. 4-5. A thyristor-controlled bridge converter based ELC controls the power dissipated in the dump load by adjusting the firing angle of thyristors connected to the loads [431, 432]. However, the phase angle control (PAC) of thyristor gives an increased burden of reactive power on the SEIG and also distorts the SEIG terminal voltage waveform due to harmonic currents drawn by the converter. Reference [433-435] describes the analysis and implementation of rectifier/chopper based ELC for SEIG in micro-hydro applications. In this
scheme, only one switching device and its driving circuit and one dump load are required. Also, it generates a low value of harmonics and does not demand reactive power [434].

![Diagram](image)

**Fig. 4- 5:** (a) Thyristor controlled converter based ELC; (b) Rectifier/chopper based ELC.

d. **Fixed capacitor thyristor controlled reactor (FC-TCR) based Static VAR Compensator**

A Static VAR Compensator (SVC) is a shunt connected static VAR generator and/or absorber whose output is varied to control specific parameters (e.g. Voltage, frequency) of the electric power system. SVCs are used for its advantages of having a fast response and continuous control of reactive power, implying that it will have some advantages compared to both series and switched capacitors. The Thyristor Controlled Inductors with fixed capacitor based SVC, as shown in **Fig. 4-6**, comprises of fixed capacitors in parallel with AC inductors, which is in series with two thyristors connected in anti-parallel.

![Diagram](image)

**Fig. 4- 6:** (a) FC-TCR static VAR compensator; (b) per phase operation. [436]

The output from a thyristor can be controlled by adjusting its firing angle. The variation in firing angle results in lagging current in the corresponding phase, thus control the reactive power consumption. **Fig. 4-6(b)** shows the basic operation principle of a phase of the generator output. Connecting this in parallel with a fixed capacitor, the actual reactive power generation $Q_C$ is adjusted by the variable reactive power absorption $Q_L$. [424, 436-437]

e. **Inductively loaded AC/DC converter**

Another configuration of SVC (only for balanced generator loads) is a full or half wave thyristor converter loaded with a single DC inductor (Fig. 4-7). Naturally commutated converters are able to draw only lagging VAR (i.e. supply only leading VAR). The lagging VAR required by the generator is obtained by the fixed capacitors bank across the converter.
terminals. The net lagging VAR may be controlled by continuous adjustment of the firing angle of the thyristors.

![Fig. 4-7: SVC based on controlled rectifier. [438]](image)

This method is one of the simplest static arrangements for drawing controllers lagging reactive current. This method faces the problems of weight losses in inductors and also introduce considerable amount of harmonic distortion into the AC system [429].

**f. Static Compensator (STATCOM)**

A STATCOM is basically a three-phase PWM AC/DC converter that controls the reactive power at its terminals by means of generating leading or lagging power factor with respect to its terminal voltages. The on-line PWM control of the converter provides a fast dynamic response for the system. Moreover, the injected current not only is free of harmful low order harmonics, but also can be used to cancel these harmonics generated by other sources [440].

As illustrated in Fig. 4-8, a STATCOM can be constructed either by a Voltage-Type or Current-Type Converter (VTC or CTC). The VTC STATCOM consists of a voltage source inverter, DC bus capacitor and AC inductors. The AC output of the inverter is connected through the AC filtering inductor to the SEIG terminals. The DC bus capacitor is used as energy storage device and provides self-supporting DC bus. By increasing the amplitude of the inverter voltage above system voltage, leading currents can be drawn from the ac system. Whereas by decreasing the inverter voltage below the ac system voltage, lagging current can be drawn from the mains. The inverter can be supplied from a separated dc source or an appropriately dimensioned capacitor bank with inverter voltage slightly lagging with respect to the ac system voltage.

![Fig. 4-8: (a) Voltage-type STATCOM [439]; (b) current-type STATCOM. [440]](image)

A CTC STATCOM consists of a voltage source inverter, and a DC bus inductor. It has some advantages over its counterpart in this application. It has a rugged, short circuit proof
operation that complies with SEIG application. Also, there is no need for rather complicated current control circuitry used in VTC, as a CTC directly produces current signals. The excitation capacitors of the SEIG also help to absorb high frequency harmonics of the current, preventing them to flow in the system. Finally, instead of three inductors in VTC output, a CTC has just one inductor at the dc side, reducing the weight of the system that is dominated by the number of magnetic components. The dc inductor at the CTC dc side can be made small by application of high frequency PWM schemes.

**g. AC–DC–AC link converter and other alternatives**

The reactive load compensation themes to improve voltage and frequency regulation using static compensators can be useful in decreasing the size of capacitors for self-excitation which reduces the cost of the system [411]. However, such compensators are based on a three-phase fully controlled converter, where the capacitive reactive power is supplied to the IG by a converter control using PWM modulation techniques. Even so, this method uses large electrolytic capacitors with auxiliary loads, increasing costs again for a reduced reliability.

Another possibility is to provide a stable inverter output voltage at a fixed frequency by connecting the IG to a cascaded uncontrolled bridge rectifier and inverter ([441-442]). Such systems are seen as a nonlinear load for the IG, draining currents with large harmonic contents, which also causes voltage distortion across the IG terminals. Thus, larger self-excitation capacitor banks are used, and they eventually increase core losses and they cause mechanical vibrations and increased costs.

![IMC power circuit connected between SEIG and a load](image)

*Fig. 4-9: IMC power circuit connected between SEIG and a load. [411]*

One simplified method to maintain the regulated load voltage and frequency with small self-excitation capacitor is the use of an indirect matrix converter (IMC) between the SEIG and the load [443-445]. IMC consists of a fully controlled rectifier stage feeding an inverter, without any DC-link energy storage element as depicted in Fig. 4-9. The IG feeds the controlled rectifier stage with a reduced self-excitation capacitor bank. The rectifier in its turn will provide power to the dc link, decoupling generator output and load with respect to the
frequency. Such topology allows for load voltage regulation, frequency control, and minimization of the self-excitation capacitors, especially when the SEIG is feeding inductive loads, which is the most ordinary case. Such a method works well only with stand-alone loads of resistive and inductive characteristics, and it is not recommended to supply nonlinear and unbalanced loads because they degrade the generated voltage and, consequently, the voltage supplied to the load.

A new configuration for a wind energy conversion system using stand-alone induction generator for variable speed drive has been proposed in [446]. This configuration is suggested in Fig. 4-10. This scheme uses a STATCOM with reduced converter power rating for generator excitation and active power control. A shunt active filter based also on reduced converter power rating to compensate unbalanced and non-linear loads and battery energy storage across the converters DC link is utilized. There are three modes of operation: (1) IG directly connected to the load, (2) battery bank directly supplying the load using a voltage inverter, and (3) battery bank acting in parallel with the IG to meet temporarily high loads. There is a circuit breaker between the generator and the load to open the direct connection when the inverter becomes the load on its inverter mode.

![Proposed WECS based on the SCIG.][446]

The mode of operation is also defined according to the turbine speed. For low wind speed, the turbine speed becomes low when operating with maximum power point tracking control. For this situation the frequency becomes lower and the IG cannot supply directly the load. Therefore, a series converter configuration (rectifier-inverter or back-to-back converter) must be used to decouple frequency of the generator and the load. However, the converter power rating in these situations cannot be reduced. In contrast, if the turbine speed is close or equal to their rated values and no series converter is used, the load can be supplied directly from the generator (if the frequency of the generated voltage is close or equal to the nominal frequency of the load). The SCIG excitation can be controlled by a STATCOM with reduced converter power rating, with approximately 30% to 50% of generator rated power. Also, for low wind speeds the power of the wind turbine is below to the nominal level. In this situation, if a series converter configuration is used, this must process about 50% to 60% of rated turbine power.
4.2.3. Feeding single-phase loads using three-phase induction generator (review)

In many cases, isolated consumers require single-phase power; thus, the single-phase induction machine appears as a reliable alternative in supplying such consumers. Single-phase induction motor can be operated as SEIG, but in general they are limited to relatively small power outputs. Most of the single-phase induction machine has two windings (main and auxiliary), but it is not necessary to use both windings for generator operation. For a single winding operation, both the excitation capacitor and the load can be connected to the main winding [447]. For two-winding operation, the excitation capacitor is usually connected to the auxiliary winding and the load is connected to the main winding.

While high capacity single-phase induction machines are available in the market, three-phase machines above 3.7 kW are cheaper than single-phase machines of the same ratings [448]. The single-phase induction machine also has lower efficiency with respect to a similar three-phase machine of the same power, thus consequently has a worse power per weight ratio. On another hand, three-phase induction motors are available in a wide power range and models. However, a three-phase machine operated as a single-phase generator is working under a very unbalanced condition, necessitating it to be de-rated to avoid overheating. Efforts have been made to allow the operation of a three-phase induction generator in single-phase mode.

a. Phase balancing methods

The main challenge of a three-phase induction generator supplying single-phase consumers is the unbalanced regime which cannot be allowed for stable operation. From literature, one of the first articles in this field, [450], proposes no less than four distinctive balancing configurations, three for star and one for delta connected induction generators. The balancing is done using passive circuit elements and employs either two capacitors, two capacitors and a unity turns ratio transformer, three capacitors and a transformer, or, in the last case, two capacitors (connected in series and parallel). The “C–2C” balancing method for a delta connected generator was first introduced in [451], while [452] proposed the use of only one capacitor for self-excitation, for both star and delta connections.

Phase balancing topologies can be divided into two major categories: based on passive circuit elements (excitation capacitors, impedances) or on power electronic converters. If the balancing methods are based on passive elements, the resulting configuration (and the number of required capacitors) is imposed by the generator internal connection (star or delta). For star connected generators, the balancing topologies are depicted in Fig. 4-11 and Fig. 4-12, and for delta connected generators in Fig. 4-13, Fig. 4-14 and Fig. 4-15.
Fig. 4-11: (a) The Fukami connection; (b) the Smith connection. [449]

Fig. 4-12: Star connected generators with one capacitor. [449]

Fig. 4-13: Delta connected generators with one capacitor. [449]

Fig. 4-14: Delta connected generators with two capacitors. [449]
When power electronics based converters are used, some might act as balancers for the threephase machine. A simple configuration relies on a delta connected machine with the C–2C connection, having in parallel with the main (resistive) load a circuit named Electronic Load Controller (ELC) that dissipates the exceeding active power [455-456]. The ELC participates at phase balancing by maintaining a constant load at the generator leads. The same configuration is encountered also for star connected machines with the Fukami connection [457].

Another simple technique of phase balancing and converting three-phase to single-phase current, which is already presented in the previous three-phase section, consists of two power converters in back-to-back configuration (AC-DC-AC link) (Fig. 4-16) [458-459]. By passing through direct current the phase balancing problem is solved.

A combination between a three phase voltage source inverter (VSI) and a dump load (DL), operating in parallel with a delta connected generator, enables balanced currents through the machine when supplying single-phase loads as presented in Fig. 4-17 ([460, 461]). Reference [462] reports and analyses the use of STATCOM which enables balanced operation for the generator when connected to a single-phase feeder. The same topology is also proposed for three-phase SEIG to feed a single-phase load in [463] (Fig. 4-18).
b. TSCAOI topology (inverter-assisted topology)

Fig. 4-19 shows the example of an ‘inverter-assisted’ topology for single-phase generator which was introduced in [464]. It is based on a split-phase induction machine, where an inverter controls the auxiliary winding (labeled A) and power is generated on the main winding (labeled B). A control law regulates the voltage and frequency on the load through proper adjustment of the inverter signals. The approach presents several interesting features [465].

1) With sinusoidal excitation, the frequency of the voltage on the load is the same as the frequency of the voltage applied by the inverter.
2) A constant frequency can be applied to the load for some range of speeds (asynchronous operation).
3) The amplitude of the voltage on the load is approximately proportional to the voltage applied to the inverter so that regulation of the load voltage is possible.
4) The harmonic content of the voltage applied to the load is smaller than the harmonic content applied to the auxiliary winding, due to the filtering provided by the machine.
5) Only one inverter is needed to generate power from two windings.
The latest topology of single-phase power generation using a three-phase induction generator is based on the inverter-assisted topology. The two-series-connected and-one-isolated (TSCAOI) topology consists of a single-phase inverter connected across one phase and the load connected between the remaining two phases [408, 409, 465] (see Fig. 4-19). The single-phase inverter supplied by a DC source is used to balance the active power circulation and provides the generator excitation current in case of varying loads/rotor speeds. A battery storage system can be used as the DC source to supply the energy requirement of the generator when the available renewable energy is low or absorb any excess energy production during high renewable energy condition.

The transient and steady-state analysis of the TSCAOI topology has been studied in [466, 467]. In Reference [468], a modified excitation control technique has been proposed where the stator flux component and load components of inverter current are decoupled and controlled independently in order to improve the transient response of the overall system. The analyses and implementation of TSCAOI configuration based on reuse has been presented in [410]. Disposal components such as induction motor and UPS units are utilized instead of newly produced components.

### 4.3. Novel Technique for Single-phase Generator based on TSCAOI Topology

While the ELC based topology is suitable for voltage and frequency regulation in a generator driven at constant mechanical power by keeping the power consumption constant, the AC-
DC-AC link or back-to-back converter topology can regulate both voltage and frequency while the generator is driven at a wide range of speed (and mechanical power). The STATCOM / PWM converter based topology can regulate the output voltage at a wide range of shaft speed but the frequency will also change with speed since there is no frequency decoupling between load and generator.

Since the frequency is fixed by the inverter of the excitation winding, the TSCAOI topology can regulate output voltage and frequency, but at a smaller speed range above the synchronous speed of the generator. This small range is also further limited by some parameters, for instance, excitation currents. Nevertheless, if the frequency is allowed to be changed, its speed range will also be increased. It is important to note that the generator speed (for all topologies) will of course be limited by the physical parameters of the generator such as mechanical constraint, core losses and core saturation. The change of frequency will affect most load equipment at lower value. However, loads are less sensitive at higher frequency; mainly the electronic devices that employ internal power supply using bridge rectifier in the first stage. In term of implementation, the TSCAOI topology may requires reduced rectifier size/number, less power switching devices and control circuits, thus costs less, compared to back-to-back converter and STATCOM / PWM converter based topology.

This study proposed a modified version of TSCAOI topology, one-isolated-and-two-isolated-inputs or OIATI, where two winding will be supplied separately by two inverters for excitation, and the remaining winding is connected to a capacitor and load as depicted in Fig. 4-21. This section seeks to evaluate the performance of the proposed topology as an alternative to the TSCAOI topology in terms of operation range, and implementation parameters.

![Fig. 4- 21: Proposed modified-TSCAOI topology (OIATI topology).](image)

### 4.3.1. Dynamic modeling

**a. Classical modeling of induction machine**

In a classical induction machine, electrical equations for stator and rotor windings with voltages, currents and winding fluxes can be expressed in matrix form as follows:
\[
[V_s] = [R_s] [I_s] + \frac{d}{dt} [\Phi_s] \quad (4.4)
\]
\[
[V_r] = [R_r] [I_r] + \frac{d}{dt} [\Phi_r] \quad (4.5)
\]

With
\[
[V_s] = \begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} ; \quad [I_s] = \begin{bmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{bmatrix} ; \quad [V_r] = \begin{bmatrix} v_{ra} \\ v_{rb} \\ v_{rc} \end{bmatrix} ; \quad [I_r] = \begin{bmatrix} i_{ra} \\ i_{rb} \\ i_{rc} \end{bmatrix} ; \quad [\Phi_s] = \begin{bmatrix} \phi_{sa} \\ \phi_{sb} \\ \phi_{sc} \end{bmatrix} ; \quad [\Phi_r] = \begin{bmatrix} \phi_{ra} \\ \phi_{rb} \\ \phi_{rc} \end{bmatrix}
\]

The stator and rotor resistances matrices can be expressed by:
\[
[R_s] = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} ; \quad [R_r] = \begin{bmatrix} R_r & 0 & 0 \\ 0 & R_r & 0 \\ 0 & 0 & R_r \end{bmatrix}
\]

Where \( R_s \) and \( R_r \) are per phase stator and per phase rotor resistances. For squirrel cage induction machine, shown in Fig. 4-22, rotor windings are shorted, thus voltages are zeros.

