Cape Peninsula
University of Technology

MODELLING OF HYBRID SOLAR WIND INTEGRATED GENERATION SYSTEMS IN AN ELECTRICAL DISTRIBUTION NETWORK

by

DOUDOU NANITAMO LUTA

Thesis submitted in fulfilment of the requirements for the degree

Master of Technology: Electrical Engineering

in the Faculty of Engineering

at the Cape Peninsula University of Technology

Supervisor: Dr. W. Fritz
Co-supervisor: Dr. A.K.Raji

Bellville Campus
September 2014

DECLARATION

I, Doudou Nanitamo Luta, declare that the content of this thesis represents my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed **Date**

ABSTRACT

The research in this thesis deals with the application of Model Based Systems Engineering (MBSE) practices in the modelling of power systems. More particularly, we have presented the modelling hybrid photovoltaic wind integrated in an electrical distribution network using SysML (System Modelling Language) which is a modelling language in support of MBSE. MBSE refers to a formalised practice of systems development through the application of modelling principles, methods, languages and tools to the entire lifecycle of a system.

Generally speaking, the modelling of power systems is performed using software such as Matlab Simulink, DigSilent, PowerWorld etc. These software programs allow modelling of a system considering only a specific viewpoint, depending on the objective that is to be assessed.

The advantage of the SysML over the above mentioned modelling languages lies from the fact that SysML includes different viewpoints of a system. These views are known as the Four Pillars of SysML. Pillar One refers to the requirements of a system and includes all the functional and non-functional requirements. Pillar Two deals with the structure representation of a system by considering all its subsystems and their different connections. Pillar Three considers the behaviour of a system and includes its activities, sequences and different states. The last Pillar includes the detailed characteristics, physical laws and constraints on the system.

The main objectives of this research are the development of models which will include: the system's requirements; the system's structure representation in term of different entities involved and the relationship between them; the system's behaviours in terms of activities in different cases considered and transitions from one state to another as well as the interaction between the system and all the stakeholders.

Keywords: Model Based Systems Engineering (MBSE), System Modelling Language (SysML), Renewable Energy systems, Hybrid power systems, photovoltaic systems, wind power systems.

ACKNOWLEDGEMENTS

First of all, I would like to acknowledge the Almighty God for providing everything I needed and giving me the strength and ability to complete this thesis.

My sincere thanks to Dr Wilfred Fritz and Dr Atanda K. Raji from the Cape Peninsula University of Technology for their supervision, advice, understanding, support and encouragement during the completion of this thesis. It has truly been a great privilege to conduct this research under their supervision.

A particular word of thanks to my brother Dr Blaise Ndandu as well as all the members of my family for all the support and the confidence that he has always had in me.

I would also like to express my sincere acknowledgement to my colleagues and friends at the Centre for Distributed Power and Electronics Systems at the Cape Peninsula University of Technology for their advice and support during this research. May they through these few lines receive my sincere gratitude.

Lastly, I would like to acknowledge the financial assistance of the University Research Foundation towards this research.

DEDICATION

This thesis is dedicated to those who are dear to me, more particularly to my mother Marie Nzonza and my father Antoine Mfulu Zowa.

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GLOSSARY

OMG:	Organisation Management Group
SysML	System Modeling Language
DC	Direct Current
AC	Alternative Current
GW	Giga Watt
INCOSE	International Council Of System Engineering
UML	Unified Modeling Language
PV	Photovoltaic
CO_2	Carbon Dioxide
MW	Mega Watt
OPEC	Organisation of Petroleum Exporting Countries
HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine
BDD	Block Definition Diagram
IBD	Internal Block Diagram
HPVWS	Hybrid Photovoltaic Wind System
EDS	Electrical Distribution System
WRIG	Wound Rotor Induction Generator
WRSG	Wound Rotor Synchronous Generator
DFIG	Double Fed Induction Generator
PMSG	Permanent Magnetic Synchronous Generator
PMWG	Permanent Magnetic Wind Generator
V_{cut-in}	Cut-in wind speed
$V_{cut-off}$	Cut-off wind speed
V_{rated}	Rated wind speed
DG	Distributed Generator
PCC	Point of Common Coupling
STC	Standards Test Conditions
I_{SC}	Short Circuit Current
V_{OC}	Open Circuit Voltage
V_{mp}	Voltage at Maximum Power Point
I_{mp}	Current at Maximum Power point
kg	kilogram
kW	kilo Watt
P_v	Power of the wind
P_t	Power of the wind turbine

λ	tip speed ratio of the wind turbine
α	Wind turbine pitch angle
$C_p(\lambda,\alpha)$	Wind turbine power coefficient
$C_q(\lambda,\alpha)$	Wind turbine torque coefficient
R	Radius
V_v	Wind speed
Cu_2S/CdS	Cadmium Sulphide/Copper Sulphide
ρ	Air density
I_{photo}	Photo current
I_o	Diode saturation current
q	Elementary charge
R_s	Series resistance
K	Boltzmann constant
T	Absolute temperature
R_p	Parallel resistance
E	Irradiance
I_{Rp}	Current of parallel resistor
V_{br}	Breakdown voltage
a	Avalanche factor
m	Avalanche exponent

CHAPTER ONE
GENERAL INTRODUCTION

1.1 Introduction

Energy is one of the key elements for the growth of a country. Of all the different types of energy, electrical energy represents one of the most important types. Starting from communication technology, transportation, food processing, lighting, storage, industrial applications and others, all around the world at any time, we need electrical energy. In order to use that electrical energy, it must first be generated. Electrical energy generation is based on different types of primary energy. Frequently used primary energies are: fossil fuels for thermal power plants; nuclear fission for nuclear power stations; water for hydropower stations; and other alternative generating systems, such as wind power systems, photovoltaic systems, biomass, fuel cell, geothermal, etc.

As shown in Figure 1.1, fossil fuels which include gas, oil and coal represent the largest primary sources used in the world for electrical energy generation and this trend is not expected to change by 2030. The common problem for all fossil fuels is the fact that they create carbon dioxide which is a greenhouse gas. The increase of greenhouse gases has a serious negative environmental impact such as climate change, ozone depletion, acid rain, global warming, loss of biodiversity, etc. Table 1.1 shows the evolution and the projection of world energy related carbon dioxide emission by fuel types over the period 1990 – 2030. These different values in the table are expressed in billion metric tons which is equivalent to 10^{10} times p/kg. Additionally, there are concerns about the finite nature of fossil fuels; it is commonly accepted that one day in future, the world reserves of fossil fuels will be exhausted. Therefore, it is important to think of other alternative energy sources to replace fossil fuels.

Another energy source mostly used as primary energy for electrical energy generation is nuclear energy (nuclear power stations) which represents, after fossil fuels, the second largest primary energy source used for electrical energy generation (Figure1.1). Nuclear energy is an important source for electrical energy generation in many countries around the world. Unlike fossil fuels, nuclear energy does not generate carbon dioxide that contributes to global warming. However nuclear energy presents two major concerns. The first one is related to the safety of a nuclear power plant. Nuclear power plants present risks to society due to the use of radioactive materials (uranium). In case of an accident in the nuclear reactor, the radioactivity can spread, attack and change the basic biological structures in human, animal and plants species. The second concern is the waste management which constitutes a serious problem for environmentalists. Furthermore, nuclear energy (uranium) is not renewable.

Hydropower stations are one of the alternatives to fossil fuels and nuclear energy. They do not have a negative impact on the environment and the water used as primary energy is renewable. The main disadvantage of these generating systems is the fact that it is difficult to supply the world electricity demand with these systems, for instance in developed countries, the available hydropower potential has largely been used. In addition, hydropower generating systems require long transmission power lines for the transport of electrical energy to the load, hence the increase of cost and the complexity of the system.

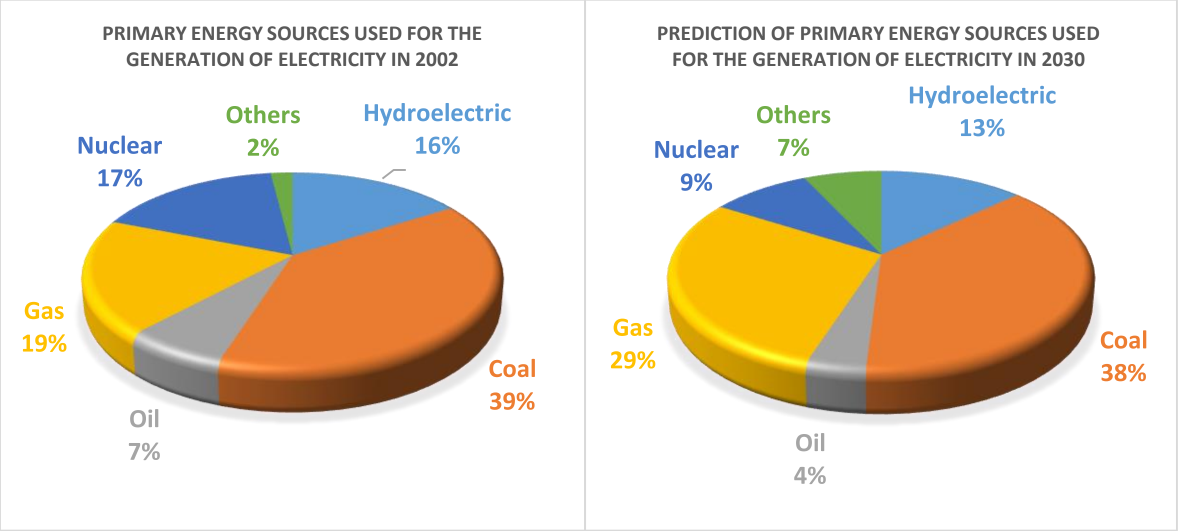


Figure 1.1 Primary energy sources for electrical energy generation (Nersesian, 2010)

Table 1.1 Billion Metric tons of carbon dioxide emission from different fuels (Watson, 2009)

Year	Liquids	Natural gas	coal	Total
1990	9.0	4.0	8.3	21.2
1995	9.3	4.3	8.2	21.8
2000	10.1	4.8	8.7	23.6
2005	11.0	5.7	11.4	28.1
2006	11.2	5.8	11.7	28.6
2007	11.3	6.0	12.0	29.3
2008	11.4	6.1	12.3	29.9
2009	11.6	6.2	12.7	30.5
2010	11.7	6.3	13.0	31.1
2015	12.6	7.1	14.7	34.3
2020	13.3	7.8	15.9	37.0
2025	14.0	8.2	17.3	39.6
2026	14.2	8.3	17.6	40.1
2027	14.4	8.4	17.9	40.7
2028	14.5	8.5	18.2	41.2
2029	14.7	8.6	18.5	41.8
2030	14.9	8.7	18.8	42.3

Presently, as mentioned earlier, the world electrical energy generation is dominated by conventional energy technologies (thermal power, nuclear power and hydropower stations). However, other electrical energy generation technologies exist using renewable energy as primary energy which do not present concerns as is the case for most conventional electrical generation technology. Renewable energy presents the advantages of being less harmful to the environment.Table1.2 shows the potential environmental impact for the different electrical energy generating technologies. Moreover renewable energy is the type of energy which is never-ending; as long as the sun shines, renewable energy will still exist. Thus far the generation of electrical energy using these types of energy is still very modest, firstly because of the expensive generating cost and secondly because most renewable energy is uncontrollable.

Table 1.2 Potential environmental impact of electricity generating technologies

Renewables: solar, wind, geothermal, biomass	Hydroelectric	Fossil	Nuclear
Air quality degradation (geothermal, biomass), extensive air used, ecosystem changes, fabrication impact (solar photovoltaic cells), noise pollution (wind).	Population displacement, lake loss and change in use, health effects and ecosystem changes, loss of biodiversity, dam failure, decommissioning.	Global climate change, air quality degradation (coal and oil), lake acidification and forest damage (coil and oil), toxic waste contamination (coal ash and slag, abatement residues), ground water contamination, marine and costal pollution (oil), land disturbance Large fuel and transportation requirement, resource depletion	Severe reactor accident release, waste repertory release

1.2 Background and awareness of the problem research

In order to solve some of the problems the world is facing such as environment destruction and global warming caused generally by the use of fossil fuels, the increasing world electricity demand and the exhaustion of the conventional energy sources, many countries around the world are now focusing on other natural energy sources for the generation of electricity. These sources known as renewable energy sources provide the opportunity to cover the world energy demand sustainably that is to say with very little negative influence on health and nature. As time progresses, the electricity generated using renewable energy sources is becoming more significant and currently seems to be the type of electrical energy generation in parity with durable development. Among these renewable energy sources, wind and solar power generation are two of the most promising renewable energy technologies. After hydropower generation, wind and solar generation are generating significant interest. According to Tong (2010:3), in 2009 the global annual installed wind generation capacity reached a record-breaking 37 GW, bringing the world total wind capacity to 158 GW. As the most promising renewable, clean, and reliable energy source, wind power is expected to be widely used in power generation in the coming decades. On the other hand, Krauter (2006) reports that according to the European Commission of Energy, the world could be getting a quarter of its electricity from solar power by 2050.

However, there are some concerns common to solar and wind powers, namely their variable nature and dependence on nature and weather conditions. These factors lead to an unpredictable electrical power output which may not match with the time distribution of load demand. In order to overcome this concern, these two energy sources are being put together in a proper combination as a hybrid power generation system, using the strengths of one source to overcome the weakness of the other. Hybrid solar wind has become a viable option and presents some advantages over conventional power systems in terms of their cleanliness and infinite availability.

In the past, hybrid solar wind systems have been considered suitable for remote systems application such as radio telecommunication, satellite ground stations and sites far from conventional power lines. Today, they are operating as grid-connected, thus breaking the traditional path of power flow in power systems and increasing its complexity. In addition, the main function of power systems is to supply power to the consumers without outage or fluctuation. However, due to the variable nature of solar and wind, hybrid system solar wind can produce uncertain power output and cause unbalanced power system operation. In order to analyse and understand the complexity of this system and predict its overall behaviour, it is important to model it.

1.3 Statement of the research problem

Modelling is very fundamental in any engineering discipline (Dzimano, 2008). According to Holt and Perry (2008), most system disasters are caused by system complexity, lack of understanding and communication issues. Modelling a system before its implementation allows a better understanding of its operation and it is also a good way of dealing with and understanding its complexity.

The design of a hybrid solar wind integrated generation system in an electrical distribution network is a complex process due to the fact that it involves different areas of engineering such as mechanical, electrical and electronics engineering. Each of these areas uses its own methodologies and development tools which makes the collaboration between team members of these different areas and the understanding of each part of the system development difficult.

The problem statement in this thesis is: To model a hybrid solar wind integrated generation system in an electrical distribution network using a shared methodology offered by System Engineering in order to integrate all the engineering areas involved in the design of this system.

1.4 Research aims and objectives

1.4.1 Aims

The aim of this research project is to develop models of a hybrid solar wind integrated generation system in an electrical distribution network based on the Model Based System Engineering (MBSE) practices.

MBSE practices are performed using three elements which are (Delligatti, 2013): a modelling language, a modelling method and a modelling tool.

1.4.1.1 Modelling language

A modelling language is referred as a semiformal language used to specify the type of elements and notation permitted to be introduced into a model as well as the relationship between these elements. Two categories of modelling languages can be found; the graphical modelling languages such as UML, SysML UPDM, BPMN, MARTE, SoaML, IDEFx and the textual modelling languages (Verilog, Modelica).

1.4.1.2 Modelling method

A modelling method can be considered as a road map or a set of rules that may be considered in order to certify whether or not a model is well implemented. Some of the well-known modelling methods are INCOSE Object-Oriented Systems Engineering Method (OOSEM), Weilkiens System Modeling (SYSMOD) method, IBM Telelogic Harmony-SE (Delligatti, 2013).

1.3 Modelling tools

Modeling tools are the tools that are used in order to model a system; these tools have to satisfy the specifications applied for a particular modeling language to be used in the modeling of a system. Lots of commercial tool vendors have implemented divers modeling tools for the different modeling languages.

1.4.2 Objectives

The objectives of this thesis are:

- To develop a model capturing some of the important requirements of the system in order for this hybrid power to be integrated in the electrical distribution system.
- To develop models describing the system in terms of the relationship between the different elements of the system and how they are connected.
- To develop models describing the behaviour of the system in terms of activities in the different cases considered.
- To develop a model describing the system’s behaviour in term of transition from one state to another.
- To develop a model taking into account the interaction between the system and all the stakeholders.

1.5 Delimitation of the research

This research project mainly focuses on the modelling of small scale hybrid solar photovoltaic wind power systems connected to a utility grid through the distribution system. Small scale hybrid power systems refer to a hybrid power system with power less than 100kW. As a structure of the system, we have considered a hybrid photovoltaic wind power system made up of a Permanent Magnetic Wind Generator, a photovoltaic system and a power electronics interface consisting of a rectifier used to convert to DC the AC power generated by the wind generator, a DC to DC boost used to boost the DC power generated by the photovoltaic system and an inverter used to convert the DC power from the hybrid power system to AC power in order to connect it to the electrical distribution system.

We have also assumed that this hybrid power system is connected to the customers’ side of the electrical distribution system which is the secondary distribution side.

1.6 Research methodology

As stated in section 1.4.1, the aim of this research project is to develop models of a hybrid solar wind integrated generation system in an electrical distribution network. Therefore, the methodology applied to achieve that aim consists of:

1.6.1 Literature review

This part refers to the first step in this research and is mostly based on gathering theoretical information about SysML (System Modelling Language), hybrid power systems configurations, wind and solar photovoltaic power systems, distribution systems as well as the information related to the grid integration of renewable energy systems based on wind and solar.

1.6.2 Modelling and simulation

1.6.2.1 Modelling

This step will consist of modelling the hybrid photovoltaic wind power systems integrated to the electrical distribution system with a SysML tool Sparx Systems Enterprise Architect. The modelling methodology applied consists of capturing the system level requirement, specification and the system architecture and design. This phase includes designing and developing structure models, behavioural models, and requirements

.Matlab Simulink is also used to model the same system modelled using SysML.

1.6.2.2 Simulation

This phase consists of simulating the SysML parametric diagrams of systems which are based on mathematical equations representing the photovoltaic and wind power subsystems constraints as well as the simulation of Matlab Simulink model.

1.7 Motivation for the project development

Wind and solar power systems are two of the most promising renewable energy systems due to their cleanliness nature and their reliability. These reasons make them very attractive all around the world. The main problem for these types of power systems is their dependency on the weather. Using them as hybrid power system, increases the overall system reliability. In order to integrate them to the utility grid, the modelling of the system needs to be done to ensure that their operation will not impact negatively on the grid and to predict their behaviour.

1.8 Outline of the thesis

This thesis is made up four chapters and one appendix which are organised as follow:

1.8.1 Chapter One

This chapter is devoted to the introduction of this research project. It presents the background and awareness of the problem investigated, the problem statement, as well as the objectives and research methodology applied in this research. In addition, we have given the motivation that guides our research and all the assumptions made.

1.8.2 Chapter Two

The second chapter of this thesis is consecrated to the review of the literature related to this research and includes five sections: the first section of this chapter deals with the modelling language used in this research project; the second section discusses the hybrid power systems; the third one deals with the wind power systems; the fourth section is dedicated to the photovoltaic system; whereas the last section discusses the electrical distribution network.

1.8.3 Chapter Three

This chapter is dedicated to the description of the proposed system. The description of some of the important components of the system as well as their behaviour is presented.

1.8.4 Chapter Four

The fourth chapter represents the results that we obtained while modelling the system proposed in chapter three. The modelling of this system includes the structure, the behaviour as well as the modelling of the constraints of the wind and photovoltaic power systems. The thesis conclusion as well as some recommendations for future research is also made in this chapter.

1.8.5 Appendix

The appendix in this thesis presents some of the key diagrams obtained after modelling of the proposed system.