![Fig. 4-22: Voltages and currents in windings of cage induction machine.](image)

The modeling of the three-phase induction machine generally retained relies on several hypotheses [469]. For this modeling, hypotheses about the physical behavior of the materials are:

- The magnetic fields are not saturated, are not submitted to the hysteresis phenomenon and are not the center of Foucault’s currents (for all practical purposes, the magnetic circuit is leafed through to limit the effects). This allows defining linear inductions.
- The skin effect is not taken into account.
- The temperature in the machine stays constant at all operating conditions, which leads to constant parameters in the models.

These hypotheses will allow adding the associated fluxes to the different currents, using proper constant inductances, characterizing couplings by sinusoidal variations of the mutual inductances and representing induction flows by a spatial vector. Without magnetic saturation, the stator and rotor fluxes’ expressions are obtained under vector form:
\[
\begin{bmatrix}
[\Phi_s] \\
[\Phi_r]
\end{bmatrix} = \begin{bmatrix}
[L_s] & [M_{sr}(\theta)] \\
[M_{sr}(\theta)]^T & [L_r]
\end{bmatrix} \begin{bmatrix}
[I_s] \\
[I_r]
\end{bmatrix}
\] (4.6)

Where the inductance matrices are expressed as below:

\[
[L_s] = \begin{bmatrix}
l_{sp} + l_{sl} & M_s & M_s \\
M_s & l_{sp} + l_{sl} & M_s \\
M_s & M_s & l_{sp} + l_{sl}
\end{bmatrix}; [L_r] = \begin{bmatrix}
l_{rp} + l_{rl} & M_r & M_r \\
M_r & l_{rp} + l_{rl} & M_r \\
M_r & M_r & l_{rp} + l_{rl}
\end{bmatrix} ; \quad [M_{sr}(\theta)] = M_{sr}[R(\theta)]
\]

\[
M_s = -\frac{1}{2}l_{sp} \quad M_r = -\frac{1}{2}l_{rp} ; \quad [R(\theta)] = \begin{bmatrix}
\cos(\theta) & \cos(\theta - \frac{4}{3}\pi) & \cos(\theta - \frac{2}{3}\pi) \\
\cos(\theta - \frac{2}{3}\pi) & \cos(\theta) & \cos(\theta - \frac{4}{3}\pi) \\
\cos(\theta - \frac{4}{3}\pi) & \cos(\theta - \frac{2}{3}\pi) & \cos(\theta)
\end{bmatrix}
\]

\(R(\theta)\) is the transformation matrix. \(M_{sr}\) is the maximal mutual inductance between a stator and a rotor phases when their axes are collinear. ‘\(\theta\)’ is the electrical angle between rotor and stator axes. The inductance of each winding is divided into a main or proper inductance (index p) that participates in the common flux and a leak inductance (index l).

- **Park reference frame**

The induction machine was modeled using two separate frames. The first one is used to express stator quantities; the second one is used to express rotor quantities. Since these two frames are linked with angle \(\theta\), which is not a constant variable, a transformation of the model of the machine into a common frame can be obtained using the Park transformation.

The Park transformation with power conservation is obtained using the following matrix:

\[
[P(\phi)] = \begin{bmatrix}
\cos(\phi) & \cos(\phi - \frac{2}{3}\pi) & \cos(\phi - \frac{4}{3}\pi) \\
\sin(\phi) & -\sin(\phi - \frac{2}{3}\pi) & -\sin(\phi - \frac{4}{3}\pi) \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix}
\]

Where \([P(\phi)]^{-1} = [P(\phi)]^T\)

Fig. 4-23 shows the disposition of the two-phase or three-phase axis systems in the electrical space. At a certain point, the position of the magnetic field rotating in the air gap is pinpointed by angle \(\theta_s\), in relation to stationary axis \(Osa\). For the development of the machine model, a Park reference frame \((dq0)\) is assumed to be lined up with this magnetic field and to rotate at the same speed \((\omega_s)\). Transforming angle \(\theta_s\) is necessary to bring the stator variables back to the Park rotating reference frame. Transforming angle \(\theta_r\) is necessary to bring the rotor variables back. The relation between these angles is:

\[
\theta_s = \theta + \theta_r; \quad \omega_s = \omega + \omega_r
\]

Where \(\omega = \frac{d\theta}{dt}; \quad \omega_s = \frac{d\theta_s}{dt}; \quad \omega_r = \frac{d\theta_r}{dt}\); \(\theta\) is electrical position of the rotor, \(\omega\) is electrical angular speed.
The transformation $P(\theta_s)$ is applied to the stator quantities; and $P(\theta_r)$ is applied to the rotor quantities:

$$\begin{align*}
[X_{s,dq0}] &= [P(\theta_s)][X_{s,abc}] ; 
[X_{r,dq0}] &= [P(\theta_r)][X_{r,abc}]
\end{align*}$$

The reverse transformation:

$$\begin{align*}
[X_{s,abc}] &= [P(\theta_s)]^{-1}[X_{s,dq0}] ; 
[X_{r,abc}] &= [P(\theta_r)]^{-1}[X_{r,dq0}]
\end{align*}$$

Applying the inverse Park’s transformation $P(\theta_s)^{-1}$ to relation (4.4) and $P(\theta_r)^{-1}$ to relation (4.5), result in:

$$\begin{align*}
\frac{d}{dt}[\Phi_{s,dq0}] &= [v_{s,dq0}] - [R_s][I_{s,dq0}] + [W_s][\Phi_{s,dq0}] \\
\frac{d}{dt}[\Phi_{r,dq0}] &= [v_{r,dq0}] - [R_r][I_{r,dq0}] + [W_r][\Phi_{r,dq0}]
\end{align*}$$

(4.9)  
(4.10)

Where:

$$[W_s] = \begin{bmatrix}
0 & \omega_s & 0 \\
-\omega_s & 0 & 0 \\
0 & 0 & 0
\end{bmatrix} ; 
[W_r] = \begin{bmatrix}
0 & \omega_r & 0 \\
-\omega_r & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}$$

(4.11)

Using the Park transformation in (4.6), and further developing the resulting formula leads to the expression of four sub-matrices that define the couplings of the equivalent model in the two-axis frame:

$$\begin{align*}
[\Phi_{s,dq0}] & = [L_{ps}][I_{s,dq0}] + [M_{psr}]^T[I_{r,dq0}] \\
[\Phi_{r,dq0}] & = [L_{pr}][I_{r,dq0}] + [M_{psr}][I_{r,dq0}]
\end{align*}$$

(4.12)

Where:

$$[L_{ps}] = \begin{bmatrix}
L_s & 0 & 0 \\
0 & L_s & 0 \\
0 & 0 & L_s
\end{bmatrix} ; 
[L_{pr}] = \begin{bmatrix}
L_r & 0 & 0 \\
0 & L_r & 0 \\
0 & 0 & L_r
\end{bmatrix} ; 
[M_{psr}] = \begin{bmatrix}
M & 0 & 0 \\
0 & M & 0 \\
0 & 0 & 0
\end{bmatrix}$$

(4.13)
In these relations, $L_s = \frac{3}{2} l_{sp} + l_{sl}$, $L_r = \frac{3}{2} l_{rp} + l_{rl}$, are stator and rotor cyclic inductance; $L_{s0} = l_{sl}$, $L_{r0} = l_{rl}$; the inductances corresponding to homopolar stator and rotor components, and $M = \frac{3}{2} M_{sp}$ is mutual cyclic inductance. It can be noted that the mutual inductances do not vary with the rotor position. Furthermore, as the matrices are now diagonal, the equations referring respectively to axes $d$ and $q$ are decoupled.

### State-space model

The equations (4.9), (4.10) and (4.12), involve the derivative terms of fluxes and currents. The state variables for state space representation can be chosen to be either fluxes, currents or the combination of fluxes and currents. In this case, the stator and rotor currents are chosen as state variables for this modeling. Using the relation between currents and fluxes vectors in (4.12), and replacing fluxes by currents in equation (4.9) and (4.10), the following state space model (4.14) can be obtained:

$$
\begin{align*}
\frac{d}{dt}[I_{s,dq0}] &= \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} I_{s,dq0} \\ I_{r,dq0} \end{bmatrix} + \begin{bmatrix} B_{11} \\ B_{21} \end{bmatrix} \begin{bmatrix} V_{s,dq0} \\ V_{r,dq0} \end{bmatrix} \\
\end{align*}
$$

(4.14)

Where: $[A_{11}] = \begin{bmatrix} -\frac{R_s l_r}{\beta} & \frac{\omega_s l_s l_r - \omega_s M^2}{\beta} & 0 \\ -\frac{\omega_s l_s l_r + \omega_s M^2}{\beta} & -\frac{R_s l_r}{\beta} & 0 \\ 0 & 0 & -\frac{R_s}{L_{s0}} \end{bmatrix}$

$[A_{12}] = \begin{bmatrix} \frac{R_s M}{\beta} & \frac{l_r M}{\beta} (\omega_s - \omega_r) & 0 \\ \frac{l_r M}{\beta} (\omega_r - \omega_s) & \frac{R_s M}{\beta} & 0 \\ 0 & 0 & \frac{R_s M}{L_{r0}} \end{bmatrix}$

$[A_{21}] = \begin{bmatrix} \frac{R_s M}{\beta} & \frac{l_r M}{\beta} (\omega_s - \omega_r) & 0 \\ \frac{l_r M}{\beta} (\omega_r - \omega_s) & \frac{R_s M}{\beta} & 0 \\ 0 & 0 & \frac{R_s M}{L_{r0}} \end{bmatrix}$

$[A_{22}] = \begin{bmatrix} \frac{l_r}{\beta} & 0 & 0 \\ 0 & \frac{l_r}{\beta} & 0 \\ 0 & 0 & \frac{l_r}{L_{r0}} \end{bmatrix}$

$[B_{11}] = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$

$[B_{21}] = \begin{bmatrix} -\frac{M}{\beta} & 0 \\ 0 & -\frac{M}{\beta} \end{bmatrix}$

$\beta = L_s l_r - M^2$

(4.15)

The state vector and input vector are defined as:

$$
[x_3] = [i_{sd}, i_{sq}, i_{s0}, i_{rd}, i_{rq}, i_{r0}]^T; [u] = [V_{s,dq0}] = [v_{sd}, v_{sq}, v_{s0}]^T
$$

It can be noticed that if the current system are balanced, the homopolar components are zeros and can be omitted from the equation reducing the dimension of the equation without any impact. In our case, stator currents are not balanced, while it is not the case in rotor currents. The equation related to homopolar component of rotor current is expressed by:
\[
\frac{d}{dt} i_r 0 = - \frac{R_r}{L_{r0}} i_r 0
\]  \hspace{1cm} (4.16)

This equation doesn’t relate to input voltages or other state variables. The general solution of
the equation is an exponential term, which decays toward zero over time. Taking into account
zero initial condition, the solution is: \( i_r 0 = 0 \). Consequently, this term can be eliminated from
(4.14), and a new state equation can be written as below:

\[
\frac{d}{dt} \begin{bmatrix} x \end{bmatrix} = \begin{bmatrix} [A_{11}] & [A_{12}'] \\ [A_{21}] & [A_{22}]' \end{bmatrix} \begin{bmatrix} x \end{bmatrix} + \begin{bmatrix} [B_{11}] \\ [B_{21}]' \end{bmatrix} [u]
\]  \hspace{1cm} (4.17)

The new state variable is written as: \( [x] = [i_{sd}, i_{sq}, i_{s0}, i_{rd}, i_{rq}]^T \); the input vector \( u \)
remains unchanged.

\[
[A_{12}'] = \begin{bmatrix} \frac{R_s M}{\beta} \\ \frac{L_r M}{\beta} (\omega_r - \omega_s) \\ 0 \end{bmatrix}; [A_{21}'] = \begin{bmatrix} \frac{R_s M}{\beta} & \frac{L_s M}{\beta} (\omega_r - \omega_s) & 0 \\ \frac{L_s M}{\beta} (\omega_s - \omega_r) & \frac{R_s M}{\beta} & 0 \\ 0 & 0 & 0 \end{bmatrix}
\]

\[
[A_{22}'] = \begin{bmatrix} \frac{R_s M}{\beta} & \frac{L_s M}{\beta} (\omega_r - \omega_s) \\ -\frac{R_s L_s}{\beta} & \frac{R_s + R_{L}}{\beta} + M \omega_s M^2 \\ -\frac{R_s L_s}{\beta} \omega_s + \omega_s M^2 \end{bmatrix}; [B_{21}'] = \begin{bmatrix} 0 \\ 0 \\ \frac{-M}{\beta} \end{bmatrix}
\]

It should be noticed that there is no separation between input and output variables in the state
equation. The input \( u \) is relating to both the two inputs and the output. Along with the two
excitation sources, a capacitor connected in parallel to the load, provides additional reactive
power to the output winding. If the capacitor is not used, and load is purely resistive \( (R_L) \), the
stator voltage equation (4.4) for output winding can be written:

\[
0 = (R_s + R_L) i_{sc} + \frac{d}{dt} \Phi_{sc}
\]  \hspace{1cm} (4.18)

From (4.18), a new stator voltages vector \( [V_e] \), and stator winding resistors can be modified
as followed:

\[
[V_e] = \begin{bmatrix} v_s a \\ v_s b \\ 0 \end{bmatrix}; [R_s'] = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s + R_L \end{bmatrix}
\]  \hspace{1cm} (4.19)

The relation (4.4) can be rewritten as:

\[
[V_e] = [R_s'] [I_s] + \frac{d}{dt} \Phi_s
\]  \hspace{1cm} (4.20)

In the same ways, the new state space equation (4.21) is obtained as below:

\[
\frac{d}{dt} [x] = \begin{bmatrix} [A_{11}] & [A_{12}'] \\ [A_{21}] & [A_{22}]' \end{bmatrix} [x] + \begin{bmatrix} [B_{11}] \\ [B_{21}]' \end{bmatrix} [u']
\]  \hspace{1cm} (4.21)
Where: 
\[ A_{11} = \begin{bmatrix} \frac{-R_{sl}}{\beta} & \frac{\omega_{sM}}{\beta} & 0 \\ \frac{-\omega_{sM}}{\beta} & \frac{-R_{lr}}{\beta} & 0 \\ 0 & 0 & -(R_s+R_L) \frac{L_{so}}{L_{sc}} \end{bmatrix} \]

And the input vector \( [u'] = [V_{e,dq0}] = [P(\theta_s)][V_e] = [v_{ed}, v_{eq}, v_{eo}]^T \)

In this new state model, the output is separated from input vector. Nevertheless, for a general load where capacitors or inductors are included, new state variables are added to the equation which could introduce the problem of different reference frames. When the capacitor is employed, an additional differential equation can be derived at the output winding:

\[
\begin{align*}
\frac{d}{dt} v_{sc} &= R_L i_L \\
C \frac{d}{dt} v_{sc} &= i_c = -i_{sc} - i_L
\end{align*}
\]  
**(4.22)**

This leads to:
\[
\frac{d}{dt} i_L = -\frac{1}{R_L C} i_L - \frac{1}{R_L C} i_{sc}
\]  
**(4.23)**

\[ i_{sc} = \sqrt{\frac{2}{3}} \left[ \cos(\theta_s - \frac{4}{3} \pi) - \sin(\theta_s - \frac{4}{3} \pi) \right] \frac{1}{\sqrt{2}} [i_{sd}, i_{sq}, i_{so}]^T \]  
**(4.24)**

Following the derived equation in (4.23), \( i_c \) can be incorporated into a state variable in (4.17). This equation can be related to other state variables by equation (4.24), in which the stator current is converted to \( dq0 \) reference frame. As a result, the new state space equation involves terms which are dependent to rotor and magnetic field position. These terms, however, could also be taken away by transforming equation (4.23) into \( dq0 \) frame. Nevertheless, in doing so, two additional variables are required: \( i_{La}, i_{Lb} \) which are defined as follows:

\[
\begin{align*}
\frac{d}{dt} i_{La} &= -\frac{1}{R_L C} i_{La} - \frac{1}{R_L C} i_{sa} \\
\frac{d}{dt} i_{Lb} &= -\frac{1}{R_L C} i_{Lb} - \frac{1}{R_L C} i_{sb}
\end{align*}
\]  
**(4.25)**

Vector \( I_L \) can be expressed by: \( [I_L] = [i_{La}, i_{Lb}, i_L]^T \)

Equations (4.23) and (4.25) can be expressed in a matrix form (stator reference frame) as:

\[
\frac{d}{dt} [I_L] = [Rc][I_L] + [Rc][I_s]
\]  
**(4.26)**

Where: \( [Rc] = \begin{bmatrix} -1/R_L C & 0 & 0 \\ 0 & -1/R_L C & 0 \\ 0 & 0 & -1/R_L C \end{bmatrix} \)

Although it is possible to add equation (4.26) into the state equation, the new model will face the same problem in equation (4.17) where both inputs and output are not independent.
- **Torque expression**

The generator shaft is connected to a turbine or a gearbox system driven by a turbine. The dynamic of the shaft can be obtained from torque balanced mechanical equation which is derived as:

\[
\frac{d\omega}{dt} = \frac{P}{2J}(T_p - T_e) - \frac{D}{J}\omega ; \quad (\omega = \frac{d\theta}{dt}) \tag{4.27}
\]

\(T_p\) is a torque given by turbine. \(\omega\) is the electrical angular speed. The electromagnetic torque \(T_e\) developed in induction generator using stator and rotor current is expressed in (4.28). \(P\) is the number of poles of the generator; \(J\) is the overall system inertia and \(D\) is the viscous friction coefficient. In dq0 reference frame, the electromagnetic torque can be expressed as bellow:

\[
T_e = \frac{P}{2} M \left( i_{sq}i_{rd} - i_{sat}i_{rq} \right) \tag{4.28}
\]

**b. Experimental setup and model verifications**

The equations developed above have been implemented in Matlab/Simulink® to simulate the system response for a given situation. The simulation results obtained from the developed Simulink model will be compared with the corresponding experimental results.

![Simulink model of the induction generator.](image)

**Fig. 4-24** shows the general layout of the Simulink’s induction machine model. There are three main parts making up the model: the generator state-space model, the mechanical dynamics block and the load model block. The main component of the model is the induction machine block (Generator model) in which the state space equations are implemented. The
dynamic model in equation (4.28) is expressed in ‘Torque dynamic’ block. Various types of loads can be implemented in ‘Load model’ block. For instance, the capacitive load (capacitor in parallel to resistor) is implemented using the equations (4.22).

The test bench consists of 1.5kW, 4 poles, 220/380V induction generator (MAS22) whose shaft is connected to another induction motor. The motor which serves as prime mover for the generator is controlled by a variable speed drive (Altivar 71, Schneider Electric). Detail information about the materials for experimentation is described in Appendix A7.

The generator equivalent circuit parameters (referred to the stator) are as follows: stator and rotor resistances are 3.84Ω and 3.94Ω respectively, and the stator and rotor leakage inductances are both equal to 0.025H. The machine magnetising inductance is estimated to be 0.388H. These parameters are given in detail in Table 4-1 while the corresponding Simulink’s model is given in Table 4-2.

![Experimental setup](image_url)

Fig. 4- 25: Experimental setup.

The synchronous speed corresponding to a 50Hz frequency of the excitation voltages is 1500rpm. To illustrate its dynamic behavior, the generator is driven at a constant speed of 1540rpm. The output of the generator is connected to a 30µF capacitor and 30Ω loads. The generator is excited by fix sinusoidal voltage sources (Ve1 = Ve2) whose phases are 120° apart. The generator is rotated in the same direction that it would run if it was only driven by the voltage sources alone (without motor drive).

Initially, when the inputs are zeros, there is no induced rotating magnetic field in the rotor. Thus the output is zero. When the 100Vrms input voltages are given at the two excitation phases, the magnetic field is induced in rotor. The transient response of the input currents and the outputs are illustrated in Fig. 4-26, Fig. 4-27, and Fig. 4-28. High initial currents can be
observed at the excitation phases. They quickly reach steady state after a few periods. To avoid this issue, the input voltage should be increased gradually to its normal value. Meanwhile, the outputs reach steady-state without overshoot.

Table 4-1: Induction generator parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>1500W</td>
<td>Rated voltage</td>
<td>220/380V</td>
</tr>
<tr>
<td>Stator/rotor resistance</td>
<td>3.84/3.94Ω</td>
<td>Magnetization inductance</td>
<td>0.388H</td>
</tr>
<tr>
<td>Stator leakage inductance</td>
<td>0.025H</td>
<td>Number pole</td>
<td>4</td>
</tr>
<tr>
<td>Rotor leakage inductance</td>
<td>0.025H</td>
<td>Moment of inertia</td>
<td>0.01Kg.m²</td>
</tr>
</tbody>
</table>

Table 4-2: Generator parameters used in Simulink model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_s$</td>
<td>3.87</td>
<td>$R_r$</td>
<td>3.94</td>
<td>$l_{sl}$</td>
<td>0.025</td>
<td>$M_{sr}$</td>
<td>0.388</td>
</tr>
<tr>
<td>Unit</td>
<td>Ω</td>
<td>Unit</td>
<td>Ω</td>
<td>Unit</td>
<td>H</td>
<td>Unit</td>
<td>H</td>
</tr>
</tbody>
</table>

For induction machine to generate active power, it has to operate over the synchronous speed which is defined by the frequency of the excitation sources. In the next test, we observe the steady-state behavior of the generator at different rotation speeds while the excitation sources are kept at 100Vrms and 50Hz. The phase difference of the two sources is always 120°. The output of the generator is connected to a 30µF capacitor and 100Ω loads (around 100W output power).

Fig. 4-26: Transient response of the input winding currents ($i_{e1}, i_{e2}$): (a) test results; (b) simulated results.
The steady-state behavior of the generator is presented in Fig. 4-29, Fig. 4-30, and Fig. 4-31. The generator starts generating net active power at speed above 1500rpm. As the speed increases about 1500rpm, it also generates increased active power and absorbs more reactive power. The input currents are also increased to accomplish the power. The output voltage changes between 10% and 20% of its normal level. The resisting torque at the shaft of the generator is depicted in Fig. 4-31. It should be noted that this result only shows the average value. In this configuration, as opposed to balance condition, the resulting torque fluctuates at double the electrical frequency.

Fig. 4-27: Transient response of the output winding current ($I_{sc}$): (a) test result; (b) simulated result.

Fig. 4-28: Transient response of the output voltage ($V_{sc}$): (a) test result; (b) simulated result.
Fig. 4-29: Test and simulated steady-state results of input active (P) and reactive power (Q) at different rotation speeds.

Fig. 4-30: Test and simulated steady-state results of input currents (a) and output voltage (b) at different rotation speeds.

Fig. 4-31: Test and simulated steady-state results of load torque of the generator at different rotation speeds.
4.3.2. Simulation and steady-state study

To evaluate the performance the proposed IG in a broader way, simulation models are implemented in Powersim’s PSIM 9.0 software. The excitation sources are first simulated using ideal sinusoidal voltage sources at rated voltage of the generator. These sources will be eventually replaced by DC sources and inverters in a close loop study. The system can be either driven by a constant-speed or constant-power prime mover connected to its shaft. It should be noted that if the generator is rotated by a turbine in a small hydro scheme, its speed-power characteristic follows the curve shown in Fig. 4-32. In this case, the water flow is not changing; there is an optimal speed at which the turbine is driven at maximum mechanical power.

![Fig. 4- 32: Simplified Power-speed characteristics for a turbine in a small hydro scheme. [418]](image)

a. Simulation models

The most basic simulation models of the TSCAOI and OIATI topology are depicted in Fig. 4-33 and Fig. 4-34. In this model, the effect of magnetic fields saturation in induction machine is not taken into consideration, and the magnetic fields are not submitted to the hysteresis phenomenon. The magnetization inductance ($M$) is thus supposed to be constant as defined in Table 4-1.

The excitation sources $V_{e1}$ and $V_{e2}$ are simulated using ideal sinusoidal voltage sources at 50Hz. The rated output voltage is 220Vrms at the same frequency defined by the excitation source.

![Fig. 4- 33: Simulation model of the TSCAOI topology.](image)
For steady state analyze, the turbine connected to the generator’s shaft is simulated by a constant-speed or constant-power mechanical loads. The dynamic analyze of the generator may require an external-control mechanical load which is programmed to emulate the actual turbine characteristic. The constant-power mechanical load is defined by the curve in Fig. 4-35 which the applied is fixed at $T_{\text{max}}$ if the mechanical speed is less than the base speed $n_{\text{base}}$. At speed above $n_{\text{base}}$, the torque is defined as:

$$T = \frac{P}{|\omega_m|} \quad (4.29)$$

Where the constant power $P$ can be written as: $P = T_{\text{max}} \times \omega_{\text{base}}$; $\omega_m$ is the mechanical speed in rad/s.

b. The effect of phase difference of the excitation sources

In a three-phase induction generator, optimal performance can be obtained if the generator is operating at balanced condition. Since only two of its phase are energized by sinusoidal voltage sources in the proposed OIATI configuration, the generator doesn’t necessarily operates at balanced condition. In this study, the excitation capacitor for the output phase is $C = 30\mu\text{F}$. The justification for this choice will be explained in next section. The output voltage ($V_s$) is kept at 220Vrms supplying a 500W resistive load ($R_L = 96.8\Omega$). The generator is running by a constant-power mechanical load.
The effect of phase difference between the two excitation sources \((V_{e1}/V_{e2})\) is verified and depicted in Fig. 4-36 to Fig. 4-38. The phase difference has opposite effect to the real power absorbed by excitation windings. Increasing the phase difference also increases real power supplied to the second winding and reduces that of the first winding. For winding currents, the optimal angle which minimizes the sum \(I_{e1}+I_{e2}+I_{sc}\) is around 120° (Fig. 4-36). This also corresponds to minimal torque ripple as shown in Fig. 4-38. Similar observation can be found if the generator is running at constant rotation speed.

Fig. 4-36: Phase currents vs. phase difference of \(V_{e1}\) and \(V_{e2}\) for a constant output power.

In actuality, the turbine has significantly higher inertia than the generator. For this reason, the result in Fig. 4-38 is obtained by assuming the motor drive (constant-power mechanical load) has a 0.2 Kg.m\(^2\) moment of inertia. In this case, the generator behaves similarly at steady-state as it is running at constant speed. In the proposed configuration, the pulsation of mechanical torque can be much smaller than that of the TSACOI when the phase difference of excitation sources is about 120°. It should be noted that, this optimization can be made slightly further by increase the difference of \(V_{e2}\) and \(V_{e1}\).

Fig. 4-37: Power vs. phase difference of \(V_{e1}\) and \(V_{e2}\) (a); Voltages vs. phase difference of \(V_{e1}\) and \(V_{e2}\) (b). (630W mechanical input)
c. Feasible operational region

The synchronous speed for a 4 poles machine at 50Hz is 1500rpm. In this study, the generator is driven at fix rotation speed which varies between 1460rpm to 1660rpm. The output voltage ($V_s$) is kept at 220Vrms by adjusting the excitation voltage sources. The excitation capacitor for the output phase is $C = 30\mu F$. The steady-states results for light load (50W) and normal load (500W) are shown in Fig. 4-39, Fig. 4-40, Fig. 4-41, Fig. 4-42, Fig. 4-43 and Fig. 4-44.

Fig. 4- 38: Torque ripple vs. phase difference of $Ve1$ and $Ve2$. (OIATI vs. TSIOAI configuration)

Fig. 4- 39: Real/reactive powers absorbed by excitation winding ($P_e; Q_e$) vs. rotation speed (rpm). (Output load at 50W and 500W; OIATI configuration)
Since the induction machine only generates net active power above synchronous speed, the operational region can be defined by the region of rotation above synchronous speed and below the certain speed defined by factors such as electrical, thermal and mechanical constraints. Based on Fig. 4-40 and Fig. 4-43, the feasible region for the proposed topology can be limited to rotation speed between 1500rpm and 1580rpm if the winding currents are limit to 4.5A. In the case of TSCAOI, this region isn’t necessarily starting at the synchronous speed. As depicted in Fig. 4-43, the machine starts generator function at around 1525rpm at 500W load. It can also be noted that for TSCAOI configuration, the feasible speed ranges are more dependent on the output load.

At speed below the feasible region, the generator absorbs both active and reactive power and thus acts a load (motor). The upper bound of the region is limited by the rating of winding currents, core saturation and mechanical structure of the generator.
Fig. 4-42: TSCAOI configuration: stator winding currents vs. rotation speed (rpm). (Output load at 50W and 500W)

Fig. 4-43: Total active power generated by the generator in the OIATI (blue) and TSCAOI (red) configuration. (Output load at 50W and 500W)

Fig. 4-44: Excitation voltages in OIATI configuration (Ve1/Ve2)(blue) and TSCAOI configuration (Ve1)(red). (Output load at 50W and 500W)
d. Choosing the size of parallel capacitor

To explain the choice of output’s capacitor, in this simulation, the generator is driven by a constant mechanical power. The excitation voltage ($V_{e1}/V_{e2}$) is kept at 212 Vrms. The steady states of generators’ parameters for various capacitor values are depicted in Fig. 4-45 to Fig. 4-48. The capacitor has significant effect on the output voltage of the generator, and more importantly in the TSCAOI topology (Fig. 4-45). However, it also has the effect on the winding current due to increased reactive power.

Increased capacitor size provides more reactive power to generator, thus reduces the reactive powers provided by the input windings. This results in increased current in the output winding and reduced currents in the input windings. The size of capacitor can be chosen to minimise all winding currents by balancing the reactive power absorbed at each winding of the generator.

As depicted in Fig. 4-47, the optimisation of the sum of all winding currents in the proposed topology can be obtained when capacitor’s value is between 20µF and 30µF. This optimisation can be also achieved at around 22µF for TSCAOI topology as shown in Fig. 4-48. However, this optimisation might depend on the limitation of each winding which is not necessarily the same. For instance, in practical application, the constraint on the input windings is also tied to the characteristic of the DC-AC converters which are employed if the excitation is made by batteries.

![Fig. 4-45: Output voltage for various capacitor values as a function of output power. (OIATI and TSCAOI topologies)](image-url)
Fig. 4-46: Excitation winding currents in the proposed configuration for various capacitor values as a function of output power. (OIATI topologies)

Fig. 4-47: Output winding current and the sum of all winding currents ($I_{abc} = I_{e1} + I_{e2} + I_{sc}$) for various capacitor values as a function of output power. (OIATI topologies)

Fig. 4-48: Winding currents for various capacitor values as a function of output power. (TSCAOI configuration)
e. Generator’s characteristic based on output power

To compare the characteristic of the generator based on OIATI configuration and generator based on TSCAOI configuration, the excitation voltage sources are adjusted manually to keep the output voltage \((V_s)\) at 220Vrms while the generator is running steadily at different speeds. The excitation capacitor for the output phase is kept at \(C = 30\mu F\). The steady states of generators’ parameters are depicted in Fig. 4-49, Fig. 4-50, Fig. 4-51, Fig. 4-52 and Fig. 4-53 for various output power.

As depicted in Fig. 4-49 and Fig. 4-50, increasing the output power requires increased input currents at the excitation winding in both cases. Note that, in TSCAOI case, the current intensity is increased more quickly. As shown in Fig. 4-53, this is also true for the input voltage. This is because in a TSCAOI configuration there is only one winding which provides extra reactive power required in addition to the fix reactive power provided by the capacitor. Hence, from certain level of output power (for a given capacitor size), the OIATI topology is better than the TSCAOI topology in terms of input currents and input voltage optimization. However, the capacitor size can be chosen so that it can provide necessary reactive at the maximum load power and maximum power factor. In this case, OIATI configuration has the benefit of requiring smaller capacitor size for the output.

Fig. 4-49: Input winding currents, \(I_{e1}\) (left), \(I_{e2}\) (right) vs. speed at different load outputs. (OIATI configuration)
Fig. 4-50: Input winding currents comparison, $I_e$ for OIATI configuration and $I_{e1}$ for TSCAOI configuration.