CHAPTER TWO
REVIEW OF LITERATURE

This chapter presents a review of the literature related to the topic under study and consists of six sections. The first section is devoted to the modelling language used in this research project. In this section, we will firstly present some types of models, mostly known, succeeded by the description of Model Based Systems Engineering and the last part of this section will deal with some of the important characteristics of SysML.

The second section of this chapter discusses the hybrid power systems. In this section we will present the different combinations of hybrid power systems as well as their components. In addition we will discuss some of the important issues related to the design of hybrid power systems.

The third section deals with the wind power systems. We will start the section by giving a brief history of wind power systems and thereafter we will present the two different types of wind power systems as well as some of their features. More focus will be on horizontal wind power systems and we will introduce some of the significant aspects of this type of wind power system such as its structure, aerodynamics, type of generator used, power curve, power output etc.

The fourth section is dedicated to the photovoltaic system. In this section we started with history of photovoltaic systems, followed by the presentation of some advantages and disadvantages of photovoltaic systems. We will also discuss solar cells (materials, equations and some other features). Another part of this section will deal with some of the important aspects of photovoltaic systems which are basically made up of solar cells.

Lastly, the fifth section of this chapter deals with the electrical distribution network. Different configurations are presented as well as some details about their characteristics.

SECTION 1
SYSTEM MODELING LANGUAGE

As stated in the preceding page, this section deals with the System Modelling Language (SysML) which is the modelling language adopted in this research project. It starts firstly by giving a definition of the concept model and the different types of models that can be found. In this section, we have also spoken about Model Based Systems Engineering. Lastly, this section presents some of the important features of SysML.

1.1 Types of models

A model is defined as an abstract or a simplified representation of a system for the purpose of study. A model can represent the structure or the behaviour of a system. Generally a model considers only the aspects of the system that affect the problem under investigation.

Different types of models and associated modelling language can be found, some of the known models are the Mathematical or Physical Model, Static Model, Dynamic Model, Deterministic Model, Stochastic Model, Discrete Model and Continuous Model.

1.1.1 Mathematical or Physical Model

This type of model generally uses symbolic notations and mathematical equations to represent a system. The difference between two of these models lies in the fact that mathematical models are based on mathematical equations and are more abstract whereas a physical model can be a touchable object.

1.1.2 Static model

Static models are the type of models which are not time dependent. These models are mostly based on the structural representation of systems rather than on their behaviours. As examples of these types of models we can mention UML class and object diagrams.

1.1.3 Dynamic model

This type of model represents systems as they change over time. They are opposed to static models because they are more focused on the behaviours than the structural representation. Some examples of this type of models are sequence of operations, state changes, activities and interactions.

1.1.4 Deterministic Model

In a deterministic model, the behaviour of a system is entirely predictable. The overall system is perfectly understood and it is therefore possible to predict what will happen. In this type of model, at a given input value, the output value generated will always be the same.

1.1.5 Stochastic Model

Stochastic models are the type of models in which the behaviour of the system cannot be entirely predictable due to the presence of random variables.

1.1.6 Discrete and Continuous Model

In a discrete model, the state variables change only at a countable number of points in time and these points represent the points at which the event occurs, whereas in a continuous model the state variables change in a continuous way. Generally simulation models are mixed both with discrete and continuous properties. Here, the choice is based on the characteristics of the system and the objective of the study.

1.2 Model Based Systems Engineering

Before going into the details of Model Based Systems Engineering we will commence by introducing Systems Engineering.

1.2.1 Systems Engineering

Systems Engineering is defined as a multidisciplinary approach used to develop balanced systems in answer to the user’s needs. Systems Engineering considers both technical and economic aspects of the system to be developed. Figure 2.1 shows a view of systems engineering technical aspects. The technical aspects of Systems Engineering includes the system specification and design and system integration and test. The role of system specification and design is to specify the system and component requirements in order to meet the user’s needs. After this step, the components are then designed, implemented and tested to make sure that they meet the requirements. The next step after the design, implementation and testing aspects, is the integration of the components into the system and test. This step’s role is to verify that the components meet the requirements.

The different processes shown in Figure 2.1 are applied continuously during the development of the system with feedback between the different processes to ensure a balanced developed system meeting the user’s needs.

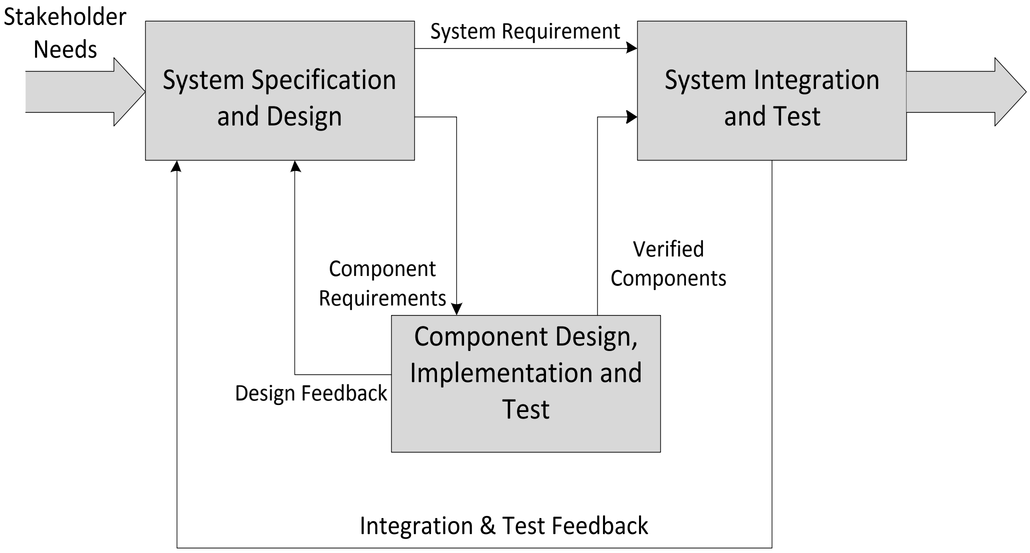


Figure 2.1 View of Systems engineering technical aspect (Friedenthal & Steiner, 2008)

1.2.2 Model Based Systems Engineering

Model based Systems Engineering is an approach to System Engineering defined as a formalised practise of systems development through the application of modelling principles, methods, languages and tools to the entire lifecycle of a system. In Model Based System Engineering, models are taken as the heart of System Engineering activities and also many artefacts (INCOSE, 2007).

Many years ago, the design of systems was based on Systems Engineering process workflows using textual documents and engineering data, requiring considerable effort in order to ensure that the information consistency between the system stakeholders is maintained. Such an approach called Document Based Systems Engineering increases the risk of inconsistency and incompleteness in the design specification and process workflows compromising the verification and validation process workflows. Model Based Systems Engineering aims to facilitate System Engineering activities by improving communications, system specification, design precision, system design integration and reuse of system artefacts (Friedenthal & Steiner, 2008).

1.2.3 SysML

SysML represents one of the modelling languages used to support Model Based System Engineering approaches. Currently, there are a wide range of modelling languages, techniques and tools used in System Engineering. SysML is intended to unify all these modelling languages, techniques and tools and serves as a standard modelling language for systems engineering as in the case of UML (Unified Modelling Language) for software development. According to Holt and Terry, SysML is a general purpose graphical modelling language for specifying, analysing, designing and verifying complex systems which may include hardware, software, information, personnel, procedures, and facilities. SysML represents a subset of UML 2 and includes some additional diagrams.

SysML extends the characteristics of UML and replaces the classes and objects by modelling blocks of System Engineering. The Venn diagrams in Figure 2.2 shows the relationship between SysML and UML. The intersection of the two circles indicates the UML diagrams that SysML reuses and the remaining part of the SysML circle (SysML's extensions to UML) indicates the new modelling diagrams defined for SysML (Ouerdi, et al., 2012).

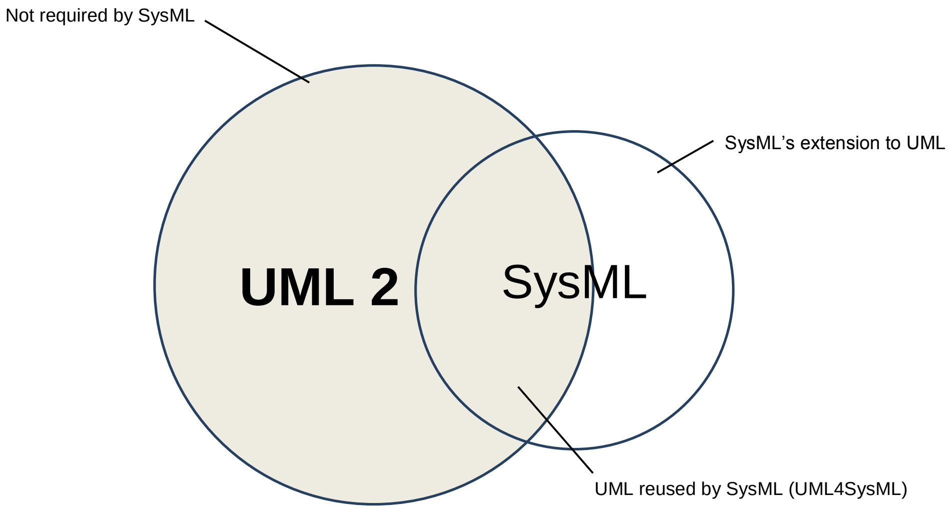


Figure 2.2 SysML and UML Relationship (Ouerdi, et al., 2012)

1.2.3.1 SysML diagrams

SysML diagrams consist of nine diagrams shown in Figure 2.3 and each diagram is dedicated to the representation of a particular concept of the system. These nine SysML diagrams are organised in four categories known as the four pillars of SysML depicted in Figure 2.4. These categories represent the system structure, behaviour, requirements and constraints.

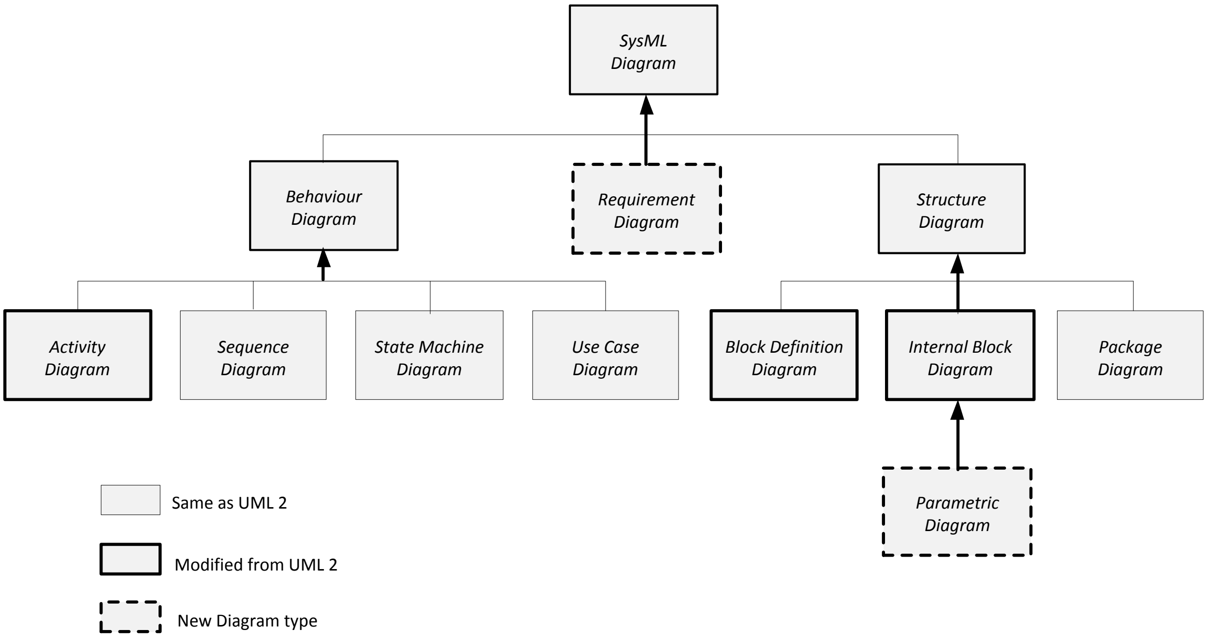


Figure 2.3 SysML diagrams (Huang, et al., 2007)

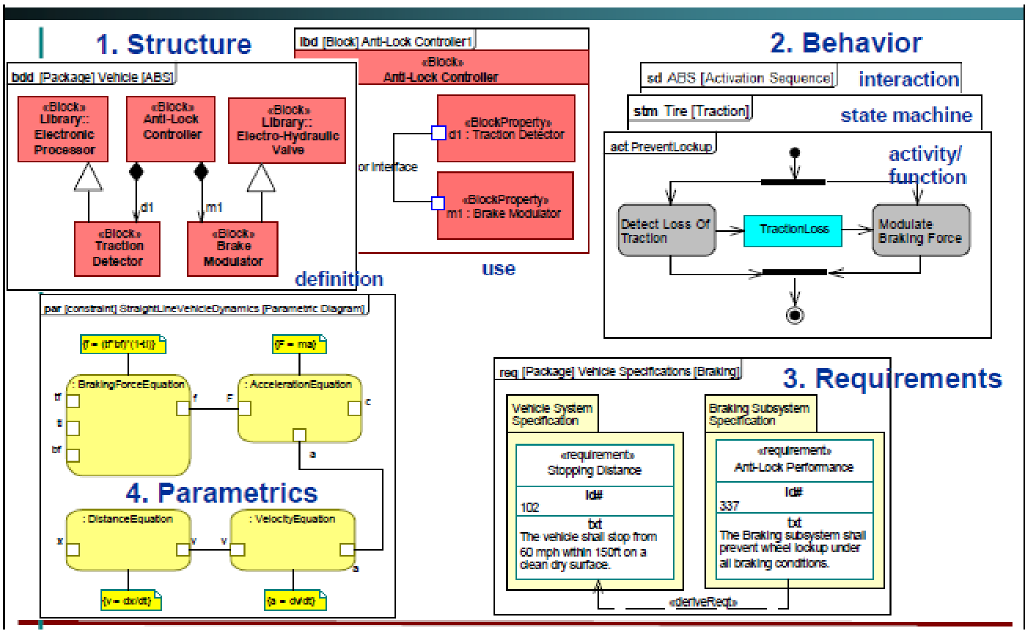


Figure 2.4 Four pillars of SysML (OMG, 2014)

1.2.3.1.1 Structural diagrams

The structural diagrams of SysML include the block definition diagram, internal block diagram, package diagram and parametric diagram.

1.2.3.1.1.1 Block Definition Diagram BDD

A block definition diagram uses blocks to describe systems hierarchy, composition and classifications. It can be considered as the instruction page of a system, providing the quantity of each part of a system and the inventory of its content. Blocks are the basic structural elements of a block definition diagram and include general system attributes and operations. The role of a block definition diagram is to represent the relationship between blocks (composite association and generalisation), the structural characteristics of blocks (part properties, value properties, ports) and the behavioural characteristics of blocks (operations).

1.2.3.1.1.2 Internal Block Diagram IBD

An internal block diagram represents interconnections and interfaces between the different parts of a block by using parts, flow ports and item flow. Its role is to describe the usage of a block in a specific context, how parts and ports are connected and what is flowing between parts and ports.

1.2.3.1.1.3 Package Diagram

A package diagram is used to organize the model and groups model elements into a name space. Its role is to provide a graphical representation of the model organisation.

1.2.3.1.1.4 Parametric Diagram

A parametric diagram is used to represent constraints between value properties of systems for technical performance analysis via simulation. These constraints are captured by constraint blocks as equations, set of parameters and expressions that constrain parameters.

1.2.3.1.2 Behavioural diagrams

The behaviour diagrams include the use case diagram, activity diagram, sequence diagram and state machine diagram.

1.2.3.1.2.1 Use Case Diagram UC

Same as in UML, a use-case diagram provides a high-level description of the system functionality. It describes the interaction between the system and the different actors and consists of the use case, the actors and the interactions between them. The use case diagram also represents a method used to describe the usage of the system. In a use case diagram, the actors are considered as external users that can interact directly or indirectly with the system.

1.2.3.1.2.2 Activity Diagram

The activity diagram represents the flow of data and control between the different activities. Activity modelling focuses on the inputs and outputs, sequence, and conditions for coordinating other behaviours. It proposes a supplementary capability such as the link between the structural modelling and the ability of modelling a continuous flow.

1.2.3.1.2.3 Sequence Diagram

A sequence diagram defines the flow of control between actors and systems or between parts of a system. It represents the sending and receiving of messages between the interacting entities referred to as lifelines, where time is represented along the vertical axis. The sequence diagrams can depict highly complex interactions with special constructs to represent various types of control logic, reference interactions on other sequence diagrams and decomposition of lifelines into their constituent parts.

1.2.3.1.2.4 State Machine Diagram

The state machine diagram describes the state transitions and actions that a system or its parts perform in response to events. It represents behaviour as the state history of an object in terms of its transitions and states. The activities that are happening during the transition, entry and exit of the states are specified together with the associated event and guard conditions. Activities that are happening while in the state are specified as "do Activities", and can be either continuous or discrete. Besides the fact that they are used to express the behaviour of a part of the system, state machines can also be used to express the usage protocol of part of a system.

1.2.3.1.3 Requirement Diagram

The requirement diagram captures requirement hierarchies and the derivation, satisfaction, verification and refinement relationships. The relationships provide the capability to relate requirements to one another and to relate requirements to system design models and test cases. The requirement diagram provides a bridge between typical requirement management tools and the system models. In order to relate requirements between them, requirement diagrams include specific relationships. These specific relationships consist of defining a requirements hierarchy, deriving requirements, satisfying requirements, verifying requirements, refining requirements and copying requirements (Friedenthal & Steiner, 2008). Figure 2.5 shows the different relationships used in requirement diagrams with their explanation.

Relationship	Explanation
Containment	Use to break a requirement into simpler requirements. All the contained requirements should not add or remove any meaning to the original requirement.
Derive	Used to depict that a requirement is derived from another requirement. Useful for mapping the assumptions made about the system based on the requirements.
Cross-cutting relationships	
Trace	Used to describe a general-purpose relationship, often used to relate a requirement to external documents
Satisfy	Used to link a model element to a requirement to show that it satisfies the requirement.
Verify	Used to link a test case to a requirement to prove that a model element satisfies it.
Refine	Used to depict that a model element is refined from a requirement. Useful to map assumptions made to reduce ambiguity in a requirement

Figure 2.5 Relationships used in requirement diagrams (Klykken, 2009)

1.3 Summary

In this section, the focus was turned on the important characteristics of SysML. Firstly, some of the well-known types of models were presented, succeeded by the description of Model Based Systems Engineering and the last part of this section dealt with some of the important characteristics of SysML.

SECTION 2
HYBRID POWER SYSTEMS

2.1 Introduction

Hybrid power systems refer to the combination of two or more power sources integrated together in order to supply the energy requirement. Most hybrid power systems are used in isolated applications and generally include at least one renewable energy source. For instance, renewable energy such as solar or wind are characterised by the uncertainty of power output due to the unpredictable nature of wind and solar. With the growth of wind and solar power industries, both power systems are now associated together as one power system unit. This type of power system offers the advantage of being more reliable because the energy supply depends not only on one source and there is a reduction of the overall power system size. Furthermore, hybrid power systems offer the possibility to fight the climate change and reduce the use of fossil fuel.

2.2 Types of hybrid power systems

Hybrid power systems are classified as stand-alone and grid connected power systems.

2.2.1 Stand-alone hybrid power system

Stand-alone hybrid systems are mostly used in remote areas where the grid utility is not accessible. A study from the World Bank has revealed that more than 40% of the world population still lives in remote areas (Valenciaga,, et al., 2003). The design of a new power line to meet the power requirement in these areas is more challenging and expensive due to the number of components in the system. Stand-alone hybrid power systems can in this case constitute the best alternative compared to the construction of a new power line.