Fig. 4-51: Active power given by input sources vs. speed at different load outputs. (OIATI configuration)

Fig. 4-52: Active power given by input source vs. speed at different load outputs. (TSCAOI configuration)
f. Practical implementation

For practical application, the excitation sources are implemented with a DC source (batteries) and inverters with a close loop controller. In the simulation, ideal PWM inverters and high voltage DC sources are employed to supply the excitation winding (Fig. 4-54). In this case, the use of transformer can be eliminated and inverter loss is not taken into account. A simple close-loop control is implemented using PI controller (Fig. 4-42). The parameters of the PI controller are manually tuned for stable generator’s output. The generator is moving by a wind turbine module which emulates the power-speed characteristics of Fig. 4-24. The maximum power point is at 600W and 1550rpm of rotation speed which is corresponding to 10m/s of wind speed.

Fig. 4-53: Excitation voltage sources vs. speed at different load outputs. (Ve for OIATI configuration and Ve1 for TSCAOI configuration)

Fig. 4-54: PWM inverter driving one of the exciting windings.
Fig. 4-55: Close-loop PI controller.

- **Steady state**

The currents and powers for excitation winding at steady state are illustrated in Fig. 4-56. It can be observed that the currents are lower in the proposed topology at low power output. At high output power, the TSCAOI topology is better for current optimisation. The TSCAOI configuration also requires lower DC voltage source for the inverter. While Fig. 4-57 shows a higher efficiency, this result ignores the losses due to inverters which are more significant in the proposed OIATI topology since there are two inverters.

![Graph showing excitation currents vs. output power and real power of excitation windings vs. output power.](image)

Fig. 4-56: Excitation currents vs. output power (a); Real power of excitation windings vs. output power (b). (OIATI and TSCAOI topologies)
**Transient responses**

The transient behaviour in response to transition change in load and wind speed are depicted in Fig. 4-58 to Fig. 4-61. For wind speed transition test, the generator is supply a 500W resistive load. It should be noticed that the dynamic of the turbine speed ties mostly to the moment of inertia of the turbine.

It can be observed that there are small overshoot of output voltage and input currents in response of step change in load. This problem, however, is insignificant for the step change of turbine speed.

---

![Graph showing generator efficiency vs. output power](image)

Fig. 4- 57: Generator efficiency vs. output power.

![Load transition graphs](image)

Fig. 4- 58: Load transition (TSCAOI): (a) output power (in W); (b) output voltage $V_s$ (Feedback $V_f$ and reference voltage $V_{ref}$) (in V); (c) winding current (in A).
Fig. 4-59: Load transition (OIATI): (a) output power (in W); (b) output voltage $V_s$ (Feedback $V_{fb}$ and reference voltage $V_{ref}$) (in V); (c) winding currents (in A).

Fig. 4-60: Wind speed transition (TSCAOI): (a) wind speed (in m/s); (b) rotation speed (in rpm); (c) output voltage $V_s$ and reference voltage $V_{ref}$ (in V); (d) winding current (in A).
4.3.3. Experimental tests

The experimentation setup has already been described in section 4.3.1b, Fig. 4-25 and Appendix A7. The generator is a 1.5kW, 4 poles, 220/380V induction generator whose shaft is connected to another induction motor serving as prime mover. Due to limitation of this motor driver, the generator will be running at constant rotation speed controlled the motor driver. The normal output voltage is 100 Vrms at 50Hz. The results recorded from the tests are compared with the results generated by PSIM’s simulation model under the same conditions.

a. Operational speeds (OIATI configuration)

The induction generator’s shaft is rotated at a steady speed which is changed step-by-step from 1480rpm to 1620rpm. For each rotation speed, the excitation input voltages are tuned until a steady-state desired output voltage is obtained (100Vrms). The output terminal is connected to a 30 µF capacitor and a 29 Ω resistor. Experimental and simulated steady-state results of input currents, input active and reactive power are shown in Fig. 4-62 and Fig. 4-63.

The test results show that the induction generator follows closely to the prediction by simulation in terms of active power consumption at the input terminals and mechanical power. Significant differences exist when comparing the results in Fig. 4-62. This may be caused by imperfection of the simulation model which does not include losses and saturation.
Also, in the model, the prime mover is modelled by constant rotation speed block which is not the accurate model for the generator’s shaft driven by another induction motor.

Fig. 4-62: Test and simulated steady-state results of input currents (a) and input reactive power (b) at different rotation speed.

Fig. 4-63: Test and simulated steady-state results of input active power (a) and input mechanical power (b) at different rotation speed.

b. **Comparison of OIATI and TSCAOI topologies**

Similar test has been made for the TSCAOI topology. The output terminal is always connected to a 30µF capacitor and a resistor. While the output is kept at 100Vrms, the generator’s shaft is rotated at a steady speed ranging from 1500rpm to 1700rpm. Experimental and simulated steady-state results for a 350W load are shown in Fig. 4-64 for the TSCAOI topology. Small differences can be observed when comparing the test results with the simulation.
The comparison between the steady-states of the TSCAOI and OIATI topologies are illustrated in Fig. 4-65. It is noted that the TSCAOI topology require significantly higher excitation current at 350W load. In this case, the excitation voltage is also slightly higher with TSCAOI topology.

The result of generator’s efficiency shown in Fig. 4-66 is calculated using different formulas at different operation ranges. By definition, the efficiency is the ratio of output power and input power. At lower speed, the generator acts as motor by the absorbing the active power from inputs. In this case, the input power includes only the input power provided by the excitation terminals. When the generator is generating net positive active power, the input mechanical power will be also included in the total input power calculation. We observed in Fig. 4-66 that the proposed OIATI topology is significantly more efficient when compared to the TSCAOI topology.
Moreover, as depicted in Fig. 4-67 and Fig. 4-68, in both configurations, torque fluctuation can be observed due to unbalance condition. However, there is smaller torque fluctuation when using OIATI topology resulting in weaker vibration of the generator structure.

Fig. 4-66: Comparison of experimental efficiency of TSCAOI and OIATI configurations at different rotation speed for a 350W load.

Fig. 4-67: Generator driving torque fluctuation in TSCAOI configuration: (a) at 1500rpm; (b) at 1700rpm.

Fig. 4-68: Generator driving torque fluctuation in OIATI configuration: (a) at 1500rpm; (b) at 1620rpm.
c. Phase difference of excitation sources (OIATI configuration)

In this test, the induction generator’s shaft is turned at a fixed rotation speed of 1520rpm. The input voltages are tuned until a steady-state 100Vrms output voltage is obtained. The rms voltage of both input sources is equal while their phase difference is varied from 90° to 150° ($V_{e1}$ leads $V_{e2}$). The output terminal is connected to a 30µF capacitor. Experimental steady-state results are shown in Fig. 4-69, Fig. 4-70, and Fig. 4-71 for 100W and 350W loads.

It can be observed that the optimal angle is once again confirmed at between 120° and 130° angles. For input currents, the optimal angle is slightly increased to about 130° at 350W load from around 120 ° angles at 100W load. Increasing or decreasing the phase angle form the optimal value does have slight effect on the total electrical power output.

Fig. 4- 69: Steady-state test results of input currents (a) and input active powers (b) at different phase difference of input voltage sources for 100W and 350W load, both at 1520rpm.

Fig. 4- 70: Steady-state test results of mechanical input power (a) and electrical output power (b) at different phase difference of input voltage sources for 100W and 350W load.
4.4. Summary

Since most autonomous power systems and loads are based on single-phase distribution schemes, and single-phase induction machines are limited to relatively small power outputs, three-phase induction generators are usually preferred over single-phase generators due to their advantages of lower weight, and lower cost. In this chapter, several existing topologies of single-phase generator based on three-phase induction machine are presented by indicating their advantages and limitations.

A new configuration of three-phase induction machines operated as stand-alone, single-phase generator (TSCAOI) has been introduced recently to allow the operation under variable speed conditions without an intermediate inverter stage. This chapter proposed and studies a new variable excitation technique which is derived from the TSCAOI topology. This technique uses a one-isolated-and-two-isolated-inputs or OIATI configuration, where two windings are supplied separately by two excitation sources and the remaining winding is connected to a capacitor and load.

Mathematical model of the proposed generator configuration has been developed and verified by laboratory tests in the same conditions as for the TSCAOI configuration. Detail steady-state behaviour of the generator has been carried using simulation model. Both experimental and simulated results confirmed the validity of the proposed OIATI generator configuration. The comparison of the proposed OIATI and the TSCAOI topologies has also been studied.

The main advantage of the OIATI topology is that it is possible to run the generator with less torque pulsation by controlling the phase difference and amplitudes of the two excitation voltage sources. The generator’s lifespan can be greatly improved as the result of less mechanical vibration. Another advantage is higher system efficiency which is likely to be related to the above point. However, the results ignore the inverters losses which are needed in actual implementation. Since the proposed topology requires two inverters, these losses are more significant assuming equal input currents.

Also, from a certain level of output power (for a given capacitor size), the OIATI topology can be better than the TSCAOI topology in terms of input currents and input voltage

Fig. 4- 71: Generator’s experimental efficiency at different phase difference of input voltage sources for 100W and 350W load.
optimization. In the same way, it has the benefit of requiring smaller capacitor size for the output since reactive power is given by two input voltages.

In term of dynamic performances, the proposed OIATI topology is less sensitive to change of load. The operation region of the generator starts at almost the same speed regardless of output power. The operation region and other parameters of the generator using TSCAOI topology are more receptive to change of load. For these reasons, the proposed topology is more stable and performs better if the operation is fixed to certain speed (the speed at which all currents are minimized) since all parameters are less sensible to load change. Moreover, the two input windings provide 3 degrees of freedom for control, the two current amplitudes and their phase difference, compared to the unique degree of freedom in the TSCAOI topology.

The main problem of the topology is the use of two windings for excitation which increases the number of required components and thus the cost and losses of the system. In addition, since only one winding is used for output, it requires higher excitation voltages for the desired output voltage in most of its operation region.
Conclusion
Conclusion and Future work

The lack of sustainable energy access in rural area of many developing countries remains one of the biggest obstacles for development and economic growth. This is mainly due to factors such as installation cost and technological barriers. In rural Cambodia, renewable resources including solar energy and hydro power are plentiful and have great potential of providing immediate energy access for the isolated communities. In order to realize such the potential, there are still some obstacles to overcome including low investment cost, and technological feasibility.

To answer the problems, this thesis has proposed the new concepts of a solar-hydro hybrid system which will employ disposal components including power supply units, UPS, induction motors, and car batteries. This original solution is cheaper and has a shorter time to design and install when compared to extension of centralized grid which may not be feasible many decades in the future. All the second life components are locally available which makes the hybrid generation solution suitable for rural applications. The harvesting of renewable energy sources to power the rural electrification also helps minimizing the use of fossil fuels which is being depleted and is causing global warming.

The proposed solution can also contribute to solve the growing e-waste problem due to the rapid expansion of technological development and consumer demand. The solution has hardly been addressed from an engineering viewpoint and has received less attention compared to other End-Of-Life options. It should be noted that reuse is always considered superior to materials and energy recovery in the waste hierarchy, a concept that also applies to electronic and electrical waste. Reuse of discarded components eliminates the impacts due to production of new components by avoiding energy consumption, emissions, and extraction of new raw materials. This work could be considered as frugal innovation for rural electrification.

The thesis was focused on the environmental and technological aspects of the solution. The environmental evaluation has been made by comparing the impacts of a conventional solution and the impacts of the reuse solution using LCA methodology. The technological problems have been addressed in two parts. The first technological part of the reuse was focused on the refurbishing and repurposing processes of the used power supply units which are the main components for solar PV generators. The second part addressed a novel topology of generator based on discarded induction motors used pico-hydro plant.

The LCA methodology has been employed compare the life cycle impact of the proposed solution based on reuse with that of the conventional solution based on newly made components. The scope of this study was limited only to the solar power sector for which the technological aspects have been thoroughly studied and tested for feasibility. To obtain this objective, the sizing of both solutions were determined based on a common goal or functional unit which is defined by satisfying the daily energy needs of a rural village over a period of 20 years. The inventories data of material input, energy and emission were collected from the EcoInvent database for most materials and processes. For lead-acid batteries, inventories data
is supplemented by the data from literature. For electronic components which include inverter and charge controller, the data is extrapolated using existing the data from the database. The assessment result has proven a significant decrease (about 40%) of the environmental burden when reuse solution is employed. It also shows most of this benefit is due to reuse of lead-acid batteries. Sensitivity analysis was used to test the reliability of the result by observing the effects of some uncertain parameters. It has demonstrated that the efficiency of inverter and charge controller has the most influence to the result of comparison. Due to high contribution of batteries in the conventional solution, the reuse solution is still preferred while the converters are 20% less efficient. It can be emphasized that the action of altering or refurbishing the used components represents negligible burden in comparison to their productions. In case of inverter and charge controller, the contribution of their productions is already insignificant in term of the total impact of the system.

The general conception and common techniques to identify the issues and modify the structure of the PSUs to operate as a general purpose DC-DC converter has been presented. Experimental test was carried out for its performance evaluation. The general converter structure, converter topologies, and type of control systems commonly found in PSUs have been introduced. The modification technique involves the removal of a number of components. Few cable connectors, sensing resistors and MOSFET drivers are also required as the interface between the modified PSUs and the external controller. One of the main issues in PSUs based on forward converter is core reset which may be affected by repurposing of the converter usage. This factor should be considered to prevent damage or instability caused by overvoltage or overcurrent.

The PSUs has been repurposed as voltage or current controlled DC-DC converter using the on-board controller which is employed for nominal and fixed voltage regulation. If the PSUs use a current-mode controller and an error amplifier with internal reference voltage, an external signal can be applied to indirectly to control the output voltage. Similar method can also be applied for current control by adding shunt resistor for current sensor. In PV generator application, the built-in controllers are not necessary; an external controller is required to implement the MPPT control and charge controller functionality. The controller, implemented in a cheap microcontroller board, provides faster dynamic response due to direct interface to the MOSFET of the PSUs. In experimental test, the selected PSU is modified as a constant current DC-DC converter for automobile alternator’s output control and as MPPT controller in a PV generation system. The performance of the repurposed PSU was compared with that of a commercial MPPT converter which was shown to have comparable conversion efficiency.

The combination of PSUs is necessary to increase the current and/or voltage capability of the association to match the application requirement. If identical PSU units are used and controlled by the same switching signal, the implementation of distribution control which increases the system’s complexity and cost may not be necessary since the outputs of each unit are in phase.
A new configuration of three-phase induction machines operated as stand-alone, single-phase generator has also been introduced in this thesis as an alternative to a newly proposed topology. The overview of various topology of isolated three-phase induction generator for three-phase and single-phase loads were presented to illustrate the different advantages and disadvantages of each technique. An inverter-assisted single-phase output generator based on three-phase induction machines (TSCAOI) has been introduced recently to allow the operation under variable speed conditions without an intermediate inverter stage. This thesis proposed and studied a new variable excitation technique which is derived from the TSCAOI topology. This technique employs a one-isolated-and-two-isolated-inputs or OIATI configuration, where two winding are supplied separately by two excitation sources and the remaining winding is connected to a capacitor and load.

Mathematical model of the proposed generator topology has been developed using classical state space model of induction machine. Laboratory tests achieved with a 1.5 kW machine in the same test conditions verified the reliability of the model. The steady-state behaviour of the generator has been carried using both simulation model and laboratory test. The comparison of the proposed topology and the TSCAOI topology has also been studied.

While the induction machine only generates net active power above synchronous speed, in OIATI (and TSCAOI) configuration, it is also possible to maintain the desired output voltage for a speed below the synchronous speed since the power can be delivered from the excitation inputs. However, below the synchronous speed the generator acts as a motor and absorbs useful power from the excitation sources. Thus the generator works best above the synchronous speed. At the output phase, a capacitor can be used in parallel to load to optimise the performance of the generator. Increased capacitor size provides more reactive power to generator, thus increasing the output voltage and reducing the reactive powers provided by the input windings. As the result, larger capacitor means higher current in the output winding and smaller currents in the input winding of the generator. For this reason, the choice of capacitor depends on the desired optimization factors.