The major requirement of a stand-alone hybrid power system is to meet the load demands at any time and therefore most stand-alone hybrid power systems are equipped with storage systems to serve as back up to handle power variation in worst weather condition periods. This will increase the initial investment of the system as well as its size. In addition to meeting the load, stand-alone hybrid power systems are required to set the frequency, the voltage control and provide the reactive power needed.

During the period when the power produced by the system exceeds the power required, the excess power must be dissipated in some way so that the hybrid power system stability can be maintained. Figure 2.6 shows an example of a stand-alone hybrid power system consisting of a wind power system, a photovoltaic system and diesel generators.

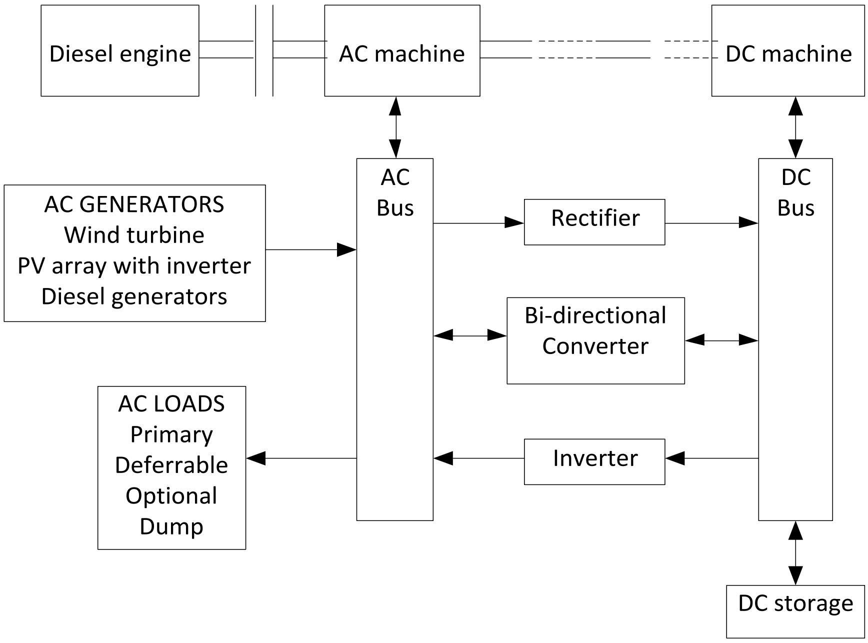


Figure 2.6 Schematic example of hybrid power system (Manwell, 2004)

2.2.2 Grid connected hybrid power systems

In grid connected applications, hybrid power systems can supply power to both local loads and the utility grid. The grid connected hybrid power systems do not require a storage system, because if there is deficit in power, the grid will supply and summarily if there is an excess, it will be injected to the grid. Compared to stand-alone systems, the design of grid connected hybrid power systems are less expensive. In this case, the frequency and the voltage are set by utility grid.

2.3 Advantages of hybrid power systems

Belmili *et al*. gives some advantages of hybrid power systems. According to them, hybrid power systems offer some advantages such as:

- possibility of combining two or more renewable energy sources, based on the natural local potential of the users,
- they are environmentally friendly, especially in terms of carbon dioxide (CO_2) emission reduction,
- they present a low cost, for instance, wind energy and also solar energy can be competitive with nuclear, coal and gas especially considering possible future cost trends and for fossil and nuclear energy there is a diversity and a security of supply,
- they are easy to deploy and quick to install,

- their costs are predictable and independent of fuel price fluctuations.

2.4 Different combinations of hybrid power systems

Hybrid power systems can be classified depending on three criteria: the first criteria are related to the presence or absence of a conventional energy source; the second one refers to the presence or absence of energy storage system; and the last criteria is related to the type of renewable energy source used.

2.4.1 Hybrid power system with conventional energy source

2.4.1.1 Hybrid photovoltaic power system / conventional energy source

This type of hybrid power system consists generally of a photovoltaic power system and a diesel generator and is mostly used in the site where the potential solar is very important. Three different configurations of this type of hybrid power systems can be found, namely, series hybrid energy system, switched hybrid energy system and parallel hybrid energy system (Rashid, 2001).

2.4.1.1.1 Series hybrid energy system

This type of hybrid power system is shown in Figure 2.5 and presents some advantages: there is no switching of AC power between the different energy sources which simplifies the electrical output interface; the power supplied to the load is not interrupted when the diesel generator is started; the inverter can generate a sine-wave, modified square wave or square wave, depending on the application. Some of the disadvantages of this type of hybrid power systems are: the inverter failure results in complete loss of power to the load unless the load can be supplied directly from the diesel generator for emergency purposes and the overall system efficiency is low, since the diesel cannot supply power directly to the load (Rashid, 2001).

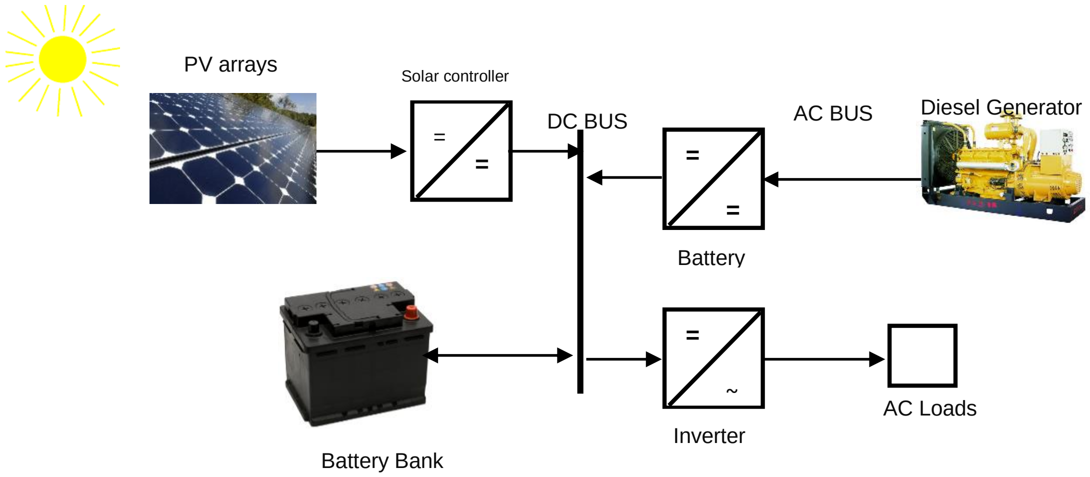


Figure 2.7 Series hybrid energy system (Rashid, 2001)

2.4.1.1.2 Switched hybrid energy system

In this hybrid power system, the consumer is powered either by the conventional source or by the PV system and the battery via the inverter. Simultaneous feeding of the two is not possible. The diesel generator can charge the battery through a rectifier. The management system must be automatic due to the complexity of the hybrid system. The main disadvantage is the fact that the power to the load is interrupted momentarily when the AC power sources are transferred (Stoyanov, 2011).

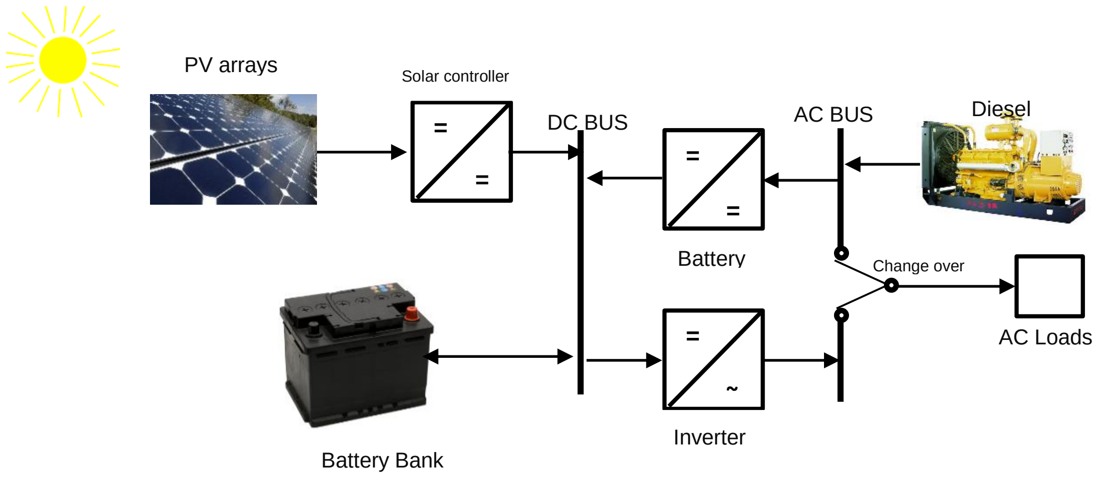


Figure 2.8 Switched hybrid power system (Rashid, 2001)

2.4.1.1.3 Parallel hybrid energy system

In this system, the diesel generator is interconnected to the AC bus while the photovoltaic system and battery are connected to a DC bus. The AC and DC buses are connected using a bidirectional inverter which can work either as a rectifier when the diesel generator covers the power consumption and participates in the battery charging or as inverter when the load (or part of it) is satisfied by the photovoltaic panels and /or battery. In this way, the load can be powered by both buses simultaneously. Some of the disadvantages here are the fact that the system requires an automatic control. The inverter must supply a sinusoidal voltage so that the synchronization with the diesel generator can be possible, the battery life is short and the DC buses are difficult to control (Stoyanov, 2011).

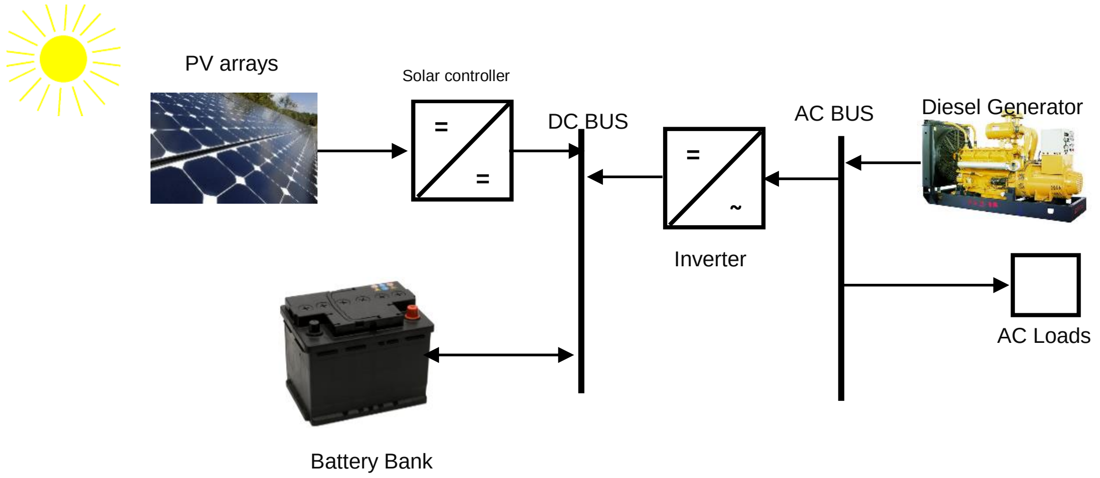


Figure 2.9 Parallel hybrid power system (Rashid, 2001)

2.4.1.2 Hybrid wind power system / conventional energy source

Research on hybrid wind power systems and conventional energy sources are different from research based on photovoltaic power systems due to the fact that wind power systems can generate AC energy. In this way, there is not a wide variety of this type of hybrid power systems. Most of hybrid wind power / conventional energy sources are located in the places where the wind promotes the use of wind energy for electricity generation such as islands. When these systems are operating as stand-alone, they are always equipped with a storage system (Stoyanov, 2011).

2.4.1.3 Hybrid photovoltaic wind and conventional energy source

This type of hybrid power consists mostly of photovoltaic wind and diesel systems. The aim of the implementation of such systems is to diversify the renewable energy sources used to generate electricity. In this case most of the electricity generated comes from photovoltaic and wind power systems rather than diesel systems.

2.4.2 Hybrid power system without conventional energy source

These types of hybrid power systems operate as stand-alone and are mostly located in isolated places where the connection to the electrical grid is difficult. Different configurations can be found.

2.4.2.1 Hybrid photovoltaic power / storage system

In order to meet the load during the night or on cloudy days, these types of hybrid systems require connection with another source of energy. The storage used can be a battery bank, an electrolyser with a hydrogen tank or a combination of two different storage devices like an electrolyser and battery or an electrolyser and a super-capacitor (Stoyanov, 2011).

2.4.2.2 Hybrid wind power / storage system

The main objectives when interconnecting a storage system with a wind generator are that the storage system plays the role of a buffer when the system operates in parallel with the grid so that the device eases the rapid variations of electrical power from wind (Nouni, et al., 2007). The storage devices used in these systems can battery bank, sometimes also an electrolyser with hydrogen container or a combination of batteries and hydrogen storage (Bin, *et al*., 2003; Diaf, *et al*., 2006; Nelson, *et al*., 2006; Sopian, *et al*., 2009).

2.4.2.3 Hybrid wind photovoltaic storage system

The inconvenience of the two preceding hybrid power systems (hybrid wind power storage system and hybrid photovoltaic power storage system) is the lack of variety of power sources because the primary resource used is unique. This leads to several disadvantages such as the oversized elements whose aim is to ensure a continuous supply, which will result in a high initial investment (and therefore limit the development of these systems) and an increase in the price per kilowatt hour. These disadvantages can be limited or even eliminated by the inclusion of a second power source. (Diaf, *et al*., 2006; Krauter, *et al*., 2004).

The storage system used in this case can be batteries, electrolyser with hydrogen container or a combination of batteries and hydrogen storage(Bin, *et al*., 2003; Diaf, *et al*., 2006; Nelson, *et al*., 2006; Sopian, *et al*., 2009).

2.4.2.4 Hybrid wind photovoltaic without storage system

This type of hybrid power system is rarely found due to the fact that it does not provide supply security with any presence of a conventional energy source and a storage system.

2.5 Hybrid power systems components

Besides the generators, hybrid power systems can consist of the following components:

- Energy storage system;
- Power converters;
- Dump loads;
- Supervisor control.

2.5.1 Energy storage system

The energy storage system is mostly used in stand-alone hybrid systems and can play two important roles: firstly it is used as interface between the electrical load and the generators to adapt the mismatch that can occur between them and secondly, it is used as backup to supply the energy to the load whenever the generators do not supply.

Two different storage topologies can be used in hybrid power systems which are the convertible storage and the end-use. In the convertible storage system, the energy stored can be converted back to electricity, whereas the end-use storage systems refer to the case in which some products such as thermal energy or pumped water are created by using the electricity then stored to be used later on whenever needed. The most used convertible storage systems are batteries. However there are some other convertible storage systems such as pumped hydroelectric, flywheels, compressed air and hydrogen which are less used.

2.5.2 Power converters

Three different types of power converter devices are used in hybrid power systems, namely, rectifiers, inverters and maximum power point trackers.

2.5.2.1 Rectifiers

Generally, the rectifiers are used in hybrid power systems for two purposes. Firstly they are used to supply DC loads from AC sources and secondly they are used to convert AC voltage to DC voltage in order to charge the batteries.

2.5.2.2 Inverters

Inverters are used to supply AC loads from DC sources such as solar photovoltaic panels or batteries. Two different types of inverters are used to fulfil this task; the line-commutated and the self-commutated inverters. The line-commutated requires an external AC line and is not able to set the frequency of the power output whenever some of the generators in the hybrid system are turned off whereas, the self-commutated inverters can control the frequency of the system of the power output.

2.5.2.3 Maximum Power Point Trackers

Maximum power point trackers are DC to DC converters mostly used in hybrid systems with photovoltaic panels. Their function is to ensure that the output voltage is kept to its desired values.

2.5.3 Dump loads

As mentioned in section 2.3.5.1, during the period when the power produced by the system exceeds the power required, the excess of power must be dissipated in some way so that the hybrid power system stability can be maintained. A dump load is the equipment used in this case. It can detect the exceeding power and dissipate it so that the total generated power can be the power required by the load plus the power dissipated.

2.5.4 Supervisor controller

The main function of a supervisor controller is to ensure that all the devices within the system are operating in a proper manner. A typical supervisor controller includes sensors, a logical unit and control commands. All the data captured from the sensors are transmitted to the logical unit within the computer. After the treatment of data, the logical unit will make decisions according to its internal algorithm and the data captured from the sensors. These decisions will be executed by the control commands part.

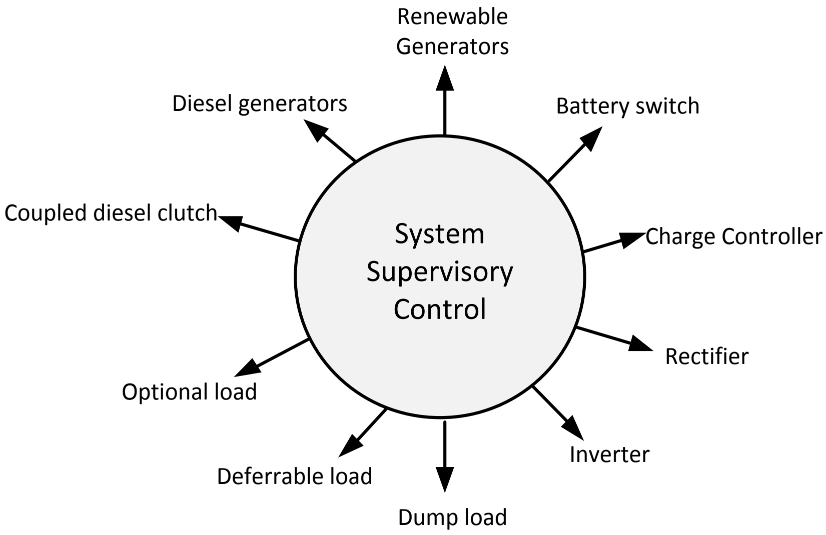


Figure 2.10 Supervisory controller functions (Manwell, 2004)

2.6 Issues related to Hybrid System Design

Many issues can arise in the process of designing a hybrid power system. These issues are related to the specifications of the existing power system, the nature of the load and the availability of renewable resources. Some of the most important issues are match of electrical load and resource, system design and constraint and system design rules.

2.6.1 Match of Electrical Load and Resource

A determining factor in hybrid power systems design is the interdependence between the electrical load and the power produced by the hybrid system.

During short time frames, the load needs to equal the power produced to ensure system stability. Maintaining this stability means the power flows need to be balanced.

During extended operating times, a hybrid system may require either long term energy storage or a backup conventional generation.

2.6.2 System Design Constraints

There are some constraints that can affect the design of a hybrid power system. These constraints are related to the nature of the load, the characteristics of the electrical distribution system, the renewable resource, the availability of maintenance personnel and the environmental factors.

2.6.2.1 Nature of the load

Due to the variable nature in magnitude of the electrical load supplied by the hybrid power system, the rated system capacity as well as the energy storage needs and the control system algorithm can be affected.

2.6.2.2 Characteristics of the electrical distribution

The electrical characteristics of any existing electrical distribution system have an impact on the economics of the hybrid system, equipment selection, and the control system design, whereas in new systems, the generation and distribution systems can be designed in such a way that they can be in common harmony with the design of the hybrid components.

2.6.2.3 Availability of renewable resource

Renewable energy such as solar, wind, hydropower and biomass are characterized by their variable nature in magnitude. This variability affects the choice of a renewable power system, the control strategy as well as the storage requirements.

2.6.2.4 Maintenance infrastructure

The maintenance of the system is also of great importance and it is therefore requires a qualified operating and maintenance personnel for the installation costs, operating cost, and long term operability of the system.

2.6.2.5 Environmental Conditions

The environmental conditions such as the site weather conditions, the nature of the terrain and the remoteness of the site can affect the requirements of equipment design, the operating system as well as the transportation of the equipment to the site.

2.7 Some rules related to the design of a Hybrid Power System

Many factors come into play when designing a hybrid power system. For instance, in the case of a hybrid wind and solar photovoltaic, the design involves some choices such as the type, size and number of wind turbines, solar panels, the size of dump loads, the instantaneous and long-term energy storage capacity, possibilities for other load management strategies and the control logic needed to decide when and how to use each of the system components. This complicates the design of system with multiple controllable power sources.

Some of the most important rules to be taken into account when designing a hybrid power system are:

- The maximum renewable energy that can be used is limited by the load;
- The use of renewable energy will be further limited by temporal mismatch between the load and the renewables;
- The introduction of energy storage increases the use of the renewable resource when there is a temporal mismatch between the load and the renewable resource;
- The maximum possible improvement in the use of renewable energy afforded by use of storage is limited by the mismatch between its availability and the load;
- The maximum possible benefit with improved controls or operating strategies, without using renewables, is a system approaching the fuel use of the ideal diesel generator – fuel use proportional to the diesel-served load;
- The maximum fuel savings arising from the use of renewables in an optimized system is never greater than the fuel savings of an ideal generator supplying the proportional reduction in load resulting from the use of renewables.

2.8 Summary

In this section, the two different types of hybrid power systems namely the stand-alone and the grid connected hybrid power systems have been presented; their advantages and their disadvantages, the different combinations of hybrid power systems in terms of the energy sources used and the components which are part of these hybrid combinations. In addition, some of the important issues related to the design of hybrid power systems have been discussed.

SECTION 3
WIND POWER SYSTEMS

3.1 Introduction

Wind is an indirect form of solar energy defined as a horizontal movement of the air across the surface of the earth. It derives its origin from the difference of pressure caused by solar irradiation between two regions of the earth. This difference of pressure exerts a force which causes the air to move from the area of high pressure to the one of low pressure (Chiras, 2010; Erich, 2006).

The total solar power received by the earth is estimated as1.8 x 10^{11} MW. From this power, only 2% is converted to wind energy (3.6x10^{9} MW) andthe available wind power that can be converted into another form of energy is approximavely 1.26x10^{9} MW, which is twenty times the rate of actual world energy consumption. This rate shows that wind energy can entirely meet the world energy needs (Tong, 2010).

3.2 History

The use of wind as source of energy dates back many centuries and was used essentially to sail ships in the Nile some 5000 years ago (Patel, 2006). In Asia the first system using wind power appeared 3000 years ago. It was for irrigation systems. The history reveals that wind power has been used in the 7th century in Afghanistan for grain milling. In Europe the windmills became important since the12th century particularly in the Netherlands for land drainage, later for milling grain and sawing wood. In North America the windmills were used in the 19th century for water pumping (Quaschning, 2005; Erich, 2006).

The use of wind as primary energy source for electrical energy generation started in the United States of America where the first wind power plants were built in New York in 1882 with a power output of about 500 kW and thereafter in Berlin in 1884. The first three phase wind turbine was introduced in 1891 (Erich, 2006). However, during this period, the use of wind power was not signicant and was mostly used to charge batteries in the areas which did not have access to power lines and it was finally replaced once the access of electricity from the grid became available (Burton, et al., 2001).

The interest in wind power began again in 1973 with the energy crisis when the countries that were members of Organisation of Petroleum Exporting Countries (OPEC) declaired an oil ambargo. At that time, oil and coal were the main primary energy sources for electrical energy generation. This situation encouraged many countries that wanted to be independent of these energy sources to initiate researchinthe development of wind turbines and other alternative energy systems (Ghosh & Prelas, 2011).

Wind turbines havegenerated much more interest with the rising concern over climate change and its rate of growth is faster than any other electricity generation systems.

3.3 Advantages and disadvantages of wind power

3.3.1 Wind power advantages

The major advantages of wind power systems can be summarize as follow (Ph.D, 2010):

- It saves substantial money on utility bills; users face no power shortages or failures as experienced by customers who depend on electrical utility grids.
- It delivers environmentally friendly and efficient electrical energy at lower cost, particularly, in areas where electrical grids are not available, for example, in remote locations with difficult terrain features.
- Installation does not jeopardize the value of a home, office building, or commercial building. The installation can be easily undone and leaves no adverse visible effects at installation sites.
- The turbine does not require frequent or intermittent maintenance or employment of operations personnel; unlike steam and gas turbine-based alternator systems, no maintenance or operational costs are incurred.
- The technology essentially offers home-made electrical energy and off-grid living, which is not readily possible with other technologies.

3.3.2 Wind power disadvantages

The main disadvantages of wind power are (Chiras, 2010; Ph.D, 2010):

- The variability of wind energy;
- Bird flying mortality;
- Unwanted wind noise;
- Concern about wind being more site specific than solar electricity;
- Concern about ice falling from turbines after ice storms and interference with radio and televisions signals;
- Wind turbine installation cost depends on site selection, tower height, and output power rating.

3.4 Classification of wind turbines

Wind turbines use the kinetic energy of the wind to generate electricity. According to Tong (2010) and Erich (2006), wind turbines are classified regarding the following aspects:

- Power generating capacity;
- Driving condition in the wind generator system;

- Constructional design;
- Location of the installation;
- Power supply mode.

3.4.1 Wind Turbines power capacities

Based on their power generating capabilities, wind turbines are categorised into micro, small, medium, large and ultra large wind turbines (Tong, 2010).

Micro wind turbines are used for street lighting, water pumping and remote residences in locations where the electrical grid is not available. This category of wind turbines has a power rate less than several kilowatts (Tong, 2010).

Small wind turbines with an electrical power output below 100kW are used mostly for remote residential homes, telecommunication dishes, and irrigation water pumping application in remote areas (Tong, 2010; Ph.D, 2010; Anaya-Lara, et al., 2009).

Medium wind turbines are the most used wind turbines with their power rate ranging from 100kW to 1MW. This category of wind turbine is suitable for grid connected or off grid systems for wind power plants, Distributed Systems, hybrid systems and village power (Tong, 2010).

Wind turbines having a power rate ranging from a few MW up to 10MW are classified as large wind turbines. Presently, most wind farms around the world are using this category of wind turbine, especially in offshore areas (Tong, 2010).

Ultra wind turbines are still under development and research is being done. This category of wind turbines has a power output rate more than 10MW (Tong, 2010).

3.4.2 Geared drive and direct drive wind turbines

Considering the driving condition in wind generator systems, wind turbines can be classified in direct drive and geared drive types. In direct drive types, the generator shaft is directly connected to the blade rotor and the system offers more reliability, energy efficiency and design simplicity (Tong, 2010).

In order to increase the rotating speed of the generator rotor to gain higher power output, wind turbines can be equipped with a multi-stage gearbox which takes the rotational speed from the low-speed shaft and transforms it to a high-speed shaft of the generator rotor. The advantage here is the lower cost, small size and weight. However there is an increase in turbine noise level, lower wind turbine reliability and mechanical losses (Tong, 2010).

3.4.3 Wind Turbines constructional design

As depicted in Figure 2.11, there are two design types of wind turbines: the Horizontal Axis Wind Turbines (HAWT) and the Vertical Axis Wind Turbines (VAWT) (Erich, 2006).

3.4.3.1 Horizontal Axis Wind Turbine (HAWT)

Also known as Danish wind turbine, the Horizontal Axis Wind Turbine is the most commercial wind turbine in the world. In this type of wind turbine, the axis of blade rotation is parallel to the ground and to the wind flow. The height of the tower of the Horizontal Wind Turbines as well as the diameter of the rotor is very important: Firstly, for the height of the tower, the wind increases with the height above the ground and secondly, the rotor diameter determines the area needed to meet the specific power output. The advantages of this type of wind turbine are the high turbine efficiency, high power density, the rotor speed and the power output can be controlled by blade pitch control, low cut-in wind speeds, and low cost per unit power output. The Horizontal Wind Turbines are designed with two or three blades. Two blade wind turbines are often downwind whereas three blade wind turbines are upwind (Patel, 2006; Burton, et al., 2001; Ph.D, 2010; Tong, 2010).

Considering the configuration of the wind rotor in the wind flowing direction, the Horizontal Wind Turbines can be classified as upwind and downwind wind turbines (Tong, 2010; Ph.D, 2010).

3.4.3.1.1 Upwind wind turbines

Most Horizontal Wind Turbines used today are upwind wind turbines, in which the blades are facing the wind. The main advantage here is to avoid the distortion of the flow field when the wind is passing through the wind tower and nacelle (Tong, 2010).

3.4.3.1.2 Downwind wind turbines

In this configuration, the wind passes through the nacelle, tower and then to the rotor blades. The rotors are made more flexible. The main disadvantage of this wind turbine is the fluctuation of the power output due to the influence of the distorted unstable wakes behind the tower and nacelle (Tong, 2010).

3.4.3.2 Vertical Axis Wind Turbine (VAWT)

The blades of vertical axis wind turbines are perpendicular to the ground. Advantages are as follows: vertical Wind Turbines can accept wind from any direction; there is no need for a yaw system; high efficiency; and high rotational speed. The disadvantages of Vertical Wind Turbines are: an external source of energy is needed to rotate the blades during initialisation;

dynamic stability problem; sensitivity to off design conditions; limitation of operation to lower speed environments because of low installation height (Ph.D, 2010; Erich, 2006; Tong, 2010).

Figure 2.11 Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (Erich, 2006)

3.5 Onshore and offshore wind turbines

Onshore Wind Turbines present many advantages compared to offshore Wind Turbines. These advantages are:

- Lower cost of foundations;
- Easier integration with the electrical-grid network;
- Lower cost in tower building and turbine installation;
- More convenient access for operation and maintenance.

However, due to the excellent wind power intensity and continuity in offshore conditions, offshore wind turbines have developed faster than onshore. For the same turbine installed, the power output in offshore wind turbines is higher than the power in onshore turbines (Tong, 2010).

3.6 Grid connected and off Grid Wind turbines

A wind turbine can be connected to the grid or off grid. Most large and medium wind turbines are used connected to the grid whereas small wind turbines are used in remote areas and are off Grid turbines. The main advantage of grid connected wind turbines is that there is no need of storage systems. Off grid wind turbine generation systems always need a battery in storage because of the unpredictable power output due to the intermittence of wind (Tong, 2010).

3.7 Structure of modern wind turbines

This section is dedicated to the Horizontal Axis Wind Turbine which is the most common design wind turbine today in the world. As illustrated in Figure 2.12, the horizontal axis wind turbine is made up of the following components: a nacelle, a tower’ a rotor consisting of a hub and blades; a power train; a foundation and a ground equipment station (Hemami, 2012).

3.7.1 Nacelle and yaw systems

The nacelle is the compartment between the rotor and the tower. Its purpose is to serve as housing for the gearbox, generator, coolers for the gearbox oil, heaters for winter time, turbine brake system, motors and gear for yaw system, the wind direction and speed measurement systems, the transformer for turbine energy supply, and other equipment based on the turbine design. In addition, the nacelle allows yawing of the turbine by adjusting the turbine orientation to the direction of the wind and provides a counterweight for the hub and blades’ weight (Hemami, 2012).

3.7.2 Tower and foundation

The tower is the structural part of the wind turbine that supports and holds the other parts in the air. There are two types of towers: the lattice tower and the tubular tower. The lattice towers are like the towers used in the overhead electrical line made with metallic bars that are bolted or welded together whereas the tubular turbines are made up of cylindrical steel or a conic shape with a slight tilt. Of the two types of towers, the tubular tower is mostly used (Hemami, 2012).

3.7.3 Rotor subsystems

The main components of wind turbine rotors are the blades which are attached on a central hub. On the majority of turbines, the blades are made from fiberglass or carbon fibre reinforced plastics and sometimes wood or epoxy laminates. A wind turbine rotor can have two or three blades. Three blade wind turbine rotors usually have a rigid hub where the blades are bolted in the hub while two blade wind turbines are equipped with a teetered hub to reduce the load on the shaft of the turbine (Manwell, et al., 2009). Medium and large horizontal axis wind turbine rotors are always equipped with a mechanism for controlling the blade pitch, which is the angle between the blade chord line at a specific reference radius and the plane of rotation.

3.7.4 Power train

A wind turbine power train consists of a set of mechanical and electrical components needed to convert the mechanical power from the rotor hub to the electrical power. The Horizontal Axis Wind Turbine power train includes the following components: a turbine shaft assembly (a low-speed or primary shaft), a speed-increasing gearbox, a generator drive shaft (a high-speed or secondary shaft), a rotor brake, an electrical generator, plus auxiliary equipment for control, lubrication, and cooling functions.

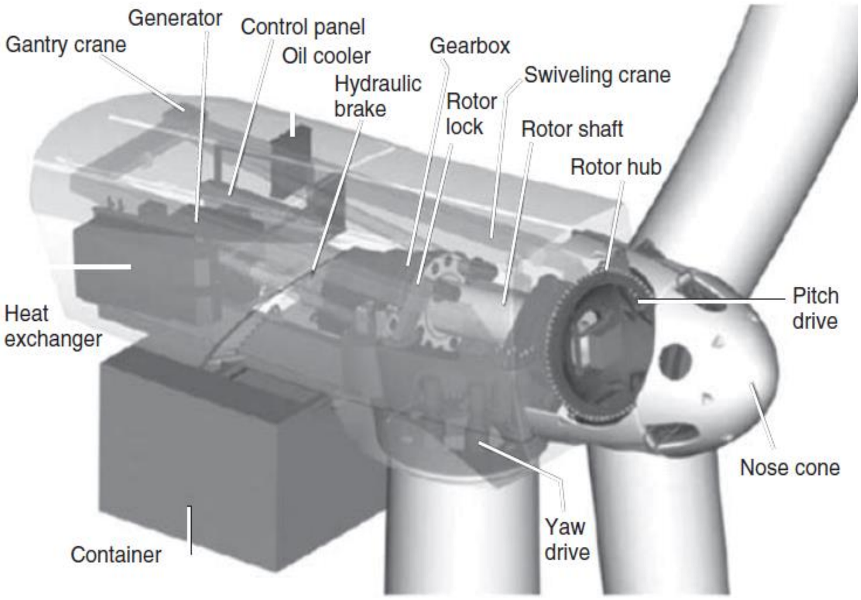


Figure 2.12 Wind turbine generator layout (Digambar, 2011)

3.7.5 Generator types for wind turbines

The three types of generators used for most wind turbines are a squirrel cage generator, a doubly fed (wound rotor) induction generator and the synchronous generator.

3.7.5.1 Fixed speed wind generator

Among the different types of generators used in wind turbines, the squirrel cage is the oldest one. It is referred to as a fixed speed wind generator. In most cases it is directly coupled to the grid to supply power via a transformer. In order to operate, a squirrel cage generator always requires a reactive power. Therefore, as shown in Figure 2.13 this type of generating system is always equipped with a bank of capacitors to compensate for the reactive power. A grid connection is realized by using a soft-starter.

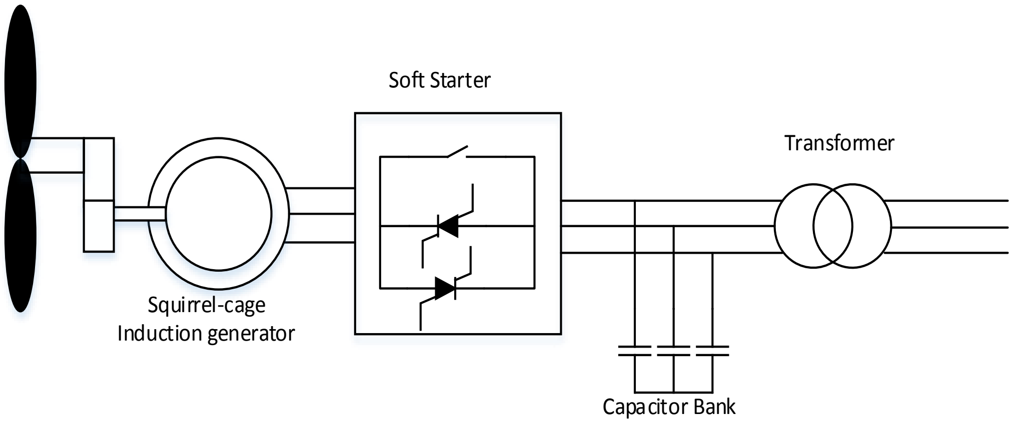


Figure 2.13 Wind turbine with a squirrel cage induction generator (Anaya-Lara, et al., 2009)

3.7.5.1.1 Different configurations of fixed speed wind generators

There are three different configurations of fixed speed wind generators used in the wind turbine industry, namely, Type I0, Type I1 and Type I2.

3.7.5.1.1.1 Type I0

Also known as a stall controlled fixed speed wind generator, this type of generator has been attractive due to its low price, its simplicity and its robustness.

3.7.5.1.1.2 Type I1

Also known as a pitch controlled fixed speed wind generator, this type of generator presents the advantage of facilitating power controllability, controlled start-up and emergency stop. However, at high wind speeds, a small variation in wind speed can lead to a large variation in output power.

3.7.5.1.1.3 Type I2

Also known as an active stall controlled fixed speed wind generator, this type has become popular because of the power quality characteristics they present. However, there prices are high due to the pitching mechanism and its controller.

3.7.5.1.2 Advantages and Disadvantages

This type of generator presents some advantages, such as: it is relatively simple, inexpensive, and easy to connect and disconnect to an electrical network. Disadvantages of this type of generator are that they do not accept speed control and they must be robust since rotor speed cannot be varied. In the case of wind speed fluctuation, drive train torque will be affected causing higher structural load (Manwell, et al., 2009).

3.7.5.2 Variable speed wind generators

Variable speed wind generators have become the dominant type of wind generators around the world. They are designed to realize maximum efficiency over different ranges of wind speed. In order to allow variable speed operation when these generators are connected to the grid, the mechanical rotor speed and the grid frequency must be decoupled via a power electronics system. The power control strategy used in variable speed generators is done via pitch control.

3.7.5.2.1 Different configurations of variable speed wind generators

3.7.5.2.1.1 Limited variable speed

As depicted in Figure 2.14, this type of generator uses a wound rotor induction generator (WRIG) with a variable resistance in the rotor. The variable resistance controls the slip and the power output of the generator. As for a fixed speed wind generator, this type of generator requires a capacitor bank and a soft-starter. The advantage here is the simple topology and improved operating speeds. However, the speed is limited as it depends on the variable rotor resistance size and only poor active and reactive power controls are realized.

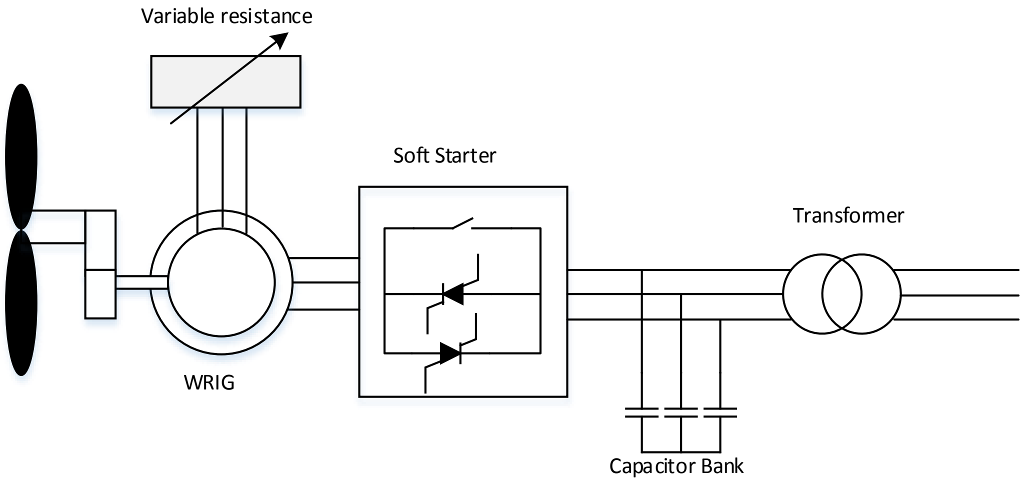


Figure 2.14 Limited variable speed wind generator (Ackermann, 2005)

3.7.5.2.1.2 Variable speed generator with partial scale frequency converter

Also known as double fed induction generator (DFIG), this configuration consists of a wound rotor induction generator (WRIG) and a bidirectional back to back voltage source converter (Figure 2.15). It is the most used configuration in the world and allows variable speed operation over a large but limited range. The reactive power compensation and the grid connection are achieved via the partial scale frequency converter. Advantages are that this configuration presents the ability to control reactive power and to decouple active and reactive power by separated control of the rotor excitation current and the generator magnetization can be done by power from the grid or the rotor circuit.