Since only two of its phase is energized by sinusoidal voltage sources in the proposed OIATI configuration, the generator usually operates in unbalanced condition. The resulting generator’s shaft torque fluctuates at the double the frequency of the input voltage. However, in OIATI topology, it is possible to minimize the torque pulsation by controlling the phase difference and amplitudes of the two excitation sources. This is one of the advantages of the OIATI topology while comparing with TSCAOI. With less mechanical vibration, the generator’s lifespan can be greatly improved.

Another advantage of the OIATI topology is higher system efficiency. It should be noted that this result ignores the losses in inverters which are used when the excitation sources are storage batteries. Also, from a certain level of output power (for a given capacitor size), the new OIATI topology is better than the TSCAOI topology in terms of input currents and input voltage optimization. In the same way, it has the benefit of requiring smaller capacitor size for the output since reactive power is given by two input voltages. In term of performance and stability the proposed original OIATI topology is less sensitive to change of load. The
operation region of the generator is less receptive to change of output power. On another hand, the operation region and other parameters of the generator using TSCAOI topology are more sensitive to change of load.

The main drawback of the topology is the usage of two windings for excitation which increases the number of required components and thus the cost of the system. The loss of the converter is also higher due to the use of two excitation inverters. In general, the OIATI topology also requires higher excitation voltages for the same desired output voltage since only one winding is used for output in contrast to two series winding employed in TSCAOI topology.

Future work

It can be said that the analysis and explanations presented in this research work provide a solid evidence of the feasibility of the proposed isolated renewable energy system based on reuse. Nevertheless, due to time and resource limitation, some problematic and worthwhile areas have not yet been addressed. These areas may be further explored in the future works:

- Diagnosis of the state of health of used lead-acid batteries: as shown in the result of the LCA study, batteries reuse has a great potential of reducing the environmental impact. The identification of the state of health of used batteries is important in the process of selecting the usable batteries from the mixture.
- Parallel and/or serial association of the PSUs: the potential problems of associating multiple PSUs may include the uneven power distribution and the effect on the dynamic response. These issues should be further addressed for the association of identical PSUs and non-identical PSUs.
- Control technique for the OIATI generator configuration: the control would be necessary to maintain a stable output level. More interestingly, it can also be implemented for generator optimization over a certain range of rotation speed by manipulating the amplitude, frequency and phase of the outputs of the excitation inverters.
- LCA study of the complete system that include solar PV generator and pico-hydro turbine with induction generator.
- Laboratory implementation with actual pico-hydro turbine and used components as well as control system which assure all regulation and optimization.
References

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Chapter 2:


Chapter 3:

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“UC3842 provides low-cost current-mode control”, STMicroelectronics, Application Note, AN 246/1188.


Chapter 4:


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Appendices
Appendix A1: The complete schematic diagram of Dell HP305P-00 power supply unit

Main converter:
Input line filter, PFC transformer and rectifier:

Secondary power supply:
Output monitoring circuit:

Heatsink thermal regulation:
Appendix A2: PSIM simulation model of HP305P-00 power supply

PSIM (v. 9.0) simulation model for output voltage control of Fig. 3-44:
PSIM simulation model for output current control in Fig. 3-51:
The functional model of UC3842 controller:

The parameters of PS2561 opto-coupler:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>PS2561</td>
</tr>
<tr>
<td>Current Transfer Ratio</td>
<td>2</td>
</tr>
<tr>
<td>Diode Resistance</td>
<td>5</td>
</tr>
<tr>
<td>Diode Threshold Voltage</td>
<td>1.1</td>
</tr>
<tr>
<td>Transistor Vce_sat</td>
<td>0.2</td>
</tr>
<tr>
<td>Transistor-side Capacitance</td>
<td>4.55n</td>
</tr>
</tbody>
</table>
Appendix A3: BOLK BOL B051099 alternator characteristics

Alternator test bench:

Parameters of the alternator:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pole pair</td>
<td>6</td>
</tr>
<tr>
<td>Output current rating (A)</td>
<td>50</td>
</tr>
<tr>
<td>Output voltage rating (V)</td>
<td>12</td>
</tr>
<tr>
<td>Stator winding configuration</td>
<td>Triangle</td>
</tr>
<tr>
<td>Rotor resistance (Ω)</td>
<td>3.7</td>
</tr>
<tr>
<td>Stator resistance (Ω)</td>
<td>0.32</td>
</tr>
<tr>
<td>Rotor inductance (mH)</td>
<td>13</td>
</tr>
</tbody>
</table>

Characteristics of the open-circuit voltage of the alternator as a function of rotor current at different rotation speed:
Appendix A4: FVG 10P solar PV panels (FVG 36 type)

FVG 10P parameters at STC (Irradiance 1000 W/m², module temperature 25 °C, AM = 1.5):

<table>
<thead>
<tr>
<th>Unit</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Polycrystalline</td>
</tr>
<tr>
<td>Power Peak</td>
<td>W 10</td>
</tr>
<tr>
<td>Maximum Power Voltage</td>
<td>V 17.5</td>
</tr>
<tr>
<td>Maximum Power Current</td>
<td>A 0.57</td>
</tr>
<tr>
<td>Open Circuit Voltage</td>
<td>V 21.0</td>
</tr>
<tr>
<td>Short Circuit Current</td>
<td>A 0.66</td>
</tr>
<tr>
<td>NOCT</td>
<td>°C 45 ± 2</td>
</tr>
<tr>
<td>Pm Temperature Coefficient</td>
<td>%/°C - 0.45</td>
</tr>
<tr>
<td>Number of cells</td>
<td>36 cells</td>
</tr>
</tbody>
</table>
Appendix A5: Arduino Due board

Processor characteristics:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microcontroller</td>
<td>Atmel SAM3X8E ARM Cortex-M3</td>
</tr>
<tr>
<td>CPU</td>
<td>32-Bit</td>
</tr>
<tr>
<td>Digital I/O Pins</td>
<td>54</td>
</tr>
<tr>
<td>PWM Output</td>
<td>12</td>
</tr>
<tr>
<td>Analog Input</td>
<td>12</td>
</tr>
<tr>
<td>Program Memory (Flash)</td>
<td>512 KB</td>
</tr>
<tr>
<td>SRAM</td>
<td>96 KB</td>
</tr>
<tr>
<td>Oscillator</td>
<td>up to 84 MHz</td>
</tr>
<tr>
<td>DAC</td>
<td>2</td>
</tr>
<tr>
<td>Others</td>
<td>UART (4), SPI, I2C</td>
</tr>
<tr>
<td>Operating Voltage</td>
<td>3.3V</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>7-12V</td>
</tr>
</tbody>
</table>
Appendix A6: Arduino Due programming

To program the Arduino Due board, download the Arduino IDE from this link: https://www.arduino.cc/en/Main/Software

By default, the Arduino Due board needs to be added to the IDE: Tools > Board: > Boards Manager. In Board Manager, search for ‘Arduino Due’ or ‘Arduino SAM board’. Select the board and choose ‘Install’.

Since the program will utilize timer interrupt, do the following steps to add the timer library: Tools > Manage libraries … > search for ‘Duetimer’ and choose ‘Install’.

The IO pins are chosen as:

- Analog input pin A0: for voltage measurement input.
- Analog input pin A2: for current measurement input.
- Pin 6: PWM output.
- Pin 2: Load controlled output.

The C/C++ code for MPPT control for P&O and INC algorithm is given below. To run the program, the Arduino board has to be connected to PC with USB port so that it can communicate with ‘Serial Monitor’ tool of the IDE.

```c
// -------------- Code begins ---------------------------------------------
#include <DueTimer.h> // To use timer library
#define Algo_period 20000 // === Algorithm period Ta in us ==
#define duty_max 0.65 // limit of duty cycle
#define duty_min 0.01 // limit of duty cycle
#define N_samplesV 100 // number of sample for voltage measurement
#define N_samplesI 100 // number of sample for current measurement
```
\#define ADC_MAX 4095 // ADC maximum = (2^12)-1
\#define volt_mesure A0 // pin A0 for voltage measure
\#define amps_mesure A2 // pin A2 for current measure
\#define PWM_CLK_E (*(volatile unsigned long int *) 0x40094000)
    // page 1006 of datasheet
\#define PWM_WPSR_E (*(volatile unsigned long int *) 0x400940E8)
    // page 1039
\#define PWM_CPRD7_E (*(volatile unsigned long int *) 0x400942EC)
    // Channel7 == PIN6
\#define PWM_CDTY7_E (*(volatile unsigned long int *) 0x400942E4)
    // page 1046
\#define PWM_CDTYUPD7_E (*(volatile unsigned long int *) 0x400942E8)
    // page 1047
\#define PWMmax 700 // For PWM_CPRD7_E (PWM period, page 1048) (f=60kHz)

int reso=32 ; // resolution for converting float variable
volatile float  Ipv = 0; // PV current
volatile float  Vpv = 0; // PV voltage
volatile float  Ppv = 0; // PV output power
volatile float alpha=0.4; // Duty cycle
volatile float alp_init=0.4; // ===== Initial duty cycle
float delta=0.01; // ====== Duty cycle step ======

int mppt_active=0;
int mppt_mode=0; // 0 for P&O ; 1 for CI
int incomingByte=0;
int k=0, j=0, m=0, n=0;

void setup() {
    analogWriteResolution(12); // DAC at 12bits resolution (10 or 12)
analogReadResolution(12); // ADC at 12bits resolution (10 or 12)
pinMode(2, OUTPUT);
digitalWrite(2, LOW);
pinMode(6, OUTPUT);
analogWrite(6, 255); // initialize pin 6

PWM_WPSR_E &= 0b11111111111111111111011011110110;
PWM_CLK_E = 0b0000000000000000000000000010;
    // Clock scaling (page 1006)
PWM_CPRD7_E = PWMmax; // define the time period of PWM.
PWM_CDTY7_E = PWMmax-10; // duty cycle (must be smaller than PWM_CPRD7_E)
    // use this line for 'inverted' PWM driver;
PWM_CDTY7_E = 10; // use this line for 'non-inverted' PWM driver;

Serial.begin(9600);
Serial.print("Bonjour! \n");
Serial.print(" \n");
Serial.print("Send 'm' to start MPPT control. 's' to stop it and reset duty cycle. \n");
Serial.print("Send 'e' to increase init duty cycle. 'd' to decrease init duty cycle. \n");
Serial.print("Send 'f' to start load transition. 'g' to stop load transition. \n");
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Serial.print("Send 'p' to set P&O mode.               'c' to set CI mode. 
");
Serial.print("   \n");

Timer1.attachInterrupt(programme).setPeriod(Algo_period).start();
// setPeriod is the period in µs.
}

// ===== Function: Read average measured voltage ============
float lire_tension(){
  long int somme=0;
  int temp;
  int i;
  int moy;
  float resu;

  for (i=0; i<N_samplesV; i++) {
    temp = analogRead(volt_mesure);
    somme += temp;
  }
  moy = somme/N_samplesV;
  resu =((float)(moy*3.3*reso)/(float)ADC_MAX);
  resu = resu/reso;       // average voltage measured at analog pin

  resu = 71*resu;         // converting to original voltage value
  return(resu);
}

// ===== Function: Read average measured current ===========
float lire_courant(){
  long int sommeI = 0;
  int tempI;
  int i;
  int moyI;
  float resuI;

  for (i=0; i<N_samplesI; i++) {
    tempI = analogRead(amps_mesure);
    sommeI += tempI;
  }
  moyI = sommeI/N_samplesI;
  resuI=((float)(moyI*3.3*reso)/(float)ADC_MAX);
  resuI = resuI/reso;       // average voltage measured at analog pin
  resuI = 351.65 - (114.11*resuI);       // 100 times of real current value
  if(resuI<0) { resuI=0;}
  return(resuI);
}

// == Function: Convert duty cycle to int value for 'PWM_CDTYUPD7_E'
void PWM_virgule_flottante(float X){
  int PW ;
  PW = X*PWMmax;
}
if (PW < 0) {PW = 0;}
if (PW > PWMmax) {PW = PWMmax;}
PWM_CDTYUPD7_E = (int)PW;

// ====== Subroutine: P&O Algo ======================
void mppt_PandO(void){
    static float Ppvk_1=0,Vpvk_1=0,alp;
    float Ipvk,Vpvk,Ppvk;
    alp = alpha;
    Ipvk=Ipv; Vpvk=Vpv; Ppvk=Ppv;
    if (Ppvk >= Ppvk_1){
        if (Vpvk >= Vpvk_1){
            alp = alp - delta;
        }else{
            alp += delta;
        }
    }else{
        if (Vpvk >= Vpvk_1){
            alp += delta;
        }else{
            alp = alp - delta;
        }
    }
    if (alp < duty_min) {alp = duty_min;}
    if (alp > duty_max) {alp = duty_max;}
    alpha=alp;
    Vpvk_1=Vpvk; Ppvk_1=Ppvk;
    alp = 1 - alp;
    //Inverted PWM driver; delete this line for non-inverted driver
    PWM_virgule_flottante(alp);
}

// ====== Subroutine: INC Algo ========================
void mppt_CI(void){
    static float Ipvk_1=0,Vpvk_1=0,alp;
    float Ipvk,Vpvk,DI,DV;
    alp = alpha;
    Ipvk=Ipv; Vpvk=Vpv;
    DI=Ipvk-Ipvk_1; DV=Vpvk-Vpvk_1;
    if (DV==0) {
        if (DI==0){
        }else{
            if(DI>=0){
                alp=delta;
            }else{
                alp+=delta;
            }
        }
    }
}
if((DI/DV)==-(Ipvk/Vpvk)){
  alp=delta;
}
else{
  alp+=delta;
}
if (alp < duty_min) {alp = duty_min;}
if (alp > duty_max) {alp = duty_max;}
alpha=alp;
Vpvk_1=Vpvk; Ipvk_1=Ipvk;

alp = 1 - alp;
// Inverted PWM driver; delete this line for non-inverted driver.
PWM_virgule_flottante(alp);

// === Interrupt program ================================
void programme(){
  Vpv = lire_tension();
  if(mppt_active==1){
    Ipv = lire_courant();
    if(mppt_mode==0) { // P&O mode
      Ppv = Ipv*Vpv;
      mppt_PandO();
    }
    if(mppt_mode==1) {mppt_CI();} // CI mode
  }
}
//=====================================
//========
Main program ===============
void loop() {
  k++;
  delay(100);
  if(k==20){
    k = 0;
  }
  if (Serial.available() > 0) {incomingByte = Serial.read();}
  // ======= key 'm' ======
  if(incomingByte==109){
    mppt_active = 1;
    alpha = alp_init;
    incomingByte = 0;
    Serial.print("MPPT activated \n");
  }
}
// ====== key 's' ======
if(incomingByte==115){
    mppt_active = 0;

    PWM_CDTY7_E = PWMmax-10;  // use this line for 'inverted' PWM driver;
    // PWM_CDTY7_E = 10;     // use this line for 'non-inverted' PWM driver;

    incomingByte = 0;
    Serial.print("MPPT deactivated 
");
    n = 0; digitalWrite(2,LOW);
}
// ====== key 'e' ======
if(incomingByte==101){
    alp_init = alp_init + 0.05;
    if(alp_init>duty_max) {alp_init=0;}
    Serial.print("alp_init:  "); Serial.println(alp_init);
    incomingByte = 0;
}
// ====== key 'd' ======
if(incomingByte==100){
    alp_init = alp_init - 0.05;
    if(alp_init<0) {alp_init=0.8;}
    Serial.print("alp_init:  "); Serial.println(alp_init);
    incomingByte = 0;
}
if(mppt_active==1){
    // ====== key 'f' ======
    if(incomingByte==102){ // f
        Serial.print("Load transition activated 
");
        n = 1;
        incomingByte = 0;
    }
    // === key 'g' ====
    if(incomingByte==103){ // g
        Serial.print("Load transition deactivated 
");
        n = 0; digitalWrite(2,LOW);
        incomingByte = 0;
    }
    if(n==1){
        j++;
        if(j==5){ // 5 for 500 ms period
            j = 0;
            if(m==0){ digitalWrite(2,LOW); } // switching loads => pin 2
            if(m==1){ digitalWrite(2,HIGH); }
            m++;
            if(m>1)(m=0;)
        }
    }
}
// ===== key 'p' ======
if(incomingByte==112){
    mppt_mode = 0;
    Serial.print("P&O algo active \n");
    incomingByte = 0;
}