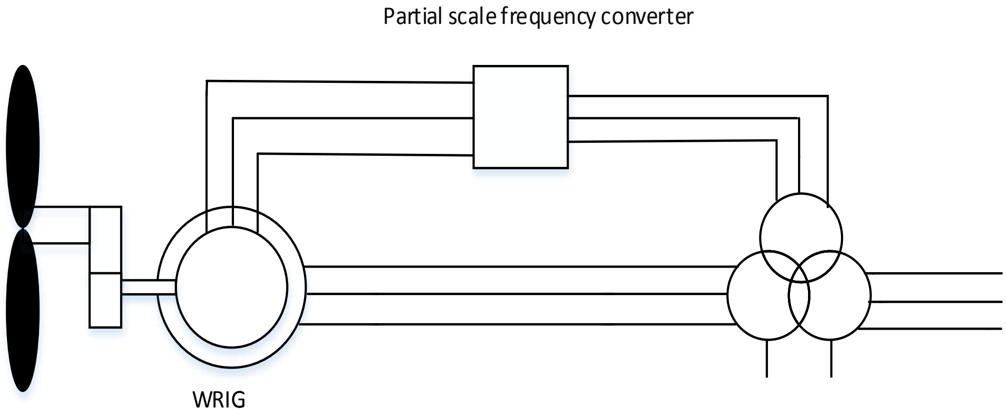


Figure 2.15 Double fed induction generator (Ackermann, 2005)

3.7.5.2.1.3 Variable speed generators with full scale frequency converter

This configuration consists of a wound rotor synchronous generator (WRSG), a wound rotor induction generator (WRIG) or a permanent magnetic synchronous generator (PMSG) and a full scale frequency converter which allows the full variation of the speed (see Figure 2.16). The frequency converter also allows reactive power compensation in the case of (WRIG) and smooth connection to the grid.

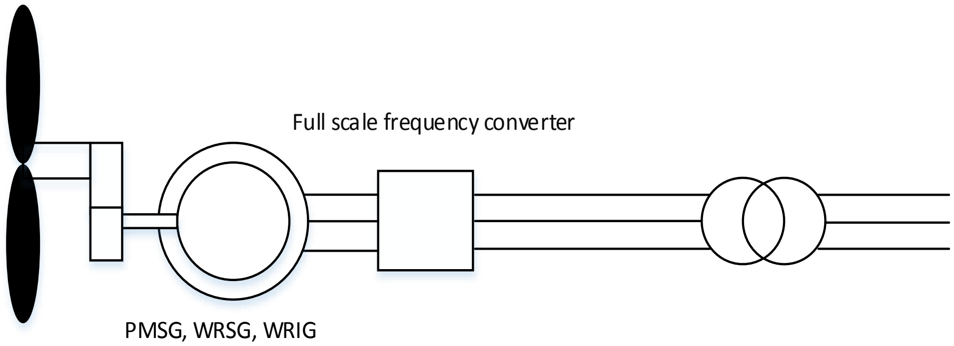


Figure 2.16 Variable speed wind generator with full scale frequency converter (Ackermann, 2005)

3.8 Wind turbine aerodynamic behaviour

In this section the focus will be on the aerodynamics of the horizontal axis wind turbines which are the most used wind turbines in the world. The aerodynamics of wind turbines is based on the concept of actuator disk theory (refer to Figure 2.17) which explains the method of extracting kinetic energy from wind.

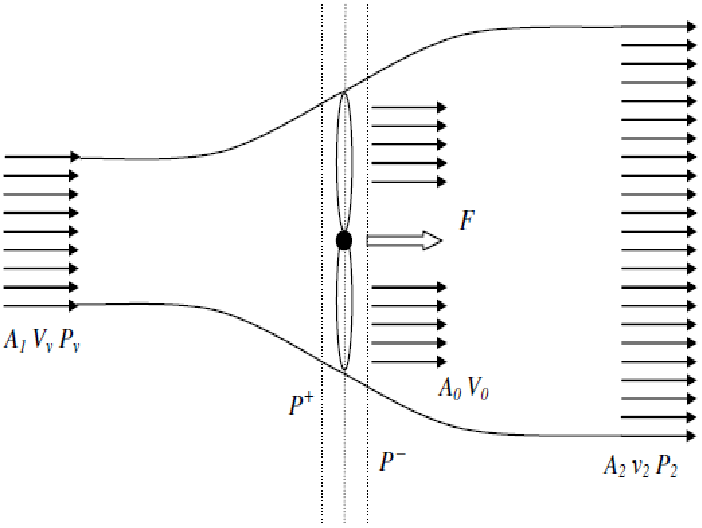


Figure 2.17 Fluid flow through an actuator disk (Abad, et al., 2011)

3.8.1 Power in the wind

By assuming that air is incompressible, the fluid motion is steady and the value of the studied variable is the same on a given section of the stream tube air.

The power contained in the form of kinetic energy in the wind passing through surface A_1 at the velocity V_V is given by the equation (Abad, et al., 2011):

$$P_V = \frac{1}{2}\rho A_1 V_V^3 \tag{2.1}$$

In this equation, ρ is the air density approximately equal to 1.225 kg/m^3 and P_V the power in the wind.

3.8.2 Power of the wind turbine

From the power P_V, the wind turbine can only extract a fraction of its P_t which is expressed in the equation 2.2 (Abad, et al., 2011):

$$P_t = \frac{1}{2}\rho\pi R^2 V_V^3 C_p(\lambda, \alpha) \tag{2.2}$$

In this equation, R and $C_p(\lambda, \alpha)$ represent the radius of the turbine and the power coefficient respectively.

3.8.3 Power coefficient

The wind turbine performance is usually evaluated by its power coefficient which represents a fraction of the power in the wind that the rotor can extract. It is then defined by the equation 2.3 below (Manwell, et al., 2009):

$$C_p(\lambda,\alpha) = \frac{P_t}{P_V} = \frac{Power\ of\ the\ wind\ turbine}{Power\ of\ the\ wind} \qquad (2.3)$$

The value of the power coefficient varies with the wind speed, the rotational speed of the wind and the pitch angle of the rotor. Figure 2.18 gives the different values of the power coefficient as a function of the tip speed ratio for different rotor pitch angles (Monroy & Alvarez-Icaza, 2006).

The value of the power coefficient can also be approximated by using the relation (Monroy & Alvarez-Icaza, 2006):

$$C_p(\lambda,\alpha) = 0.5\left(\frac{116}{\lambda_i} - 0.4\alpha - 5\right)e^{-\frac{21}{\lambda_i}} \qquad (2.4)$$

With

$$\lambda_i = \left(\frac{1}{\lambda+0.08\alpha} - \frac{0.035}{\alpha^3+1}\right)^{-1} \qquad (2.5)$$

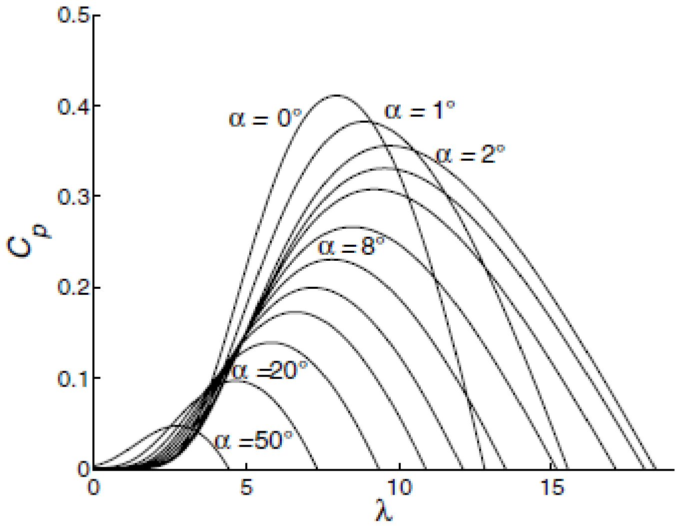


Figure 2.18 Wind Turbine Power coefficient for different pitch angles (Monroy & Alvarez-Icaza, 2006)

3.8.4 Tip speed ratio

The wind turbine performance can also be evaluated by its tip speed ratio which is defined as:

$$\lambda = \frac{\omega R}{V_V} \tag{2.6}$$

In the equation 2.6, ω is the rotational speed of the turbine

3.8.5 Betz limit

The Betz limit defines the theoretical maximum value of the power coefficient that the wind turbine can extract. This value is estimated as equal to 59,3%. No wind turbine exceeding this value has been designed to date. In reality the wind turbine power coefficient varies between 25% and 45% (Digambar, 2011; Burton, et al., 2001).

3.8.6 Wind turbine rotor Torque

The torque of the wind turbine rotor is obtained from the power of the wind turbine and the turbine speed of rotation and is given by the relation (Abad, et al., 2011):

$$T_t = \frac{P_t}{\omega} = \frac{\rho \pi R^2 V_V^3}{2\omega} C_p(\lambda, \alpha) = \frac{\rho \pi R^3 V_V^2}{2\lambda} C_p(\lambda, \alpha) \tag{2.7}$$

Another parameter that can be used to evaluate the performance of the wind turbine rotor is the torque coefficient $C_q(\lambda, \alpha)$. It is related to the power coefficient by the equation (Bongani, et al., 2003):

$$C_p(\lambda, \alpha) = \lambda C_q(\lambda, \alpha) \tag{2.8}$$

3.8.7 Wind Turbine power Curve

The wind turbine power output varies with the wind speed. With the power curve, it is possible to predict the energy production of the wind turbine without considering the technical details of its different components. For different existing machines, the power curve can be obtained from the manufacturer. Figure 2.19 gives an example of a power curve of a particular wind turbine as function of the hub height wind speed. In this figure the performance of a given wind turbine can be described regarding three different points on the velocity scale (Manwell, et al., 2009; Anaya-Lara, et al., 2009):

- Cut-In Speed represents the minimum wind speed at which the wind turbine will deliver useful power. It is noteworthy that from o m/s to the cut-in speed the power output of the wind turbine generator is zero. This happen because there is not enough kinetic energy to move the turbine.

- Rated Wind Speed represents the wind speed at which the maximum power output of the electrical generator is reached. Typical values are around 13 to 16 m/s.
- Cut-Out Speed represents the maximum wind speed at which the wind turbine is allowed to deliver power. The Cut-Out Speed is usually limited by engineering design and safety constraints. Typical values are around 25 to 30 m/s.

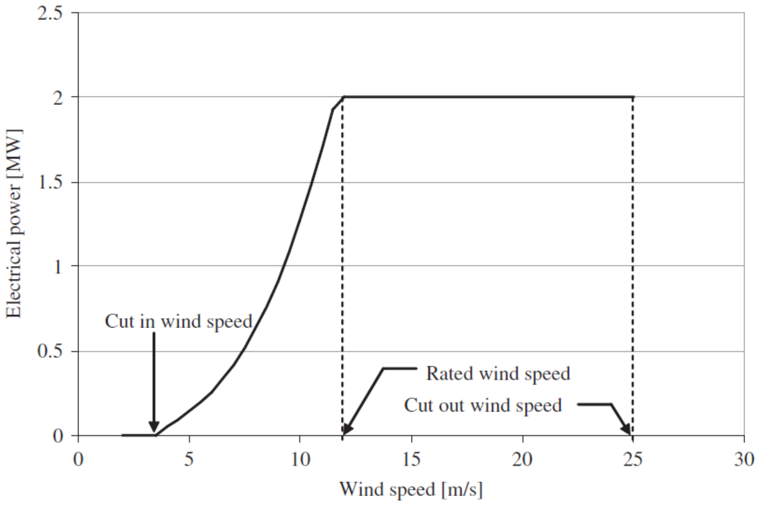


Figure 2.19 Typical Wind Turbine Power Curve (Anaya-Lara, et al., 2009)

3.8.8 Some proposed mathematical models of wind system power curve (Stoyanov, 2011)

In this section, we present two different proposed models of wind power systems which are generally used in wind power systems studies. In these models, V_{cut-in}, $V_{cut-off}$, V, V_{rated} and p refer to the cut-in speed, cut-off speed, wind turbine speed, rated speed of the wind turbine and the electrical power generated, respectively.

3.8.8.1 Linear model

The model is called a linear model and supposes that the variation of power between the cut in speed V_{cut-in} and the rated speed V_{rated} is linear. The equations representing this model are shown below:

$$\begin{cases} p = 0 & V \leq V_{cut-in} \\ p = a + bV & V_{cut-in} < V \leq V_{rated} \\ p = 1 & V_{rated} < V < V_{cut-off} \end{cases} \tag{2.9}$$

In these equations, a and b is obtained by solving the equations:

$$\begin{cases} a = \frac{V_{cut-in}}{V_{rated}-V_{cut-in}} \\ b = \frac{1}{v_{rated}-V_{cut-in}} \end{cases} \tag{2.10}$$

3.8.8.2 Model of Pallabazer

This model is different from the linear model in the non-linear shape of the curve between the speed latching and that for which the rated power is obtained. In this part, the equation representing the power is given by

$$p = \left(\frac{V^2-V_{cut-in}^2}{V_{rated}^2-V_{cut-in}^2}\right) \tag{2.11}$$

3.8.8.3 Commonly used model of wind power

The commonly used model to calculate the output power P_w of a wind turbine generator is expressed in kW/m^2 as given in the equation 2.12 below (Chedid & Rahman, 1998):

$$\begin{cases} P_w = 0 \quad V < V_{cut-in} \\ P_w = a.V^3 - b.P_{rated} \quad V_{cut-in} < V < V_{rated} \\ P_w = P_{rated} \quad V_{rated} < V < V_{cut-off} \\ P_w = 0 \quad V > V_{cut-off} \end{cases} \tag{2.12}$$

In this equation, a and b are defined by the equations:

$$a = \frac{P_{rated}}{V_{rated}^3-V_{cut-in}^3} \tag{2.13}$$

$$b = \frac{V_{cut-in}^3}{V_{rated}^3-V_{cut-in}^3} \tag{2.14}$$

P_{rated},V_{cut-in}, $V$and$V_{cut-off}$ are the rated powers, cut-in, rated and cut-out wind speeds respectively.

The real electrical power of the wind turbine generator $P_{e,w}$is calculated as (Chedid et al., 1998):

$$P_{e,w} = P_w.A_w.eff_w \tag{2.15}$$

Where A_w is the total swept area and $eff_w$is the efficiency of the wind turbine.

3.8.9 Wind turbine output power control

There are many different ways of controlling the wind turbine output power. The most common ways used are passive and active stall and pitch control.

3.8.9.1 Passive stall control

In a stall control, the wind turbine power output is regulated through specifically designed rotor blades. The blades are bolted onto a hub at a fixed angle. The design is made in such a way that when the wind speed is too high, it creates turbulences on the side of the rotor blades. As a result, the turbulences will decrease the aerodynamic efficiency of the wind turbine. This type of wind turbine control is the simplest, the most robust and cheapest control method (Abad, et al., 2011; Fox et al., 2007).

3.8.9.2 Pitch control

Pitch control is an active method which is used to reduce the aerodynamic efficiency of a wind turbine by changing its rotor blade pitch angle which involves turning the rotor blades out of wind. The pitch angle can change at a low finite rate due to the size of the rotor blades. The maximum rate of change of the pitch angle is in the order of 3 to 10 degrees/second. It is noted that a variable speed system normally has lower cut-in speed. The rated speed is also normally lower than a constant speed system. For wind speeds between the cut-in and the nominal speed, there will be a 20-30% increase in the energy captured with variable speed compared to the fixed-speed operation. For pitch controlled wind turbines, the power for wind speeds over the nominal value can be held constant precisely, whereas, for a stall controlled constant speed system, the output power will reach its peak value somewhat higher than its rated value and then decrease as wind speed grows (Abad, et al., 2011; Fox, et al., 2007).

3.8.9.3 Active stall control

The stall of the blade is actively controlled by pitching the blades. At low wind speeds the blades are pitched similar to a pitch-controlled wind turbine, in order to achieve maximum efficiency. At high wind speeds the blades go into a deeper stall by being pitched slightly into the direction opposite to that of a pitch-controlled turbine. The active stall wind turbine achieves a smoother limited power, without high power fluctuations as in the case of pitch-controlled wind turbines. This control type has the advantage of being able to compensate for variations in air density. The combination with the pitch mechanism makes it easier to carry out emergency stops and to start up the wind turbine (Abad, et al., 2011; Fox, et al., 2007).

3.9 Summary

This part of the literature review dealt with some of the knowledge concerning the wind power systems, beginning with a brief history of wind power systems, their advantages as well as their disadvantages, the type of wind turbines, wind generators, and their configurations. At the end, the different characteristics of wind power systems as well as the type of control strategies applied to them are discussed.

SECTION 4
PHOTOVOLTAIC POWER SYSTEMS

4.1 Introduction

Solar energy contributes approximately 94% of the earth's energy. It is the most important source of energy available to the earth and it is responsible for all the biomass on the surface of the earth. Without it, the earth temperature would be close to zero absolute and there would be no life at all (Luque & Hegedus, 2011).

Solar energy can also be used to generate electrical energy. There are two types of solar power generation systems, namely, solar thermal and solar photovoltaic generation systems. Solar thermal power generation uses the sun as source of heat. This heat is captured, concentrated and used to drive a turbine which is coupled to an electrical generator. Solar photovoltaic captures solar energy and converts it directly to electricity using solar cells.

In this chapter, we will present some of the important knowledge of solar photovoltaic generation systems.

4.2 History

The genesis of the photovoltaic process dates back to the nineteenth century and the first man who attempted to produce electricity using solar cells was Fritts in 1883, who noticed the presence of a current from Selenium melted into a thin sheet on a metal substrate and pressed an Argent-leaf as the top contact. The beginning of the modern era of photovoltaic started in 1954 at the Bell Labs in the United States of America when researchers discovered by accident that pn junction diodes could generated a voltage when the room lights were on. A year later they were able to produce a 6% efficient silicon pn junction solar cell. In the same period, many similar achievements were reported in other places in the United States of America as well as in the former USSR. By this time, the first application of photovoltaic was used in the United States of America space programs where Silicon photovoltaic cells were used to power the satellites. As for wind power systems, the interest in photovoltaic systems took on a new turn in 1973 with the world oil embargo. This led many developed countries to encourage photovoltaic research for terrestrial applications. The first thin-film solar cell with efficiency greater than 10% using Cu_2S/CdS (copper sulphide / cadmium sulphide) was produced in the United States of America in 1980 and the year 1982 saw the first 1 MW utility scale PV power plant (USA) with Arco Si modules on 2-axis trackers. In 2002 the cumulatively installed photovoltaic power worldwide reached 2000 MW (Luque & Hegedus, 2003) and Krauter (2006) reports that according to the European Commission of Energy, by 2050, the world could be generating 40% of its electricity from solar power.

4.3 Advantages and disadvantages

4.3.1 Advantages of photovoltaic energy

Solar photovoltaic energy presents some advantages such as (Digambar, 2011; Patel, 2006):

- Energy is free and does not cause pollution of the environment;
- Solar energy is universally available and the increases in solar radiation lead to increases in solar array output;
- Photovoltaic power systems can be dispersed far from utility grids for remote or rural areas where a grid has not been able to reach;
- Short lead times to design, install, and start up a new plant:
- Highly modular, hence, the plant economy is not strongly dependent on size;
- Power output matches very well with peak-load demands;
- Static structure, no moving parts: hence, no noise. High power capability per unit of weight;
- Longer life with little maintenance because of no moving parts. Highly mobile and portable because of light weight.

4.3.2 Disadvantages of photovoltaic energy

The main disadvantages of photovoltaic systems are (Digambar, 2011):

- High cost of solar;
- Low power density;
- No constant and probability nature of power entry (solar);
- Efficiency improvements. A cost-effective use of photovoltaic requires a high-efficiency approach to energy consumption. This often dictates replacing inefficient appliances;
- Some Photovoltaic systems use batteries for storing energy, which increase the size, cost, and complexity of a system.

4.4 Solar cell

4.4.1 Introduction

The principal elements of photovoltaic systems are solar cells and the process of photovoltaic conversion is done in two steps. These steps consist of the absorption of sunlight by solar cells which generate an electron-hole pair. The electron and hole are then separated by the structure of solar cell: the electron to the negative terminal and the hole to the positive to generate electricity.

Figure 2.20 describes a simple schematic of a solar cell showing the creation of electrons and holes. The sunlight hits the solar cell on the top. The two solar cell electrical contacts are formed by the metallic grid on the top and the metallic layer on the back of the cell. The electrons migrate to metallic grids whereas the holes migrate to the metallic layer. The anti-reflective layers between the metal grid lines play the role of increasing the amount of the light transmitted by the semiconductor (Luque & Hegedus, 2011; McEvoy et al., 2003).

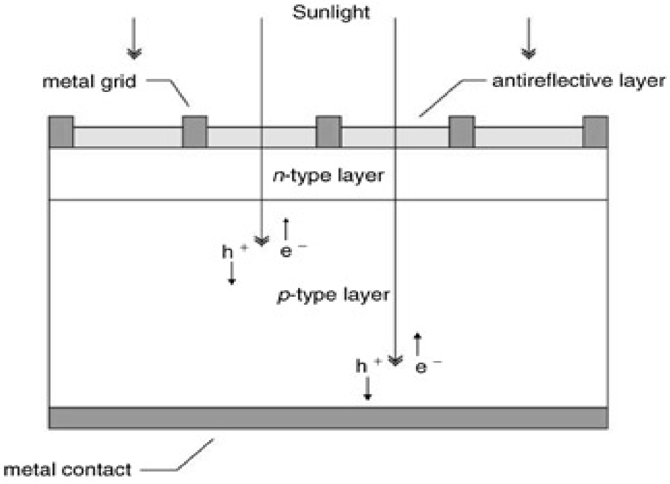


Figure 2.20 Solar cell conventional schematic (Luque & Hegedus, 2011)

4.4.2 Solar cell materials

Diverse types of solar cell materials are used in photovoltaic technology and the most common are crystalline, amorphous and thin-film cells (Kamal, et al., 2011; Wenham, et al., 2007).

4.4.2.1 Crystalline cells

Crystalline solar cells are divided into two types: monocrystalline and polycrystalline cells.

4.4.2.1.1 Monocrystalline cells

Monocrystalline cells are made using cells cut from a single cylindrical crystal of silicon. They are slightly more expensive due to their complex manufacturing process and offer the highest efficiency (approximately 18% conversion of incident sunlight) (Kamal, et al., 2011).

4.4.2.1.2 Polycrystalline cells

Polycrystalline cells are made by cutting micro-fine wafers from ingots of molten and recrystallized silicon. They are cheaper to produce and offer a slightly lower efficiency than monocrystalline cells (approximately 14% conversion of incident sunlight) (Kamal, et al., 2011).

4.4.2.2 Amorphous and thin film cells

Amorphous cells are one type of thin film technology used in many photovoltaic modules. They are made from randomly arranged atoms lacking ordered structure (Maricar, et al., 2003).

Unlike crystalline cells, amorphous and thin film cells offer further advantages such as (Lynn, 2010):

- Relatively simple fabrication at low temperatures using inexpensive substrates and continuous ‘ production line ’ methods;
- Integrated, monolithic, design obviating the need to cut and mount individual wafers;
- Potential for manufacturing flexible, lightweight products.

However, their efficiency range varies between 6 and 7% (Maricar, et al., 2003).

4.4.3 Solar cell equations

Figure 2.21 below displays the equivalent circuit of a PV Solar cell according to the one diode model. This model includes a current source in parallel with a diode and a parallel and series internal resistance R_p and R_s.

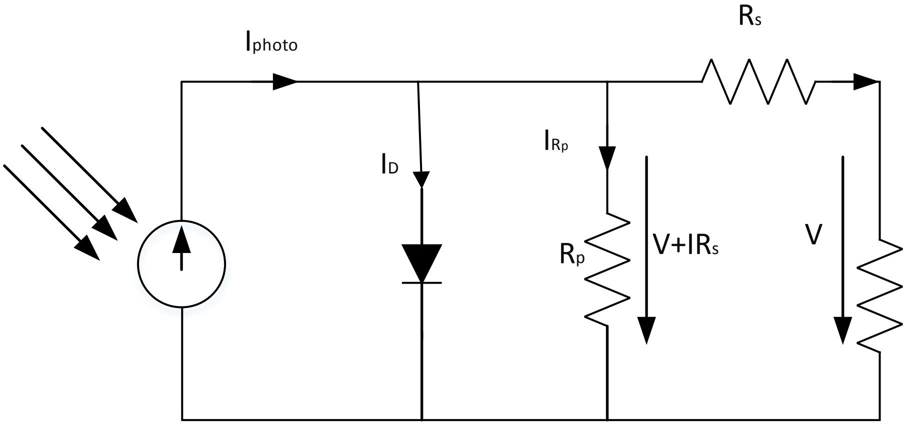


Figure 2.21 Equivalent circuit of a PV Solar Cell (Masoum et al., 2002)

From this equivalent circuit in figure 2.21, the output current of the PV solar cell is given by (Krauter, 2006):

$$I = I_{photo} - I_0\left(exp\frac{q(V+I.R_S)}{kT} - 1\right) - I_{R_p} \tag{2.16}$$

$$R_p = R_{p,dark}.\,e^{-\alpha E} \tag{2.17}$$

$$I_{R_p} = \frac{V+I.R_S}{R_p}\left(1 + a\left(1 - \frac{V+I.R_S}{V_{br}}\right)^{-m}\right) \tag{2.18}$$

where a is the avalanche factor, E the irradiance in W/m², I_0 the diode saturation current in Amp, I_{photo} the photo current in A, I_{Rp} the current of parallel resistor in A, k the Boltzmann constant (1.381.10^{-23} J/K), m the avalanche exponent, q the elementary charge (1.602.10^{-19} As) , R_P the parallel (or shunt) resistor in Ω, R_S the series resistor in Ω (0.05-0.5 Ω), T the absolute temperature in K, V_{br} the breakdown voltage in Volt and α the coefficient for dependence of irradiance in R_p, in m²/W.

4.4.4 Solar cell output characteristics

The different parameters used to characterise the solar cell output are the short circuit current, the open circuit voltage, maximum power point and the fill factor.

4.4.4.1 Open circuit voltage

An open circuit voltage is defined as the voltage between the two terminals of the solar cell when no load is connected to it. The open circuit voltage (U_{0C}) is given by the equation (McEvoy et al., 2003):

$$U_{OC} = \frac{k.T}{q} ln\left(1 + \frac{I_{photo}}{I_O}\right) \tag{2.19}$$

4.4.4.2 Short circuit current

A short circuit current (I_{sc}) is the maximum current that can flow from a solar cell when its terminals are short circuited or when the voltage across the solar cell is equalled to zero (see Figure 2.22). Its value is proportional to the irradiance level.

4.4.4.3 Maximum Power Point

A maximum Power Point (MPP) is the point where the solar cell supplies its maximum power. The voltage and the current corresponding to the Maximum Power Point are respectively Maximum Power Voltage U_{MPP} and the Maximum Power Current I_{MPP}.

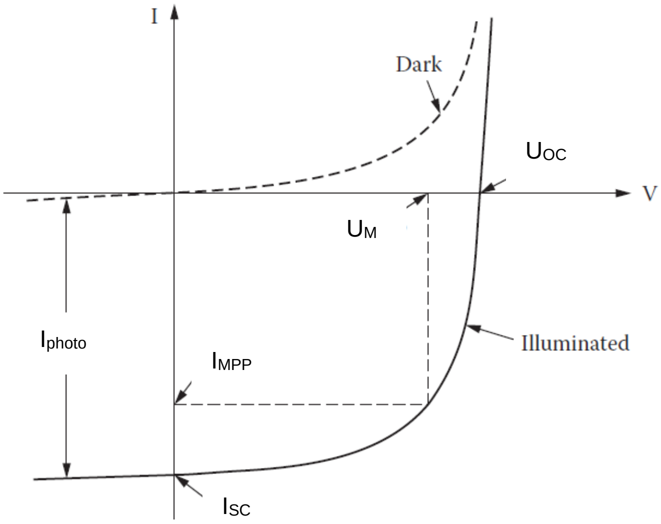


Figure 2.22 Current versus voltage curve of a PV cell in dark and under illumination (Foster et al., 2009)

4.4.4.4 Fill Factor

The Fill Factor expression is given by the equation 2.21 (McEvoy et al., 2003):

$$FF = \frac{U_{MPP} I_{MPP}}{U_{OC} I_{sc}} \tag{2.20}$$

Where FF, U_{MPP} , I_{MPP}, U_{OC} and I_{sc} are the Fill Factor, the voltage at the maximum power point, the current at the maximum power point, the open circuit voltage and the short circuit current respectively.

Another expression giving the Fill Factor is (McEvoy et al., 2003):

$$FF = \frac{\upsilon_{oc} - ln(\upsilon_{oc} + 72)}{\upsilon_{oc} + 1} \tag{2.21}$$

Where υ_{oc} is the normalised voltage defined by:

$$\upsilon_{oc} = \frac{U_{OC}}{\left(\frac{k.T}{q}\right)} \tag{2.22}$$

Where U_{OC}, k, T, q are the voltage at the maximum power point, the Boltzmann constant (1.381.10^{-23} J/K), the absolute temperature in K and the elementary charge (1.602.10^{-19} As) respectively.

4.4.5 Solar cells efficiency

Solar cell efficiency is defined as the amount of electrical energy produced by a solar cell and divided by the sunlight energy striking it. This efficiency depends not only on available solar energy but also on how the solar cell converts the sunlight to electrical energy. The expression showing the solar cell efficiency is given by the equation (Maricar, et al., 2003):

$$\eta = \frac{P_{max}}{(Irradiance*Area)*100} \tag{2.23}$$

Where P_{max} is the solar cell maximum power output in kWh, the irradiance is defined as the solar radiation intensity expressed in kWh/m^2, the area in m^2.

The solar cell efficiency can also be expressed by the following equation (Foster, et al., 2010):

$$\eta = \frac{U_{MMP}.I_{MMP}.FF}{P_{in}} \tag{2.24}$$

Where P_{in} is the total power in the light incident on the solar cell, FF the Fill Factor, U_{MPP} the voltage at the maximum power point and I_{MPP} the current at the maximum power point.

From the equation 2.24, an efficient solar cell must have a high short-circuit current, a high open-circuit voltage and a fill factor *FF* as close as possible to 1 (Luque & Hegedus, 2011).

4.4.6 Current versus voltage curve of a solar cell

The characteristics of current versus voltage curves of the solar cell for different degrees of insolation as well as their corresponding maximum power P_{max} is shown in Figure 2.23. The curves in locus represent the solar cell generator voltage as a function of the current.

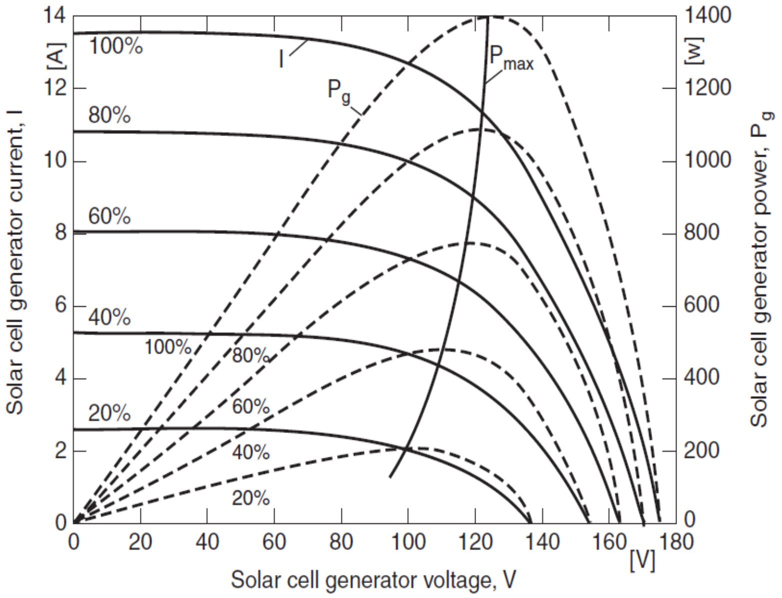


Figure 2.23 Current versus Voltage of a PV Cell (Digambar, 2011)

4.4.7 Effect of temperature on solar cell output

As shown in Figure 2.24, the solar cell operating temperature has an effect on its voltage versus current characteristic. When the temperature is higher, I_{SC} increases while U_{OC} decreases and consequently there is a decrease in the maximum power output of the solar as well as its efficiency.

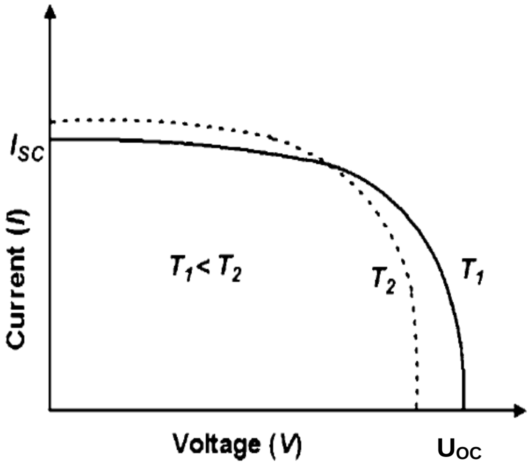


Figure 2.24 Effect of temperature in I-V solar cell curve (Ghosh & Prelas, 2011)

4.5 Photovoltaic Systems

Photovoltaic systems are designed around a photovoltaic cell (solar cell) and other key components. A typical solar cell produces less than 3 watts at approximately 0.5 volt dc. To obtain enough power and voltage rating for high power application, solar cells are connected in series and parallel configurations. Figure 2.25 shows how a single solar cell can be connected to form a module and how modules can be connected to form an array. Modules can have an output power ranging from a few watts to hundreds and an array output power can vary from hundreds of watts to Megawatts (Messenger & Ventre, 2005).

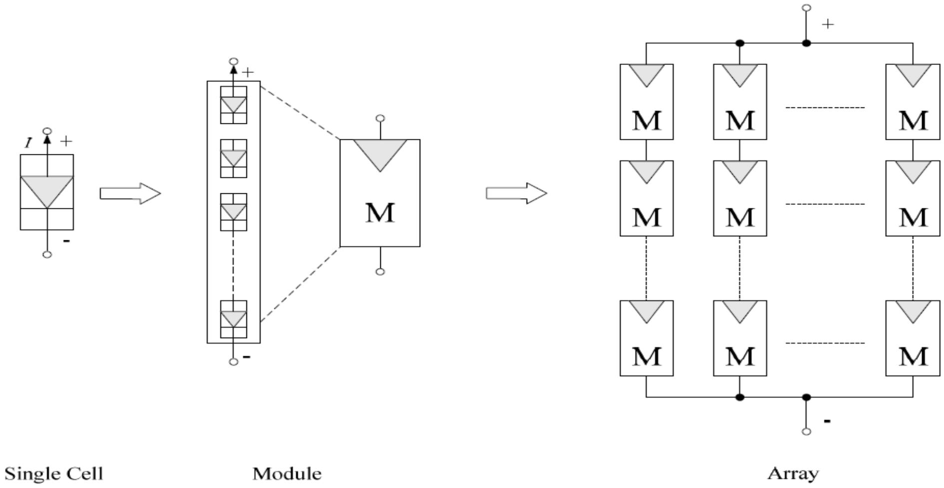


Figure 2.25 Solar cell, module and array (Wang, 2006)

4.5.1 Series configuration

By adding cells or identical modules in series, the current in the branch remains the same while the voltage rises proportionally to the number of cells or modules in series. This is illustrated in Figure 2.26 below.

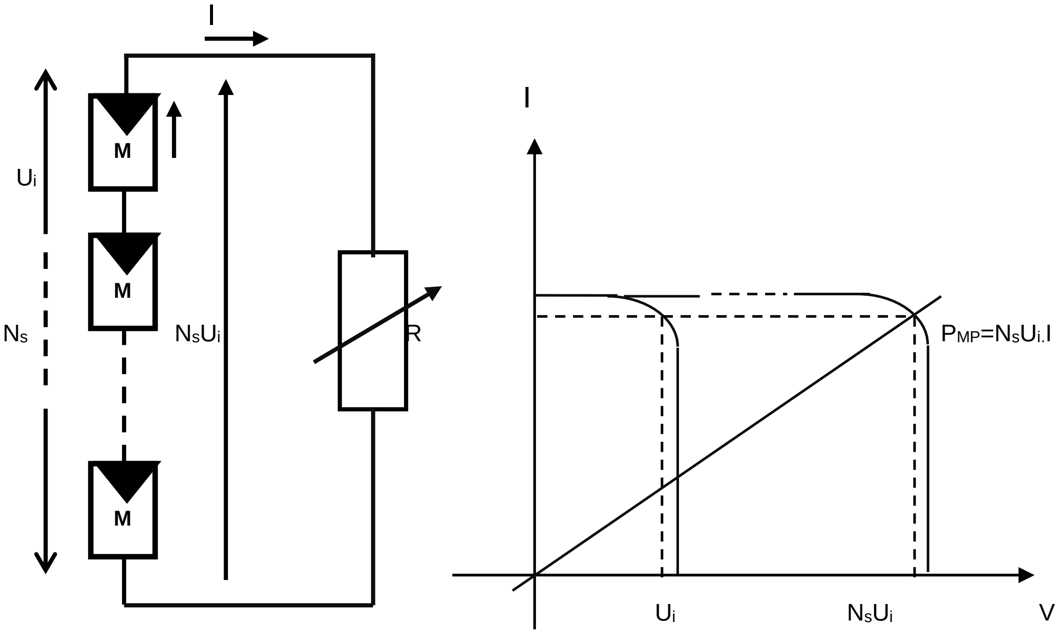


Figure 2.26 Voltage versus current characteristics of identical modules in series

The total voltage of modules in series U_s is given by the equation:

$$U_s = N_s U_i \tag{2.25}$$

Where, N_s and U_i are the number of modules in series and the voltage of each module respectively.

The total current of modules in series I_s is given by the equation:

$$I_s = I \tag{2.26}$$

Where I_s is the current in each module.

4.5.2 Parallel configuration

By adding cells or identical modules in parallel, the voltage in the branch remains the same while the current rises proportionally to the number of cells or modules in series. This is illustrated in Figure 2.27.