// === key 'c' ====
if(incomingByte==99){
    mppt_mode = 1;
    Serial.print("CI algo active \n");
    incomingByte = 0;
}

// ------------ Code ends ---------------------------------------------
Appendix A7: Induction machines test bench

Generator test bench (by LANGLOIS):

MAS22 three-phase induction machine characteristics:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power:</td>
<td>1500W</td>
</tr>
<tr>
<td>Rated voltage (3-phase):</td>
<td>230/400V</td>
</tr>
<tr>
<td>Rated current:</td>
<td>5.7/3.3 A</td>
</tr>
<tr>
<td>Dimension:</td>
<td>112x190x355 (mm)</td>
</tr>
<tr>
<td>Weight:</td>
<td>20kg</td>
</tr>
</tbody>
</table>

CR2-V22 (50Nm) torque sensor:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum torque:</td>
<td>65Nm</td>
</tr>
<tr>
<td>Maximum speed:</td>
<td>3000rpm</td>
</tr>
<tr>
<td>Torque output signal:</td>
<td>+/-5V for 50Nm</td>
</tr>
<tr>
<td>Speed output signal:</td>
<td>5V for 2500rpm</td>
</tr>
</tbody>
</table>
VAV20 three-phase induction machine characteristics:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>1500W</td>
</tr>
<tr>
<td>Rated voltage (3-phase)</td>
<td>230/400V</td>
</tr>
<tr>
<td>Rated current</td>
<td>5.9/3.4 A</td>
</tr>
<tr>
<td>Dimension</td>
<td>112x190x580 (mm)</td>
</tr>
<tr>
<td>Weight</td>
<td>24kg</td>
</tr>
</tbody>
</table>

Variable speed drive for VAV20:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Altivar 71 (Schneider Electric)</td>
</tr>
<tr>
<td>Type</td>
<td>3-phase power supply.</td>
</tr>
<tr>
<td>Rated power</td>
<td>2.2kW (3Hp)</td>
</tr>
<tr>
<td>Voltage range</td>
<td>380-480V</td>
</tr>
<tr>
<td>Frequency</td>
<td>50/60Hz</td>
</tr>
<tr>
<td>Maximum line current</td>
<td>8.2A (380V), 7.1A (480V)</td>
</tr>
<tr>
<td>Apparent power</td>
<td>5.6kVA</td>
</tr>
<tr>
<td>Weight</td>
<td>3kg</td>
</tr>
</tbody>
</table>

Drive:

- Output frequency: 1… 1600Hz.
- Type of control for asynchronous machine:
  - sensor/sensorless flux vector control,
  - voltage/frequency ratio (2 or 5 points), ENA System.
- Type of control for synchronous machine: vector control with or without speed feedback.
### Chroma programmable AC power source:

<table>
<thead>
<tr>
<th>Model: 61705</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input 3-phase AC rating</strong></td>
</tr>
<tr>
<td>Voltage range: 190-250V (47-63 Hz)</td>
</tr>
<tr>
<td>Current: 28A max.</td>
</tr>
<tr>
<td>Power factor: 0.98 Min.</td>
</tr>
</tbody>
</table>

| **AC output rating** |
| Max. power: 12 kVA |
| Power per phase: 4 kVA |
| Voltage range: 150V /300V |
| Output voltage: 0~150V/0~300V, 0~140V/0~280V @ >1000Hz |
| Max. current per phase: 32A/16A (rms); 192A/96A (peak) |
| Line regulation: 0.1% |
| Load regulation: 0.2% |
| Frequency: DC – 1.2kHz |
| Phase: 0 ~ 360° (0.3° resolution) |

| **DC output rating** |
| Power: 2kW |
| Voltage: 212V/424V |
| Current: 16A/8A |

| **Others** |
| Protection: UVP, OCP, OPP, OTP, FAN |
| Operation temperature: 0°C to 40°C |
THÈSE

En vue de l’obtention du
DOCTORAT DE L’UNIVERSITÉ DE TOULOUSE
Délivré par l'Institut National Polytechnique de Toulouse

Présentée et soutenue par
Bunthern KIM
Le 28 mai 2019

Contribution à la conception et la commande optimale d'un système hybride génération d'énergie électrique à base d'énergies renouvelables et de constituants recyclés en vue de l'alimentation d'un village isolé dans un pays en voie de développement.

Ecole doctorale : GEET - Génie Electrique Electronique et Télécommunications : du système au nanosystème
Spécialité : Génie Electrique
Unité de recherche :
LAPLACE - Laboratoire PLAsma et Conversion d’Énergie - CNRS-UPS-INPT

Thèse dirigée par
Pascal MAUSSION et Maria PIETRZAK-DAVID

Jury
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Résumé Substantiel

L'expansion du réseau centralisé pour fournir de l'électricité est toujours absente dans de nombreuses zones rurales du Cambodge en raison des coûts d'investissement initiaux élevés. La solution temporelle consiste à employer un système de production d'énergie distribué qui présente un coût de cycle de vie inférieur et introduit une diversité de technologies pour répondre aux applications.

Les ressources en énergies renouvelables ont été bien comprises comme les solutions pour alimenter le développement rural et réduire les impacts environnementaux de la production d’énergie. Minimiser les impacts environnementaux représente un objectif majeur du développement durable, compte tenu de l'épuisement des ressources et des capacités d'adaptation limitées de l'environnement. Suivant les progrès technologiques et de la demande croissante des consommateurs, de grande quantité de déchets électriques et électroniques ont entraîné de graves conséquences pour l’environnement. Les stratégies actuelles reposent principalement sur les techniques classiques de collecte et de traitement des déchets. La réutilisation de composants mis au rebut permet de réduire les pertes et les émissions dues à la production de nouveaux composants en prolongeant leur durée de vie utile.

Ce travail de thèse proposait une solution de réutilisation des composants électroniques dans un système d'énergie renouvelable hybride isolé pour la solution d'électrification pour la zone rurale du Cambodge. Une configuration choisie pour le système proposé est un système de génération hybride solaire-hydroélectrique, car les ressources solaires et hydrauliques sont abondantes dans les zones rurales du Cambodge. Cette solution repose sur le concept de ‘l’innovation frugale’, une solution locale avec des matériaux locaux pour et avec les populations locales.

1. Introduction


1.1. Solution de système distribué d'énergie renouvelable hybride

La consommation de combustibles fossiles pour la production d’énergie est une cause majeure du changement climatique. Les énergies renouvelables, telles que l’énergie solaire, éolienne, hydraulique et la biomasse, ont le potentiel d’atténuer les effets négatifs des émissions de CO₂, ce qui entraîne également une réduction du réchauffement de la planète. Le Cambodge est bien situé dans la région tropicale où le paysage physique est dominé par
les plaines situées autour du Mékong et du lac Tonle Sap. Actuellement, la majorité de l'énergie fournie par le réseau électrique est générée par de grandes centrales hydroélectriques.

L’extension du réseau électrique centralisé nécessite une longue période de planification et de mise en œuvre, ainsi que des coûts d’investissement élevés. Dans les zones reculées, les systèmes de production décentralisée à faible puissance tels que les centrales pico-hydroélectriques et les systèmes de générateurs photovoltaïques sont plus favorables aux besoins urgents des communautés. Ces systèmes permettent de réduire les coûts d'investissement et offrent une diversité de technologies permettant de mieux répondre aux besoins spécifiques des applications.

Cependant, les systèmes photovoltaïques ou éoliens autonomes ne produisent pas une énergie fiable de manière cohérente en raison de leur nature imprévisible. La combinaison de l'énergie photovoltaïque et éolienne ou hydroélectrique dans un système hybride permet d'équilibrer les fluctuations d'énergie et de réduire la taille du système de stockage de batterie.

1.2. Solution de réutilisation

La fréquence extrême à laquelle nous achetons et jetons des appareils électroniques a des impacts sérieux pour notre planète. Pour réduire l'impact environnemental et l'empreinte énergétique, les industries de l'électronique se tournent vers des produits plus écologiques en réduisant leur consommation d'énergie lors de la fabrication et en augmentant l'efficacité énergétique des appareils.

La meilleure méthode pour la gestion de déchets électroniques consiste à augmenter la longévité des produits, soit en prolongeant la première vie des produits, soit en résolvant les problèmes de réparation, de réutilisation et de remise à neuf. La réutilisation des produits est préférable au recyclage ou la mise en décharge car c'est la solution la moins énergivore.

Fig. 1: Le système d'énergie renouvelable pour l'électrification dans la zone rurale.

Les composants comprenant les blocs d'alimentation, les batteries et les moteurs asynchrones peuvent être réutilisés dans les systèmes d'énergie renouvelable en zone rurale. Ce système pourrait aider à réduire les impacts des déchets électroniques et constituer une solution d'accès à l'énergie intermédiaire et abordable pour les communautés rurales. Comme illustré
à la Fig. 1, le système proposé peut inclure une partie "solaire", composée de panneaux photovoltaïques, de blocs d'alimentation modifiés (PSU), une partie "hydraulique" composée d'unités d'alimentation sans interruption modifiées (UPS) et machine à induction triphasée transformée en un générateur monophasé et un stockage d'énergie utilisant des batteries de voiture.

La validation de cette solution nécessite des considérations sur les aspects économiques, environnementaux et technologiques. Bien que l'économie doive être justifiée, seuls les aspects technologiques et environnementaux sont abordés dans cette thèse.

2. Analyse de cycle de vie

Outre les batteries de véhicules électriques, les avantages environnementaux de la réutilisation des composants n'ont pas encore été étudiés ni exploités de manière significative. Bien que des effets positifs de la réutilisation sur l'environnement et l'économie aient été démontrés dans un certain nombre de littératures, ce résultat pourrait être atténué et très dépendant de divers paramètres du système.

L’analyse du cycle de vie ou ACV est une méthode d'évaluation normalisée permettant d’analyser un bilan environnemental multicritère des produits, systèmes ou procédés sur l'ensemble de leur cycle de vie.

2.1. Définition des objectifs et du champ de l'étude

L’étude ACV présentée dans cette section se limite au système de production d’énergie solaire photovoltaïque dont les aspects technologiques ont été étudiés et testés pour en déterminer la faisabilité. La méthodologie ACV est un outil d’évaluation des scores d’impact à la fois pour la solution proposée et pour la solution conventionnelle. Le logiciel Simapro (V.7.3.2) développé par ‘PRé Consultants’ est utilisé dans cette étude. SimaPro inclut la base de données Ecoinvent intégrée (v2.2) qui donne accès à la plupart des données des inventaires utilisés aux niveaux du procédé de base et du système. Il fournit également des outils d'évaluation d'impact, notamment Eco-Indicator 99, CML et IMPACT 2002+.

La Fig. 2 montre un système de production photovoltaïque autonome conventionnel adapté à la consommation de petits villages. Dans la solution de réutilisation illustrée à la Fig. 3, le contrôleur de charge de batteries est remplacé par des blocs d'alimentation modifiés, un onduleur par des UPSs modifiés et des batteries SLI remplaçant les batteries de stockage. Une carte microcontrôleur et quelques composants d'interface sont nécessaires pour le contrôle.

![Fig. 2: Système de génération photovoltaïque utilisant la solution classique.](image)
L'unité fonctionnelle pour laquelle les impacts des deux solutions sont évalués est basée sur la consommation d’énergie pour l’électrification d'un petit village. Le profil de consommation du village de Thaïlande est choisi pour cette étude en raison du manque de données réelles d'un village rural au Cambodge (Fig. 4).

Dans la solution classique, chaque étape du cycle de vie des composants du système est analysée, comme illustré dans la Fig. 5. Dans le cas de réutilisation, les composants peuvent être classés en deux catégories, les nouveaux composants et les composants utilisés. Les impacts de chaque phase du cycle de vie des nouveaux composants sont pris en compte. Les articles utilisés sont des PSU, des UPS et des batteries SLI. Dans leur seconde vie, les composants utilisés sont rassemblés et transportés pour être testés et réutilisés. Seules ces étapes de leur cycle de vie sont prises en compte dans les frontières du système (Fig. 6).
Les modifications mineures qui doivent être apportées dans la structure des PSUs et UPSs impliquent le retrait de certains composants et le soudage de certaines pièces en ajoutant des composants. Les batteries de voiture usagées doivent être testées pour déterminer leur état lors de la sélection de celles qui sont en bon état.Bien que ces processus nécessitent de l’énergie et quelques composants supplémentaires, cela est supposé être négligeable par rapport à la production d’une nouvelle unité. Dans ce cas, seul l’impact du transport de l’installation de collecte des déchets au site d’installation est pris en compte.

2.2. Dimensionnement du système et inventaire du cycle de vie

Dans les deux scénarios, le dimensionnement de l’onduleur est défini par la puissance maximale consommée par la charge en tenant compte de son rendement. Pour des conditions météorologiques optimales, une batterie peut être dimensionnée pour offrir assez de stockage pour supporter la charge pendant la nuit et le lendemain jusqu’au lever du soleil. Pour accroître la fiabilité du système, les batteries sont dimensionnées pour 2 jours de stockage.

La dimension du générateur photovoltaïque est obtenue en prenant en compte la durée de l’insolation effective dans la région, les pertes et le profil de consommation indiqué dans la Fig. 4. Les pertes dues au convertisseur, à la température du panneau, à la saleté et au déséquilibre des modules sont estimées à 35%.

Tableau 1: Paramètres des composants du système.

<table>
<thead>
<tr>
<th></th>
<th>Paramètres</th>
<th>Rendement</th>
<th>MDOD*</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solution classique</strong></td>
<td>Onduleur</td>
<td>90%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Contrôleur de charge</td>
<td>90 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batteries</td>
<td>24 V</td>
<td>75 %</td>
<td>80%</td>
<td>2000 cycles</td>
</tr>
<tr>
<td>Panneau solaire</td>
<td>Polycristalline</td>
<td>15 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Solution de réutilisation</strong></td>
<td>PSUs, UPSs</td>
<td>80 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batteries SLI</td>
<td>24 V</td>
<td>70 %</td>
<td>20 %</td>
<td>500 cycles</td>
</tr>
<tr>
<td>Panneau solaire</td>
<td>Polycristalline</td>
<td>15 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dans la solution classique, l’efficacité de l’onduleur et du contrôleur de charge est supposée être de 90%. L’efficacité des PSUs modifiés et des UPSs modifiés en cas de réutilisation est supposée être 10% moins efficace en raison du vieillissement. L’efficacité des batteries SLI utilisées est supposée être inférieure de 5% à la valeur typique. La densité de puissance des
PSUs basées sur les échantillons collectés est d'environ 500 W/kg et d'environ 120 W/kg pour les UPS (sans la masse de la batterie). Les hypothèses de paramètre et les dimensionnements du composant sont répertoriées dans le Tableau 1 et le Tableau 2.

Tableau 2: Les dimensionnements du composant du système.

<table>
<thead>
<tr>
<th></th>
<th>Dimension</th>
<th>Masse</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solution classique</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Onduleur</td>
<td>3333 W</td>
<td>24.67 Kg</td>
</tr>
<tr>
<td>Contrôleur de charge</td>
<td>7326 W</td>
<td>24.67 Kg</td>
</tr>
<tr>
<td>Panneau solaire</td>
<td>48.84 m²</td>
<td>586 Kg</td>
</tr>
<tr>
<td>Batteries</td>
<td>1794 Ah</td>
<td>1230 Kg (35 Wh/Kg)</td>
</tr>
<tr>
<td><strong>Solution de réutilisation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PSUs</td>
<td>9936 W</td>
<td>19.87 Kg</td>
</tr>
<tr>
<td>UPSs</td>
<td>3750 W</td>
<td>31.25 Kg</td>
</tr>
<tr>
<td>Panneau solaire</td>
<td>66.24 m²</td>
<td>795 Kg</td>
</tr>
<tr>
<td>Batteries SLI</td>
<td>8073 Ah</td>
<td>3875 Kg</td>
</tr>
<tr>
<td>Carte Arduino Due</td>
<td>100x50 mm²</td>
<td>45g (5g microprocesseur)</td>
</tr>
</tbody>
</table>

Les hypothèses concernant les distances et les modes de transport sont présentées au Tableau 3. On suppose qu'une distance moyenne de 200 km en camion transporte les composants du centre de collecte situé en ville au site d'installation situé à la campagne.

La durée de vie attendue des modules PV est supérieure à 20 ans. Elle est choisie comme durée totale de cette ACV. L'onduleur et le contrôleur de charge neufs sont supposés être remplacés tous les 7 ans. Une durée de vie de 5 ans est présumée pour la deuxième vie des UPS et des PSU. Les durées de vie des batteries sont déterminées par leur nombre de cycles de charge/décharge (Tableau 4).

Tableau 3: Distances et modes de transport.

<table>
<thead>
<tr>
<th></th>
<th>Route</th>
<th>Océan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composants neufs</td>
<td>Fabrication aux utilisations</td>
<td>500 km</td>
</tr>
<tr>
<td></td>
<td>Mis en décharge</td>
<td>500 km</td>
</tr>
<tr>
<td>Composants de récupération</td>
<td>Site de collecte jusqu'au site d'installation</td>
<td>200 km</td>
</tr>
</tbody>
</table>

Tableau 4: Durées de vie et remplacements.

<table>
<thead>
<tr>
<th></th>
<th>Cycles</th>
<th>Durées de vie (ans)</th>
<th>Remplacements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solution classique</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panneau solaire</td>
<td>-</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>Batteries</td>
<td>2000 cycles</td>
<td>5.48</td>
<td>3.65</td>
</tr>
<tr>
<td>Onduleur /Charge controller</td>
<td>-</td>
<td>7</td>
<td>2.86</td>
</tr>
<tr>
<td><strong>Solution de réutilisation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panneau solaire</td>
<td>-</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>Batteries SLI</td>
<td>500 cycles</td>
<td>1.37</td>
<td>14.6</td>
</tr>
<tr>
<td>PSUs/UPSs</td>
<td>-</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Carte microcontrôleur</td>
<td></td>
<td>10</td>
<td>2</td>
</tr>
</tbody>
</table>

2.3. L'inventaire du cycle de vie
La plupart des données d'inventaire sont extraites de la base de données EcoInvent (Tableau 5). Comme la base de données pour les onduleurs n’est disponible que dans quelques puissances, une extrapolation des données a été appliquée pour évaluer les impacts de l’électronique de puissance à réutiliser. Les données détaillées pour les contrôleurs de charge n’ont pas été trouvées dans la littérature. Cependant, il existe des articles qui utilisent la même énergie intrinsèque pour l’onduleur ainsi que pour le contrôleur de charge (1MJ/W). Pour cette raison, l’impact environnemental des deux éléments est supposé identique par unité de

Tableau 5: Base de données EcoInvent.

<table>
<thead>
<tr>
<th>Composition</th>
<th>EcoInvent 2.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Onduleur /Charge controller</td>
<td>Inverter, 2500W, at plant/RER</td>
</tr>
<tr>
<td>Panneau solaire</td>
<td>Photovoltaic panel, multi-Si, at plant/RER</td>
</tr>
<tr>
<td>Carte Arduino Due</td>
<td>Printed wiring board, surface mounted, solder mix, at plant/GLO</td>
</tr>
<tr>
<td></td>
<td>Integrated circuit, IC, logic type, at plant/GLO</td>
</tr>
<tr>
<td>Transport</td>
<td>Truck 16t (road)</td>
</tr>
<tr>
<td></td>
<td>Transport, barge/RER (ocean)</td>
</tr>
</tbody>
</table>

Les données d'inventaire du cycle de vie des batteries au plomb ont été recueillies auprès de diverses sources documentaires pour leurs étapes de production et d'assemblage. Le Tableau 6 présente les pourcentages moyens de la composition des batteries et des données Ecoinvent correspondantes. Étant donné que les batteries plomb-acide sont généralement recyclées après leur durée de vie utile, plus de 90% du plomb et de l’oxyde de plomb sont supposés être recyclés.

Tableau 6: Composition matérielle de la batterie au plomb par pourcentage moyen de masse.

<table>
<thead>
<tr>
<th>Composition</th>
<th>Pourcentage de masse</th>
<th>EcoInvent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>65.3</td>
<td>Lead, primary, at plant/GLO</td>
</tr>
<tr>
<td>Sulphuric acid</td>
<td>9.2</td>
<td>Sulphuric acid, liquid, at plant/RER</td>
</tr>
<tr>
<td>Water (unsalted)</td>
<td>14.86</td>
<td>Water, deionised, at plant/CH</td>
</tr>
<tr>
<td>Polypropylene (case)</td>
<td>7.15</td>
<td>Polypropylene, granulate, at plant/RER</td>
</tr>
<tr>
<td>Fibreglass mat separator</td>
<td>2.3</td>
<td>Glass fibre, at plant/RER</td>
</tr>
<tr>
<td>Tin</td>
<td>0.4</td>
<td>Tin, at regional storage/RER</td>
</tr>
<tr>
<td>CH = Switzerland.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.4. Impact assessment results for both systems

Cette évaluation d’impact a été réalisée avec des valeurs normalisées en utilisant la méthode IMPACT 2002+ avec les catégories de ‘mid-point’. Dans le scénario classique, Fig. 7, l’évaluation de l’impact a été évaluée pour deux taux différents de recyclage du plomb afin d’illustrer l’effet du recyclage, car les batteries représentent une partie la plus importante dans les deux cas. La contribution des convertisseurs est relativement faible (7 à 8%). Bien que les modules PV partagent une partie de l’impact (24-29%), ce sont les batteries qui contribuent le plus à l’impact global du système sur son cycle de vie (47-55% de l’impact global).
Fig. 1: Impacts normalisées par les catégories de mid-point.

Le résultat de l’évaluation pour la solution de réutilisation est illustré à la Fig. 8. L’impact associé aux PSUs, UPSs et la carte de microcontrôleur reste toujours très faible (0,12%). Néanmoins, l’impact de la réutilisation de batteries au plomb est assez important (33%) à cause de la nécessité de les remplacer fréquemment.

La comparaison des impacts environnementaux des deux scénarios présentée à la Fig. 9 montre une réduction de 40% des dommages environnementaux obtenus dans la solution de réutilisation.

2.5. Analyse de sensibilité

Les résultats positifs pour la réutilisation reposent en partie sur certaines hypothèses, interpolations ou extrapolations en raison du manque de données. Pour tester la fiabilité des
résultats, une analyse de sensibilité a été réalisée en faisant varier les paramètres et observant les effets associés sur les résultats.

Le tableau 7 illustre l’impact global de la solution de réutilisation pour une variation de 10% des paramètres choisis en conservant les paramètres de système conventionnels comme références. Influence de variation des distances de transport pour les deux scénarios est présenté dans le tableau 8.

Tableau 7: Influence de variation des paramètres sur l’impact de la solution de réutilisation.

<table>
<thead>
<tr>
<th>Catégories</th>
<th>Rendement des PSU/UPS</th>
<th>Rendement des batteries</th>
<th>Durée de vie de batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-10%</td>
<td>+10%</td>
<td>-10%</td>
</tr>
<tr>
<td>Carcinogens</td>
<td>+29.52 %</td>
<td>-20.33 %</td>
<td>+15.57 %</td>
</tr>
<tr>
<td>Non-carcinogens</td>
<td>+26.90 %</td>
<td>-18.73 %</td>
<td>+12.93 %</td>
</tr>
<tr>
<td>Respiratory inorganics</td>
<td>+22.69 %</td>
<td>-16.2 %</td>
<td>+8.6 %</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>+24.15 %</td>
<td>-17.08 %</td>
<td>+10.11 %</td>
</tr>
<tr>
<td>Global warming</td>
<td>+26.12 %</td>
<td>-18.27 %</td>
<td>+12.09 %</td>
</tr>
<tr>
<td>Non-renewable energy</td>
<td>+26.40 %</td>
<td>-18.44 %</td>
<td>+12.38 %</td>
</tr>
</tbody>
</table>

Les efficacités du convertisseur sont les paramètres les plus sensibles. Cet effet est deux fois supérieur à l'efficacité de la batterie et environ 8 fois supérieur à celui de la durée de vie de la batterie. La durée de vie des piles peut également avoir un impact considérable sur le résultat, car les piles partagent l’impact important de la potion. Cependant, le changement profitera probablement davantage à la solution de réutilisation qu’à la solution classique. Par conséquence, le résultat démontre que les impacts environnementaux de la solution de réutilisation restent plus faibles, même dans l'hypothèse la plus prudente.
Tableau 8: Influence de variation des distances de transport sur l'impact de la solution de réutilisation et de la solution classique.

<table>
<thead>
<tr>
<th>Catégories</th>
<th>Solution classique</th>
<th>Solution de réutilisation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-10% distance</td>
<td>+10% distance</td>
</tr>
<tr>
<td></td>
<td>-10% distance</td>
<td>+10% distance</td>
</tr>
<tr>
<td>Carcinogens</td>
<td>-0.17 %</td>
<td>+0.17 %</td>
</tr>
<tr>
<td>Non-carcinogens</td>
<td>-0.09 %</td>
<td>+0.09 %</td>
</tr>
<tr>
<td>Respiratory inorganics</td>
<td>-2.17 %</td>
<td>+2.17 %</td>
</tr>
<tr>
<td>Terrestrial eco-toxicity</td>
<td>-0.88 %</td>
<td>+0.88 %</td>
</tr>
<tr>
<td>Global warming</td>
<td>-1.41 %</td>
<td>+1.41 %</td>
</tr>
<tr>
<td>Non-renewable energy</td>
<td>-1.17 %</td>
<td>+1.17 %</td>
</tr>
</tbody>
</table>

3. Réutilisation des PSUs dans le système photovoltaïque

Les blocs d'alimentation (PSU) contiennent généralement des convertisseurs continu-continu abaissieur. Ils peuvent être utilisés dans un système de stockage de batteries ou dans des charges continues à basse tension. Par exemple, dans un système photovoltaïque, les panneaux solaires doivent être associés pour obtenir la tension d’entrée requise du convertisseur principal de l’alimentation. Le convertisseur de PSU peut être programmé en tant que contrôleur MPPT pour les batteries utilisant la programmation du microcontrôleur. L’exemple du système de production photovoltaïque basé sur les PSUs réutilisés est illustré à la Fig. 10.

![Fig. 10: Système photovoltaïque basé sur les PSUs réutilisés.](image)

3.1. Structure générale des PSUs

L’alimentation de l’ordinateur est en général un type de convertisseur alternatif-continu fonctionnant à partir de la ligne alternative. Les alimentations à découpage dans les appareils modernes utilisent principalement un convertisseur continu-continu isolé. La Fig. 11 montre le schéma simplifié des alimentations à découpage isolées.

PSUs emploient certain nombre de type de convertisseurs continu-continu isolés, notamment ‘Flyback’, ‘Forward’, ‘Push-pull’, half bridge’ et ‘full bridge’. Les convertisseurs Forward sont couramment utilisés pour les applications de puissance moyenne en raison de la simplicité de leurs circuits, leur rendement élevé et leur fiabilité.

Le convertisseur Forward peut être classé par les différences de techniques de démagnétisation de transformateur. La technique du convertisseur Forward classique consiste à réinitialiser le flux magnétique en renvoyant l’énergie magnétisante à la source d'entrée via
un troisième enroulement de transformateur. La technique de démagnétisation basée sur le circuit RCD est illustrée à la Fig. 12 (A). La dernière adaptation de la technique consiste à remplacer la diode par un transistor MOSFET, appelé technique de ‘active clamp’ (Fig. 12 (B)).

![Diagram](image)

Fig. 11: Schéma simplifié des alimentations à découpage isolées.

![Diagram](image)

Fig. 12: Types de convertisseur Forward: (A) RCD clamp; (B) active clamp.

Il existe deux méthodes principales pour la régulation des sorties du convertisseur. Dans le contrôle en mode tension, seule la tension de sortie est mesurée pour le retour. Le contrôle en mode tension est généralement mis en œuvre avec des circuits intégrés telles que TL494, NE5560 et SG3524, qui étaient populaires dans les premiers ordinateurs. Le contrôle en mode courant consiste une boucle de courant interne en plus de la boucle de tension. Le but de cette boucle interne est de forcer le courant de l’inductance à suivre un signal de référence fourni par la boucle de tension. Le contrôle en mode courant a un temps de réponse rapide des entrées et des sorties et une protection inhérente contre les surintensités. Les contrôleurs UC3842 ou UC3843 sont généralement utilisés dans les convertisseurs Forward pour le contrôle en mode courant.

Comme la plupart des PSUs sont conformes à la conception de la carte mère ATX, il existe de nombreuses fonctionnalités communes aux différents modèles et fabricants. Les blocs d'alimentation Dell H305P-00 (305W) ont été sélectionnés pour l'étude des étapes de modification et de transformation pour la réutilisation dans un système de génération photovoltaïque. Le contrôleur est le circuit intégré de commande en mode courant UC3843. Le schéma fonctionnel du convertisseur principal détaillé à la Fig. 13.

3.2. Méthodes de modification de PSUs
La principale fonction d'un PSU est de générer des tensions continues régulées nécessaires à partir d'une source d'entrée de quelques centaines de volts. Dans les systèmes de production d'énergie renouvelable, les fonctions principales des convertisseurs ne consistent pas seulement à réguler la tension ou le courant, mais également à optimiser la conversion de puissance des sources aux charges ou aux dispositifs de stockage.

Le contrôleur original du PSU ne peut pas gérer tous les contrôles et fonctionnalités nécessaires à l’application d'énergie renouvelable. Normalement, un contrôleur externe serait nécessaire pour telle application. Il est également plus flexible d'implémenter toutes les systèmes de contrôle globaux dans le contrôleur externe.

- Des circuits de sécurité du PSU

La première étape de modification de PSU consiste à isoler le convertisseur principal de toute limitation imposée par leurs fonctionnalités d'origine. Cette limitation est généralement mise en œuvre avec des circuits de surveillance qui détectent les tensions de sortie de l’alimentation et communiquent avec la carte mère de l’ordinateur.

- 'Sub-harmonic oscillation'

Lorsque la tension d'entrée continue de l'alimentation principale est inférieure au seuil de tension prédéfini, qui est d'environ 120V pour H305P-00, le contrôleur est désactivé. Cela empêche l'alimentation de fonctionner à la valeur critique du rapport cyclique. Au-dessus d'un certain seuil de rapport cyclique, le convertisseur qui utilise le contrôle en mode courant devient instable. Cette instabilité peut causer des dommages irréversibles à l’alimentation.

Le problème peut être évité en limitant le rapport cyclique maximal du convertisseur. Cette limitation est posé par le phénomène 'sub-harmonic oscillation', qui se produit lorsque le courant d'inductance ne revient pas à sa valeur initiale au début du prochain cycle de commutation comme démontré dans la Fig. 14.
Entrée = 140V.

Entrée < 120V.

Fig. 14: Signal de MLI à (a) Entrée = 140V; (b) Entrée < 120V (sub-harmonic oscillation).

- Réduction de la plage de tension d’entrée en utilisant le point milieu de l’enroulement primaire

En condition normale, tension d’entrée continue de PSU peut atteindre de 250V à 350V. Il y a certaines solutions possibles pour réduire cette plage de tension d’entrée quand c’est nécessaire. Une solution simple consiste à modifier la bobine primaire du transformateur si elle possède une troisième broche de point milieu qui n’est pas utilisée mais qui est accessible. Le résultat expérimental obtenu avec cette solution est illustrée à la Fig. 15.

Fig. 15: Caractéristique de régulation de tension de sortie de H305P-00 à différentes tensions d’entrée.