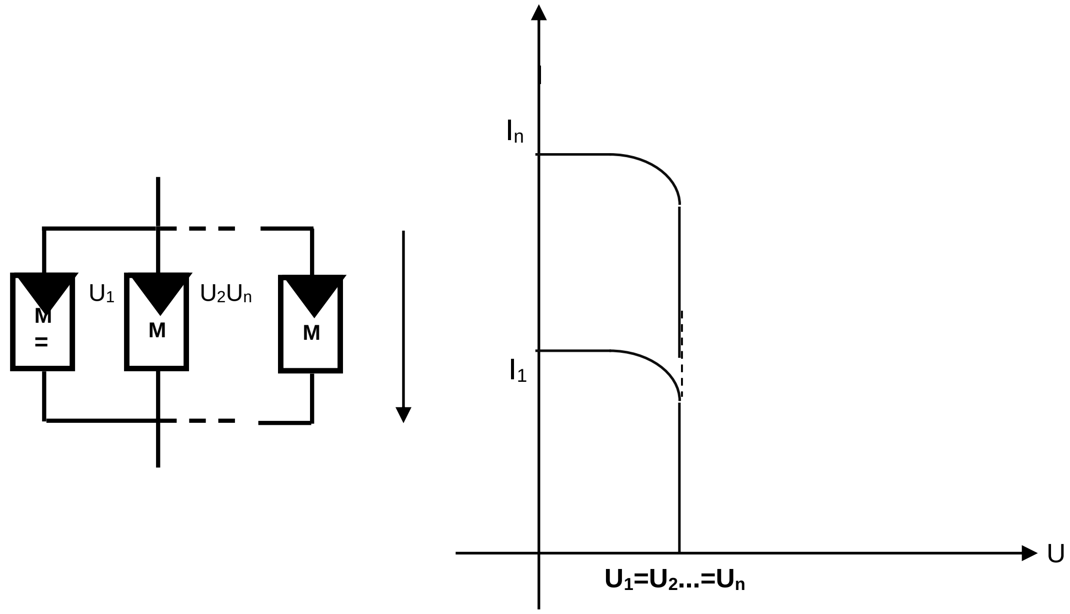


Figure 2.27 Voltage versus current characteristics of identical modules in parallel

The total voltage of modules in series U_p is given by:

$$U_p = U_1 = U_2 \ldots = U_n \tag{2.27}$$

Whereas the total current of modules in series I_p is given by the expression:

$$I_p = N_p I_i \tag{2.28}$$

Where, N_p and I_i are the number of modules in parallel and the current of each module respectively.

4.5.2 Classification of photovoltaic systems

Photovoltaic systems are classified according to the diagram in Figure 2.26. As depicted in this figure, the two main classifications are off grid and on grid photovoltaic systems. This section describes the different photovoltaic system configurations.

4.5.2.1 Small off grid DC Photovoltaic systems

Most small off grid photovoltaic systems are used directly to supply power to DC loads such as: space-based systems, portable solar devices and small consumer products, very small residential systems, water pumping, and other DC small applications that are less than 1 kW in size (Luque & Hegedus, 2011).

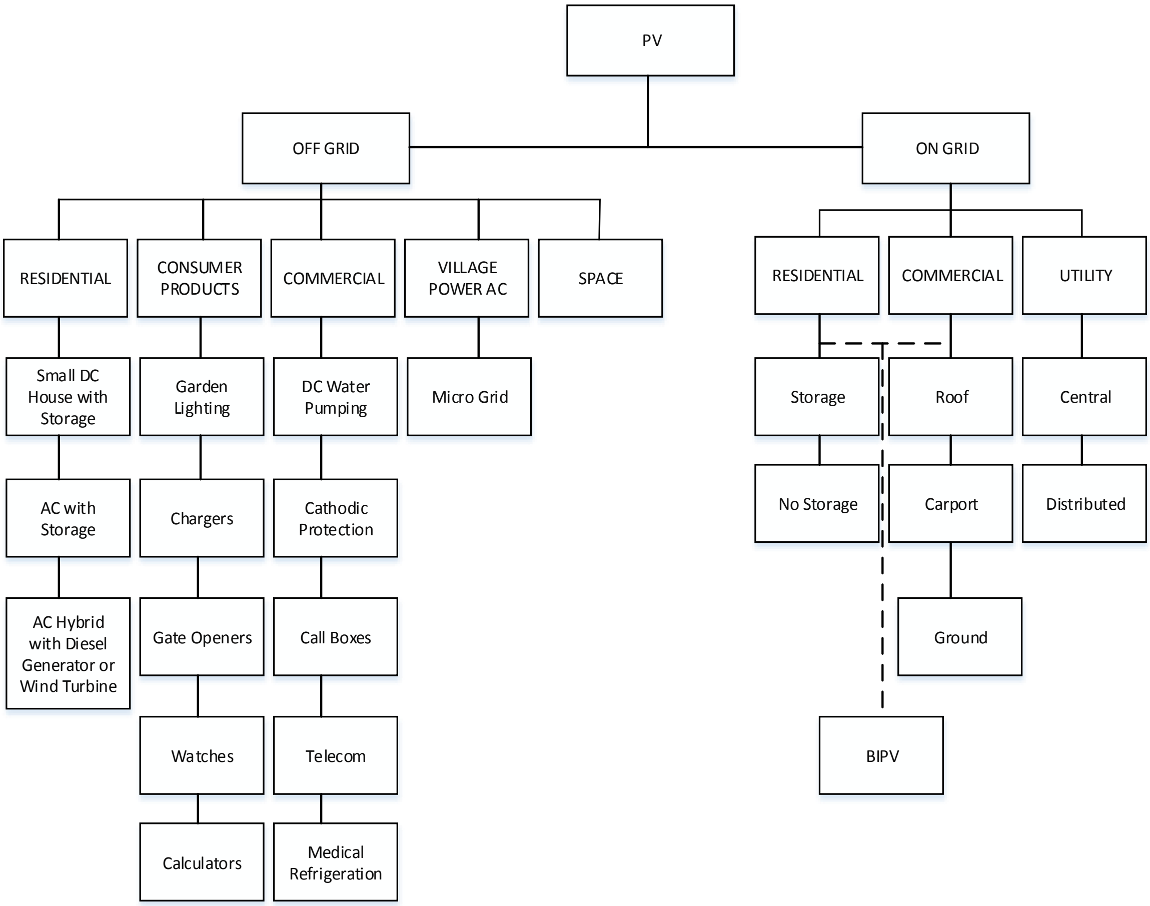


Figure 2.28 Photovoltaic systems taxonomy (Luque & Hegedus, 2011)

4.5.2.2 Off-grid AC System

In off grid photovoltaic AC systems the energy is converted to AC power via an inverter which also acts to regulate the AC voltage to all of the loads. Due to the intermittence, this configuration always requires energy storage for the power balance between Photovoltaic energy sources and the load requirements. A simple schematic of an off-grid system is shown in Figure 2.27 (Luque & Hegedus, 2011).

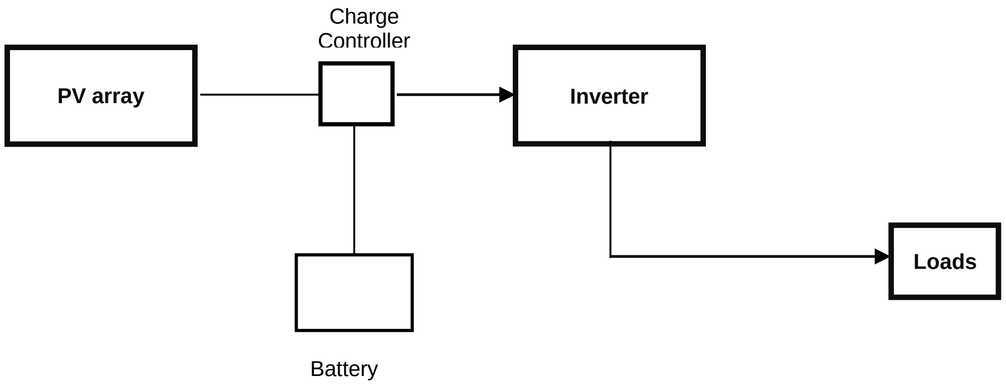


Figure 2.29 Off grid photovoltaic systems

4.5.2.3 Grid connected photovoltaic systems

In grid connected photovoltaic systems, the Photovoltaic power is converted to AC current by an inverter and injected into a utility grid. The AC voltage and frequency from the photovoltaic system must be synchronized with the utility grid it is interconnected with. Figure 2.28 shows a block diagram of a grid connected photovoltaic system (Luque & Hegedus, 2011). Photovoltaic grid connected systems are classified as roof-mounted and utility scale large systems.

In roof-mounted systems, the energy produced by the PV is used for household needs and the exceeding power is injected to the grid. The disadvantage here is the PV array orientation which is dictated by the roof.

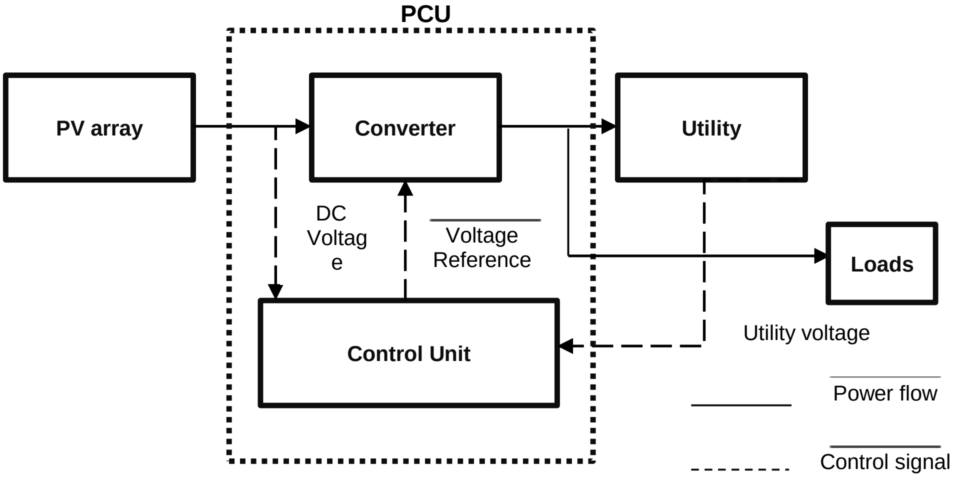


Figure 2.30 Block diagram of an on grid photovoltaic system

4.6 Model of photovoltaic system power output

The expression of a power output of a photovoltaic system having an area A_s and subjected to a horizontal irradiance H is given by the equation (Chedid & Rahman, 1998):

$$P_s = H.A_s.eff_s \tag{2.29}$$

In this equation, $\boldsymbol{P_s}$ and $\boldsymbol{eff_s}$ are the power output of the photovoltaic system and the efficiency of the corresponding inverter respectively.

4.7 Summary

A photovoltaic system also known as solar photovoltaic system or photovoltaic power system is simply the conversion of the sunlight into electrical power in the form of direct current using photovoltaic arrays. In this section, some of the important knowledge on these types of systems have been presented: the different types of these solar cells as well as the solar cell equivalent circuit, the characteristics of electrical current versus voltage, voltage versus electrical power and the different parameters of a solar cell. At the end of this section, the different configurations of photovoltaic systems was discussed.

SECTION 5
ELECTRICAL DISTRIBUTION SYSTEM

5.1 Introduction

The electric power generated from the generating power station is delivered to the consumers through the distribution systems. The electrical distribution network is referred as the portion of the electric power system starting from the distribution substation to the consumers. Its role is to take the electric power from the sub-transmission line and deliver it to the consumers. Typically, the electrical distribution systems are divided into six different parts which are: the sub-transmission circuits, the distribution substation, the primary distribution, the distribution transformer, the secondary distribution and the consumers' service connections. In this chapter, we will give an overview of these six different parts of an electrical distribution network mentioned above as well as the distribution systems topology**.** Lastly, we will describe the new configuration of the electrical distribution network.

5.2 Different parts of an electrical distribution

As stated in the introduction, a typical electrical distribution consists of six different parts shown in Figure 2.29.

5.2.1 Sub-transmission circuits

The sub-transmission circuits consist of either an aerial cable, or overhead open wire conductors, underground cable and in some cases a combination of these. Their voltage level varies from 11 to 33 kV depending on countries or companies. They cover the part between the bulk power source or sources to the distribution substations. The sub-transmission systems can be radial circuits connected to a bulk power source at only one end or loop and ring circuits connected to one or more bulk power sources at both ends.

5.2.2 Distribution substation

The principal function of the distribution substation is to reduce the voltage to the distribution voltage level. The distribution substations are generally fed by the sub-transmission lines with a standard distribution voltage level of 34.5kV, 23.9 kV, 14.4 kV, 13.2 kV, 12.47 kV, and, in older systems, 4.16 kV, but in other cases, the distribution substations are fed directly via high voltage transmission lines rather than the sub-transmission lines. Generally, the distribution substation includes the components such as the transformer, the circuit breakers and switches. They may also include capacitor banks to provide reactive power support. The distribution substations are situated near the consumers and include step down transformers to step down the voltage for domestic usage.

5.2.3 Primary distribution

The primary distribution refers to the part of the substation fed by the sub-transmission or transmission lines (Bulk transmission). Larger commercial and industrial customers often receive their service directly at higher voltages, through the primary distribution system.

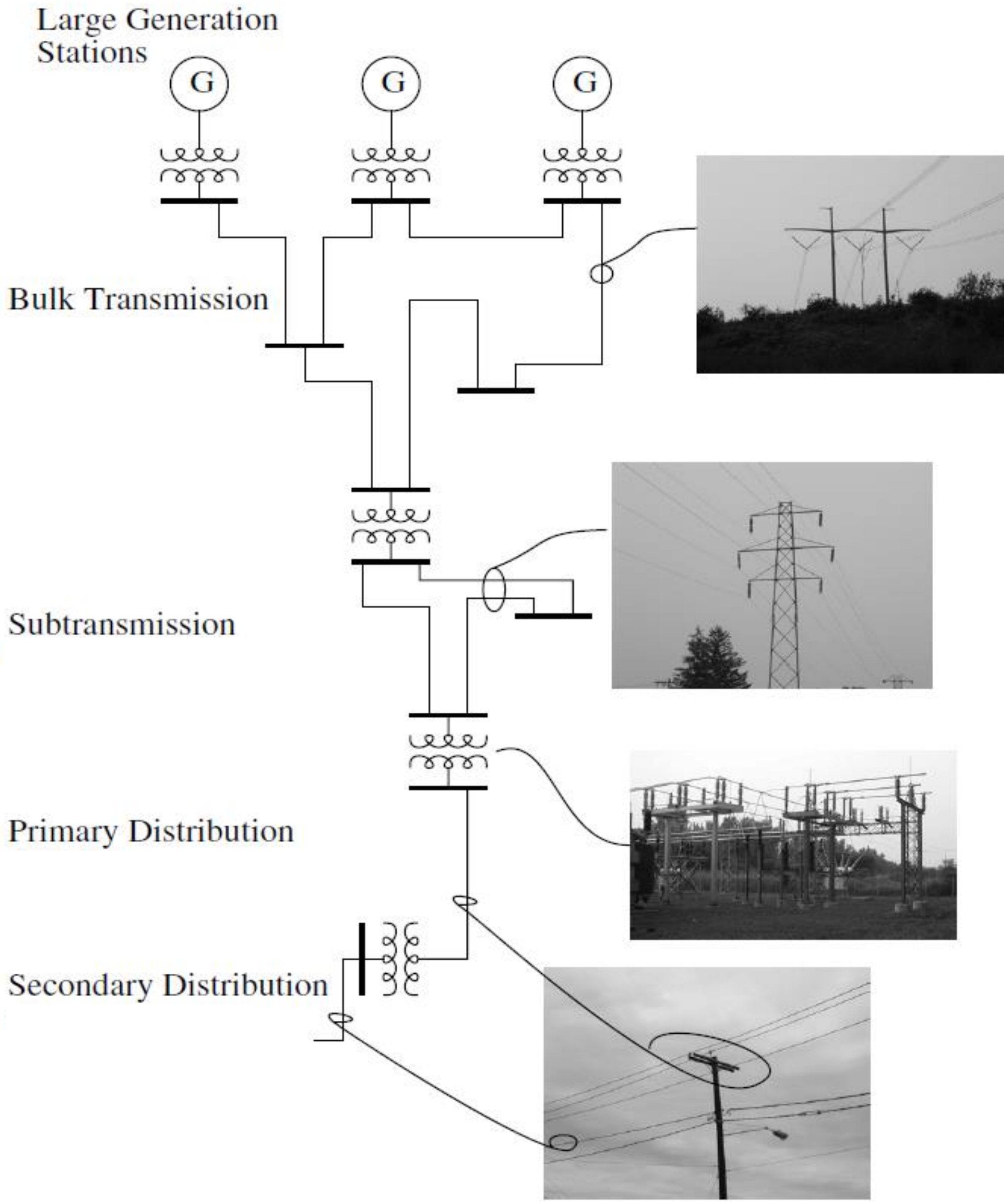


Figure 2.31 Power system layout (Short, 2005)

5.2.4 Secondary distribution

The secondary distribution is the part of the electrical distribution where the domestic consumers are connected. The standard level of voltage used in the secondary distribution is 400/230 kV.

5.3 Different topology of the distribution system

Distribution systems can be found in three different configurations which are radial configuration, loop configuration and network configuration.

5.3.1 Radial configuration

The radial configuration is the simplest distribution system configuration in which the power flows to the loads in only one path. It consists generally of an electrical substation, radial feeders for energy delivery and a transformer which converts the voltage to the utilization level. The principal advantage of the radial configuration is its lowest initial cost compared to other configurations. However, this configuration presents some drawbacks, for example: If the consumers depend only on one feeder and there is any fault on the feeder, all the consumers on the side of the fault will be deprived of power. Another drawback is the fact that the end of the distributor which is the conductor from which the tappings are taken for supply are heavily supplied nearest the feeding point and in this configuration the consumers at the end of the distributor would be subjects to serious voltage fluctuations when the load on the distributor changes. As a result of these drawbacks, radial distribution systems are only used for short distance supply. Figure 2.32 illustrates the scheme of a radial distribution system.

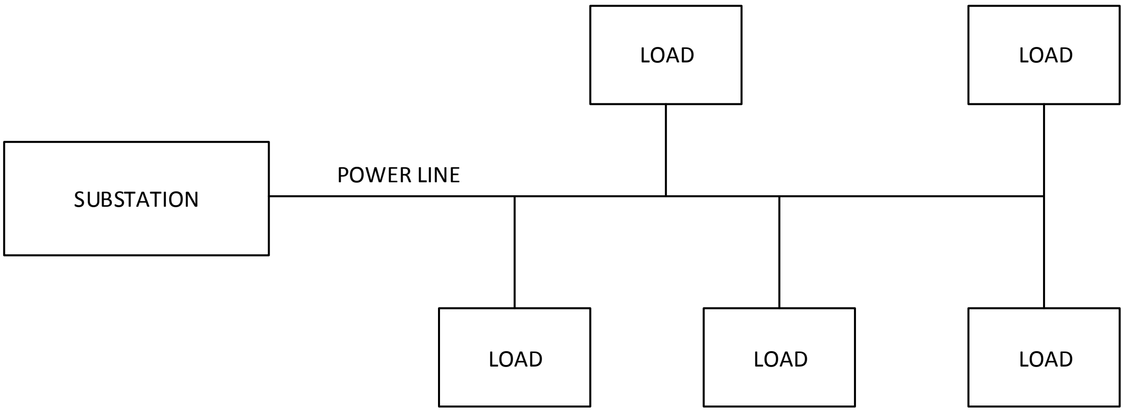


Figure 2.32 Radial distribution system configuration (Patrick & Fardo, 2008)

5.3.2 Loop configuration

In this configuration, the primary distribution transformers form a loop from the substation through the serving supply area. The loop configuration has some advantages: There is less voltage fluctuation at the consumer's terminals and also better system reliability due to the fact that distributors are served by two feeders. In case of a fault on any of the feeders the consumers can still be supplied through the other feeder.