- Le contrôle de sortie par le contrôleur de la carte de PSU

La modification ne portera que sur cette sortie de +12V comme il fournit la puissance la plus significative et, plus important encore, le niveau de tension utilisable. La représentation du
système de contrôle de l'alimentation est illustrée à la Fig. 16. La régulation des sorties 12V et 5V est gérée par l'utilisation d'une inductance couplée. Les résistances R416, R417 et R418 et la tension de référence interne du TL431 définissent la tension de sortie du convertisseur.

![Diagramme du système de contrôle de tension de sortie de H305P-00.](image)

Fig. 16: Le schéma simplifié de système de contrôle de tension de sortie de H305P-00.

L'une des solutions pour contrôler la tension de sortie consiste à modifier indirectement la référence à partir d'un signal externe. Cette méthode est montrée dans la Fig. 17. Pour contrôler la tension de sortie, un signal d'entrée $V_1$ est appliqué à la broche de référence de TL431 en passant par $R_2$. Ce signal modifiera effectivement la tension de référence de la boucle de tension. L'équation obtenue en régime permanent est défini par:

$$
(1 + \frac{R_{418}}{R_1} + \frac{R_{418}}{R_2})V_{ref} = \frac{R_{418}}{R_1}V_0 + \frac{R_{418}}{R_2}V_1
$$

![Diagramme modifiant le système de contrôle de tension de sortie.](image)

Fig. 17: La modification de système de contrôle de tension de sortie.
Si $R_1=R_2=10\,\text{K}\Omega$, l’équation (1) devient $V_0 = 15.42 - V_1$ (2). Le même procédé appliqué pour le contrôle de la tension est également possible pour le contrôle du courant de sortie, comme indiqué sur la Fig. 18. Le signal $V_i$ servira à modifier la valeur de référence de contrôle.

La stabilité et les performances des méthodes proposées sont testées avec les simulations et tests expérimentaux. Les résultats des expérimentations avec une charge résistive ($3\,\Omega$) et une charge inductive (rotor de l’alternateur) sont illustrés à la Fig. 19.

Fig. 18: La modification de système de contrôle pour l’asservissement de courant de sortie.

Fig. 19: Relation entre le courant de sortie ($I_o$) et la tension de référence $V_i$ en régime établi pour une charge résistive et une charge inductive.

### 3.3. Régulateur de charge MPPT basé sur les PSUs

Pour démontrer sa faisabilité, le PSU est modifié et transformé en un contrôleur MPPT pour le générateur photovoltaïque. Un petit système solaire de 120W est mis en œuvre. La sortie du PSU est connectée à une batterie au plomb de 12V, 44Ah et à une charge résistive. La commande MPPT est réalisée dans une carte de microcontrôleur (Arduino Due). L’installation de test expérimental est illustrée à la Fig. 20.
Fig. 20: Installation du contrôleur MPPT pour le générateur photovoltaïque.

Les deux techniques MPPT les plus utilisées dans le système photovoltaïque, Perturb and Observe (P&O) et Conductance Incrémental (CI), ont été sélectionnées pour cette expérience. Les paramètres utilisés pour les méthodes P&O et CI dans cet essai sont les suivants: période d'échantillonnage $T_a = 0,02s$ et incrément du rapport cyclique $\Delta \alpha = 0,01$. La période d'échantillonnage des algorithmes ($T_a$) est choisie en fonction du temps de réponse de la tension d’entrée indiqué à la Fig. 21.

La courbe PV expérimentale du panneau solaire représente un point de puissance maximale situé autour de tension de sortie de 75V à 80V. Les performances du contrôle MPPT ont été testées pour les changements de charge et le changement d'intensité de la lumière. Les résultats de l'algorithme CI sont présentés à la Fig. 22. Le rendement du contrôle MPPT basé sur PSU est également comparé à celles d'un module MPPT du marché.

Fig. 21: La réponse de la tension d’entrée pour l’échelon du rapport cyclique.
Fig. 22: La réponse de la tension de sortie du panneau solaire en échelon de charge et d'éclairements du soleil.

4. Nouvelle structure d'un générateur monophasé autonome basé sur une machine asynchrone triphasée

Traditionnellement, les générateurs synchrones ont été utilisés pour la production d'électricité. Cependant, au cours des dernières années, les générateurs asynchrones ont acquis un grand intérêt en raison de leurs avantages par rapport aux générateurs synchrones dans les systèmes d'énergie éolienne et d’hydrogénation dans des zones isolées.

Bien que la plupart des systèmes électriques autonomes reposent sur des réseaux monophasés, l'utilisation d’une machine asynchrone monophasée est limitée à des puissances relativement faibles. Aux puissances supérieures à 3 kW, les générateurs asynchrones triphasés sont préférés aux générateurs monophasés en raison de leurs avantages en termes de poids, coût et disponibilité. Le fonctionnement des machines asynchrones auto-excitées triphasées en tant que générateur monophasé autonome avec source d'excitation fixe a été largement étudié. Cependant, les machines asynchrones auto-excitées ne conviennent que pour le fonctionnement à vitesse fixe. Les performances optimales dans des conditions de vitesse et de charge variables peuvent être obtenues en utilisant un étage de conversion intermédiaire en courant continu. Cette méthode augmente la complexité du système et introduit des coûts supplémentaires en raison de l'utilisation de deux étages de convertisseurs.

Une nouvelle configuration d'un générateur monophasé basé sur une machine asynchrone triphasée et un seul convertisseur a été récemment proposée. Cette technique utilise une configuration d'enroulement de stator appelée TSCAOI où l'un des trois enroulements est utilisé pour l'excitation. Les deux enroulements restants, connectés en série, fournissent la tension de sortie monophasée. L'excitation du générateur est donnée par un système de stockage de batterie et un onduleur monophasé.
Fig. 23: Nouvelle configuration d'un générateur monophasé basé sur une machine asynchrone triphasée (OIATI).

Cette étude proposait une version modifiée de la topologie TSACOI, appelée OIATI, dans laquelle deux enroulements seraient alimentés séparément par deux onduleurs pour l'excitation, et l'enroulement restant étant connecté à un condensateur et à la charge comme illustrée à la Fig. 23. Les études par simulation et expérimentation de la configuration proposée du générateur en boucle ouverte sont présentés à l'aide d'un générateur asynchrone de 1,5 kW, 4 pôles. Les paramètres du circuit équivalent du générateur (référs au stator) sont les suivants: les résistances du stator et du rotor sont respectivement de 3,84Ω et 3,94Ω, et les inductances de fuite stator et rotor sont égales à 0,025H. L'inductance de magnétisation de la machine est estimée à 0,388H.

4.1. Les études par simulation en régime permanent

Pour évaluer les performances de la configuration proposée, les modèles de simulation sont réalisés dans le logiciel PSIM. Le système peut être entraîné par un bloc à vitesse constante ou à puissance constante connecté à son arbre. Il convient de noter que si le moment d'inertie est suffisamment élevé, le générateur tournera à une vitesse presque constante lorsqu'il sera entraîné par un bloc à puissance constante. Les sources d'excitation $Ve1$ et $Ve2$ sont simulées à l'aide de sources de tension sinusoïdales idéales à 50Hz. La tension de sortie nominale est de 220Vrms.

- **Choix du condensateur de sortie**

Le condensateur peut aider à augmenter la tension de sortie du générateur. Cependant, cela a également un effet sur le courant de bobinage en raison de la consommation de puissance réactive. Un condensateur plus grand fournit plus de puissance réactive au générateur, réduisant ainsi les puissances réactives fournies par les enroulements d'entrée. Cela entraîne une augmentation du courant dans l'enroulement de sortie et une réduction des courants dans les enroulements d'entrée. La taille du condensateur peut être choisie pour minimiser tous les courants d'enroulement en équilibrant la puissance réactive absorbée à chaque enroulement du générateur.

- **Plage de vitesse de fonctionnement**

- 18 -
Etant donné que la machine asynchrone génère une puissance active à la vitesse supérieure à la vitesse synchrone, la région opérationnelle peut être définie par la plage de vitesse située au-dessus de la vitesse synchrone et inférieure à certaine vitesse définie par des contraintes électriques, thermiques et mécaniques. Les résultats en régime établi pour une charge de 50W et une charge normale de 500W sont illustrés à la Fig. 24. Dans cette simulation, le générateur est entraîné à une vitesse de rotation fixe qui varie entre 1460 et 1660 tr/min. La tension de sortie ($V_s$) est maintenue à 220Vrms en ajustant les tensions de sources d'excitation. Le condensateur d'excitation pour la phase de sortie est $C = 30\mu F$.

![Graphique illustrant la variation de puissance active et réactive avec la vitesse de rotation](image)

Fig. 24: Puissance active et réactive absorbée par les enroulements d'excitation ($P_e; Q_e$) vs. vitesse de rotation (tr/min).

Par la simulation, la plage de vitesse de fonctionnement peut être limitée à des vitesses de rotation comprise entre 1500 et 1580 tr/min si les courants de bobinage sont limités à 4,5A.

- **L'effet de déphase entre les entrées d’excitation**

Dans un générateur asynchrone triphasé, des performances optimales peuvent être obtenues si les courants dans les enroulements sont équilibrés. Comme seulement deux phases sont alimentées par des sources de tension sinusoidales dans la configuration OIATI, le générateur ne fonctionne pas nécessairement dans des conditions équilibrées. L'effet du déphasage des deux sources d'excitation ($V_{e1}, V_{e2}$) sur les courants d'enroulement du générateur est illustré à la Fig. 25. Dans ce cas, le condensateur d'excitation pour la phase de sortie est $C = 30\mu F$. La tension de sortie ($V_s$) est maintenue à 220Vrms fournissant une charge résistive de 500W ($RL = 96.8\Omega$). Le générateur est entraîné par une charge mécanique à puissance constante.

Le déphasage optimal qui minimise la somme de tous les courants d’enroulement ($I_{e1}+I_{e2}+I_{sc}$) est observé entre 120° et 130°. Cela correspond également à une ondulation minimale de couple. On obtient le résultat similaire quand le générateur fonctionne à une vitesse de rotation constante.
Fig. 25: L'effet de déphase entre les entrées d'excitation sur les courants d'enroulement.

- **Comparaison de la configuration OIATI et TSCAOI**

Dans les deux configurations, la fluctuation de couple peut être observée en raison du déséquilibre des courants de stator. Cependant, dans la configuration proposée (OIATI), la pulsation du couple mécanique est beaucoup plus faible que celle du TSCAOI lorsque la différence de phase des sources d'excitation est de 120° à 130°.

Les caractéristiques de courants du stator du générateur en fonction de la puissance de sortie dans la configuration OIATI et TSCAOI sont illustrées à la Fig. 26. On peut noter que dans le cas de TSCAOI, l'intensité du courant augmente plus rapidement. À partir d'un certain niveau de puissance de sortie (pour une valeur de condensateur donnée), la topologie OIATI est meilleure que la topologie TSCAOI sur l'optimisation des courants de stator et des tensions d'excitation.

Fig. 26: Les caractéristiques de courants du stator du générateur en fonction de la puissance de sortie dans la configuration OIATI (le1) et TSCAOI (le).
4.2. Résultats expérimentaux

Pour valider les études en simulation, le test expérimental a été réalisé avec un générateur asynchrone triphasé de 1,5 kW, 4 pôles, et 220/380V. Son arbre est connecté à un autre moteur asynchrone dont la vitesse est contrôlée par un variateur de vitesse. En raison de la limitation du variateur, le générateur fonctionne toujours à une vitesse de rotation constante. La tension de sortie normale est de 100Vrms à 50Hz. Les résultats expérimentaux et simulés pour la configuration OIATI sont illustrés aux Fig. 27 et Fig. 28. Les tests expérimentaux confirment également que la différence de phase optimale se situe entre 120 ° et 130 °.

Le résultat expérimental de la comparaison de la configuration OIATI et TSCAOI est présenté aux Fig. 29 et Fig. 30. En plus des fluctuations de couple moins importantes, l'expérience montre également que la topologie OIATI est plus efficace que TSCAOI.

Fig. 27: Les résultats expérimentaux et simulés pour la configuration OIATI.

Fig. 28: Les résultats expérimentaux et simulés pour la configuration OIATI.
5. Conclusion

Un nouveau concept de système hybride solaire-hydroélectrique utilisant des composants de récupération, notamment des blocs d'alimentation de PC, des module d’ASI, des moteurs asynchrone triphasé et des batteries de voiture, a été proposé comme solution immédiate pour l'électrification rurale. La solution proposée peut également contribuer à résoudre le problème croissant des déchets électroniques en raison de l’expansion rapide du développement technologique et de la demande des consommateurs.

La thèse portait sur les aspects environnementaux et technologiques de la solution. L'évaluation environnementale a été réalisée en comparant les impacts d'une solution conventionnelle et ceux de la solution de réutilisation à l'aide de la méthodologie ACV. Les problèmes technologiques ont été traités en deux parties. Le premier volet technologique de la réutilisation a été axé sur les processus de modifier le fonctionnement des blocs d'alimentation usés qui sont les composants principaux dans le système de générateur.
photovoltaïque. La deuxième partie abordait une nouvelle topologie de génératrice basée sur les moteurs asynchrone utilisés dans les centrales pico-hydro.

La méthodologie ACV a été utilisée pour comparer l'impact du cycle de vie de la solution basée sur la réutilisation à celui de la solution conventionnelle basée sur des composants neufs. Pour atteindre cet objectif, le dimensionnement des deux solutions a été déterminé sur la base d'un objectif commun définie en satisfaisant les besoins énergétiques quotidiens d'un village rural pour la même durée de vie. Les données d’inventaire ont été recueillies à partir de la base de données EcoInvent et des études bibliographiques. Le résultat de l'évaluation s'est avéré être une réduction significative (environ 40%) de la charge environnementale pour la solution de réutilisation. L'analyse de sensibilité a été faite pour tester la fiabilité du résultat en observant les effets de certains paramètres incertains. Il a démontré que la solution de réutilisation est toujours préférée, même dans le pire des cas, en raison de la contribution des batteries dans la solution conventionnelle.

La conception générale et les techniques permettant d'identifier les problèmes et de modifier la structure des blocs d'alimentation de PC afin qu'elles fonctionnent comme un convertisseur à usage général ont été présentées. La technique de modification implique le retrait d'un certain nombre de composants. Quelques connecteurs, résistances et drivers de MOSFET sont également requis en tant qu'interface entre les PSUs et le contrôleur externe. Les PSUs ont été modifiées pour l’asservissement de tension et de courant de sortie sans le contrôleur externe. Pour l’application dans le générateur photovoltaïque, les contrôleurs des PSUs ne sont pas nécessaires. Un contrôleur externe est requis pour mettre en œuvre des tous les régulations et optimisations. Les performances du contrôleur MPPT basé sur le PSU modifié ont été comparées à celles d'un convertisseur MPPT du marché, dont le rendement était comparable.

Une nouvelle configuration de générateur monophasé autonome basé sur la machine asynchrone triphasé a été introduite dans cette thèse comme alternative à une topologie TSCAOI qui est récemment proposée. Cette thèse a proposé et étudié une nouvelle technique d’excitation variable qui utilise une configuration OIATI, dans laquelle deux enroulements sont alimentés séparément par deux sources d’excitation et l’enroulement restant est connecté à la charge et un condensateur. Un modèle mathématique de la topologie de générateur proposée a été développé à l’aide d'un modèle classique de machine à induction. Les tests de laboratoire effectués avec une machine de 1,5 kW dans les mêmes conditions de test ont permis de vérifier la fiabilité du modèle. Par rapport à la configuration TSCAOI, la condition de générateur dans la configuration OIATI est plus proche de la condition équilibrée. Par conséquent, la configuration OIATI introduit moins de vibrations mécaniques et est plus efficace. Aussi, à partir d'une certaine puissance de sortie (pour une valeur de condensateur donnée), la topologie OIATI est meilleure que la topologie TSCAOI en termes d’optimisation des courants du stator. Le principal inconvénient de la topologie proposée est l'utilisation de deux enroulements pour l'excitation, ce qui augmente le nombre de composants de puissance requis et le coût du système. La perte est également plus importante à cause de l'utilisation de deux onduleurs pour l’excitation.