Figure 2.33 below shows a scheme of a loop configuration.

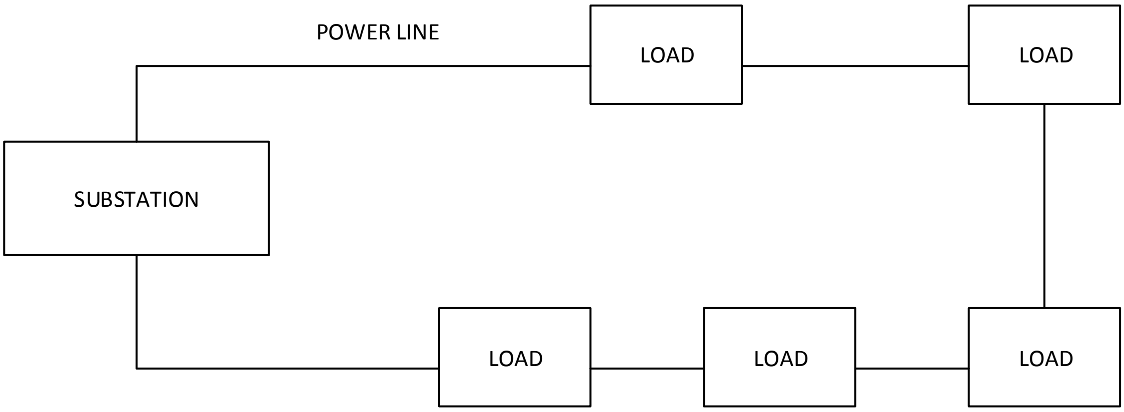


Figure 2.33 Loop distribution system configuration (Patrick & Fardo, 2008)

5.3.3 Network configuration

This configuration is among the most complex electrical distribution configurations in which each load receives its power and its energy from several different transformers that are simultaneously supplied from different feeders by interconnecting the secondary winding of these transformers in parallel so that the load can be served by these different transformers.

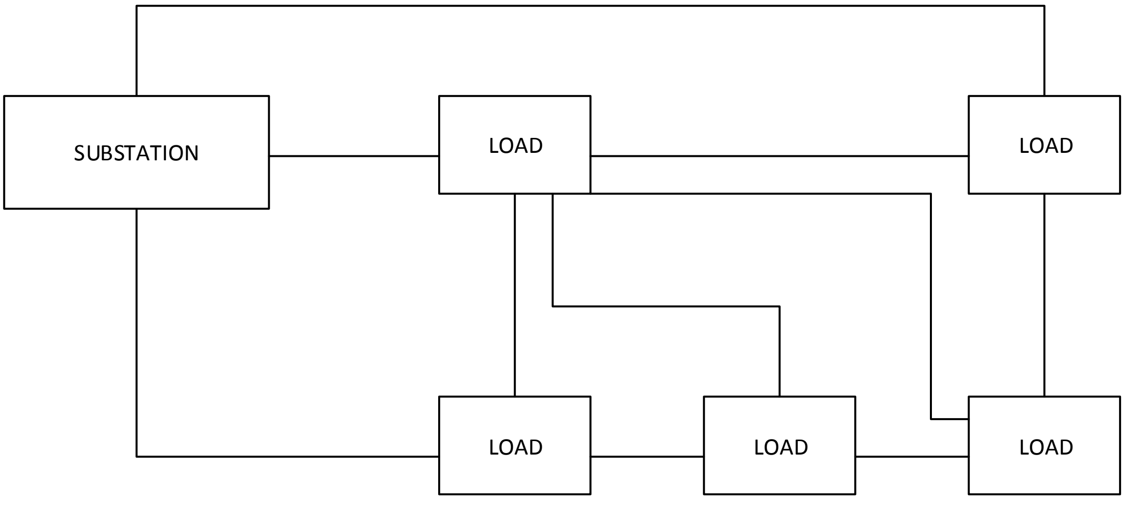


Figure 2.34 Network distribution system configuration (Patrick & Fardo, 2008)

5.4 New architecture of electrical distribution systems

Originally, the electrical distribution system was designed to supply electricity to the consumers using a unidirectional path by transmitting the electricity from the generation systems to the transmission system, the sub-transmission and finally to the primary and secondary distribution. Nowadays, this traditional path is broken. Today, the distribution system has other generation systems known as distributed generation (DG) which brings new challenges in how to plan and operate networks distribution. Depending on the conditions of the load and generation, the distributed generation may cause bidirectional flow and many other problems. In this section we are going to discuss the impact of distributed generations in the distribution system in terms of electrical parameters, planning and operation.

5.4.1 Distributed generations

Distributed generations are defined as intermittent generation sources (wind, solar etc.) or non-intermittent (central heat, diesel among other groups) that are connected to the distribution network. Their installed capacity must be less than 12 MW at the Point of Common Connection (PCC) when the system is connected to an area that is not interconnected with the main utility network and less than 17 MW otherwise. Generally, the distributed generations with power higher than the power mentioned above are directly connected to the transmission systems (Alvarez-Hérault, 2009).

5.4.2 Impact of distributed generation on the electrical parameters of the distribution system

5.4.2.1 Impact of the voltage

In an electrical distribution system, the level of voltage has an effect on consumers' equipment. Depending on whether we have a lower or higher level of voltage, consumers' equipment can malfunction or be damaged. Therefore, it is required to retain the grid voltage at an acceptable level.

Considering a three-phase electrical conductor of length L represented in Figure 2.35 characterised by r and x resistance and inductance per kilometre, respectively, and a voltage phase to phase U supplying an electrical current I to a three phase load.

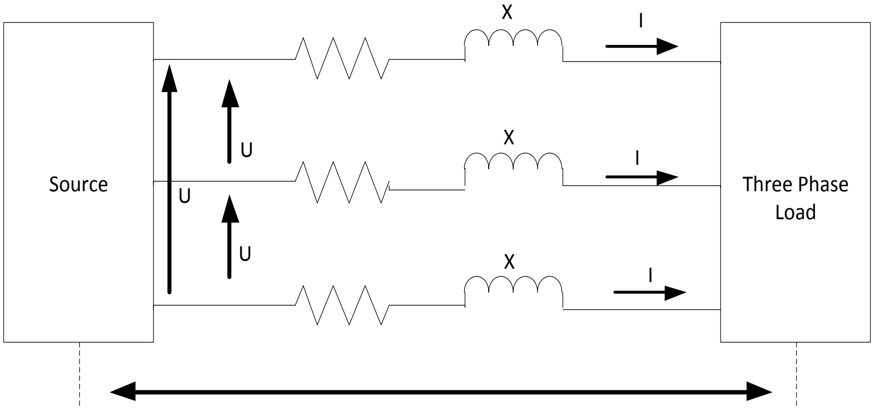


Figure 2.35 Three phase system with load (Alvarez-Hérault, 2009)

The voltage drop between the source and the load expressed in percentage is given by the equation:

$$\frac{\Delta U}{U} = \frac{r.L.P + x.L.Q}{U} \tag{2.30}$$

Where P and Q are active and reactive powers, respectively, and defined by the equations:

$$P = U.I.cos\varphi$$

$$Q = U.I.sin\varphi$$

In the equations (2.31) and (2.32),φ is the angle between the current and the voltage.

From the equation (2.30), it appears that the voltage drop depends mostly on the length of the electrical conductor as well as on the active and reactive powers.

In the conventional distribution system, the voltage and reactive power control equipment are meant to operate based on an assumption that the power can flow using one direction only which is from the transmission to distribution system, whereas with the presence of a Distributed Generator in the distribution system, this assumption can no longer be applied. The power generated by Distributed Generators increases voltage in the distribution system and the voltage at the Point of Common Coupling can be higher than the voltage at the substation. Moreover, when the Distributed Generator's power output is high, the power can flow from the distribution system to the utility grid (Caples, et al., 2011).

5.4.2.2 Impact on the power

The presence of Distributed Generators changes the power flow in the distribution system. Consider for instance the example in Figure 2.36 representing a distribution transformer connected to five loads in nodes 2, 3, 4, 5 and 6 and a Distributed Generator connected to node 5. By assuming that all the loads are equally distant and the DG operating at its maximum power, the DG will not only supply power to the load connected to node 5 but also to the other loads.

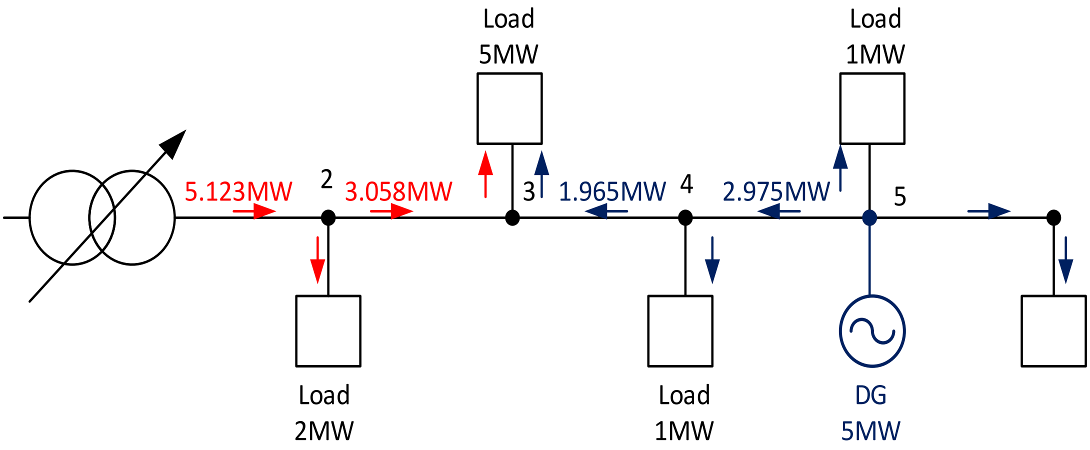


Figure 2.36 Power flow in the distribution network with a DG connected to node 5 (Alvarez-Hérault, 2009)

In this case, the power flow in the distribution system will become bidirectional and the power lost will be reduced according to the equation:

$$P_l = \frac{R}{U^2}(P^2 + Q^2)$$

Where P_l, R, U, P and Q are power lost, resistance, Voltage, active power and reactive power respectively.

Depending on the size and number of DG connected to the distribution system, it may happen that the DG are exporting power to the transmission system as shown in Figure 2.37 where DGs are connected to nodes 3 and 5.

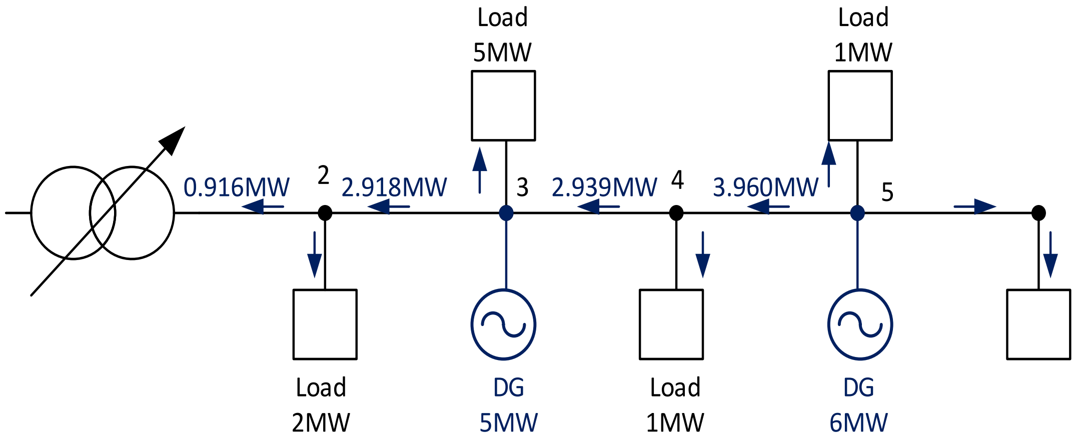


Figure 2.37 Power flow in the distribution network with a DG connected to nodes 3 and 5 (Alvarez-Hérault, 2009)

5.4.2.3 Impact on short circuit current

The integration of Distributed Generators (DG) in the distribution network changes the overall impedance of the network and therefore the short-circuit current and the short-circuit power. It is possible that the short-circuit current is modified and provokes the dysfunction of protective equipment.

5.4.2.4 Impact on voltage quality

Connecting Distributed Generators (DG) to the distribution network can also affect the quality of the voltage wave. This is determined by a set of indices such as Flicker, voltage dips, harmonics and unbalanced three phase system.

5.4.2.4.1 Flicker

Flicker effect refers to the change of the voltage lower than 10% of the rated voltage repetitively. It comes from the operation of some machines such as arc furnaces, for instance. The Flicker effect does not have an impact on the equipment. However, it causes visual discomfort because it is responsible for the flicker of incandescent bulbs. The "flicker" can appear because of the intermittent nature of Distributed Generators (DG) such as wind turbines or solar panels.

5.4.2.4.2 Voltage dips

This is an abrupt decrease in the voltage of up to 90% of the voltage rated for a period between 10 ms and 1 minute. The operation of a protection system can limit the duration of voltage dips due to multi-phase faults. Voltage dips can also occur when a Distributed Generator is connected to the electrical grid.

5.4.2.4.3 Harmonics

Harmonics are defined as deformed waves, voltage or current. Some Distributed Generator (photovoltaic and others) may have power electronic interfaces. It is these electronic power devices that are responsible for creating more high frequency harmonics that can cause premature aging of materials. In addition, they are responsible for acoustic discomfort in transformers and vibration in rotating machinery.

5.4.2.4.4 Imbalanced three-phase system

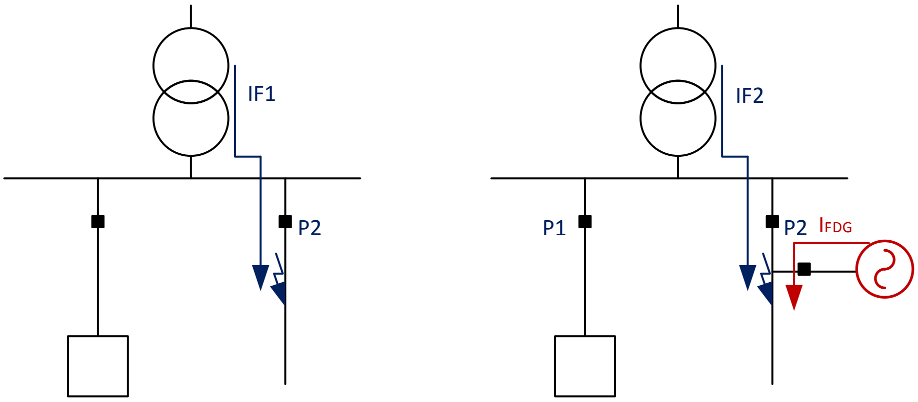
An imbalanced three-phase system is caused by a bad phase balancing and can provoke voltage decreases or increases. Such problems can occur in the medium voltage when connecting a single phase Distributed Generator on the low voltage electrical network in the same way as conventional single-phase loads.

5.4.3 Impact of Distributed Generator in the exploitation of electrical network

The integration of distributed generators in the electrical network can present some negative impacts. Two types of problems can occur: the problem of blindness and nuisance tripping of protections devices.

5.4.3.1 Blindness of protection devices

This type of problem is shown in Figure 2.38 and appears when a fault occurs on a feeder with a Distributed Generator (DG). In the feeder without a DG the protection devices are set in such way that the current I_{P2} in the protection threshold P_2 is equal to the fault current I_{F1} and once a DG is integrated it will participate with the fault current and the fault current from the upstream network I_{F2} is then less than I_{F1}, therefore below the protection threshold P_2 and does not trigger.

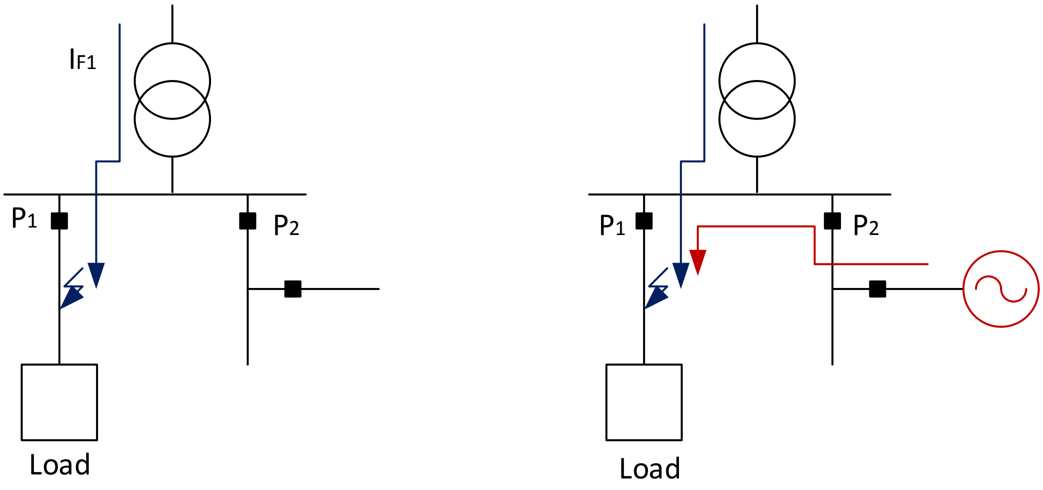


$I_{P2} = I_{F1}$ $\quad$ $I_F = I_{F2} + I_{FDG}$ and $I_{F2} < I_{F1}$

Figure 2.38 Blindness of protection devices in a feeder with DG (Alvarez-Hérault, 2009)

5.4.3.2 Nuisance tripping of protections devices

The nuisance tripping of protection devices is shown in Figure 2.39 and appears when a fault occurs in an adjacent feeder initially with a DG, being part of the fault current, the DG can trigger P_2 protection if the fault current from the DG (I_{FDG}) is above the threshold P_2 protection (I_{P2}).



$I_{FDG} > I_{P2}$

Figure 2.39 Nuisance tripping of protection devices (Alvarez-Hérault, 2009)

5.5 Summary

This section was dedicated to the electrical distribution network and some of the problems that may occur when a Distributed Generator is integrated to it. Firstly, the different parts of a normal electrical distribution system as well as the different topologies of the electrical distribution system was discussed and in conclusion, the new configuration of the electrical distribution system which includes distribution generators and the impact of these distribution generators on the distribution system has been presented.

CHAPTER THREE
OUTLINE OF THE PROPOSED SYSTEM

3.1 Introduction

This chapter is dedicated to the description of the different components which are part of the system under study. A modelling process with SysML, requires a clear description of the system, identification of all its components, their properties as well as their behaviour.

3.2 Description of the system

3.2.1 Description of the system operation

Figure 3.1 shows the overall view of the proposed system which consists of a small hybrid photovoltaic wind power systems connected to the secondary distribution of a utility grid through a distribution system.

In this study, we have considered that this hybrid power system is operating according to four modes of operation depending on the availability of primary energy sources (wind and solar) used to generate the electricity. These operating modes will be presented in section 3.2.2.1.5.

For power management in these different modes, the operation of the system is controlled and monitored by a supervisory and control unit. We assume that the value of the voltage and the current are detected by the sensors placed on different points of the system and then transmitted to the supervisory and control unit through the data acquisition unit for control and supervision in order to ensure that all the subsystems within the system are operating in a proper manner. Sensors are also used in this system to measure and monitor the necessary daily weather data values, such as the wind speed, the wind direction, the sunshine in the horizontal plane and the ambient temperature.

3.2.2 System components

As can be seen in Figure 3.1, the proposed system is composed of subsystems, namely, photovoltaic, wind power and distribution systems, inverter, control and supervising unit, the DC bus and the load. In normal circumstances, the connection of this hybrid power to the grid is done using a disconnection in order to isolate it from the grid to prevent damage to the equipment.

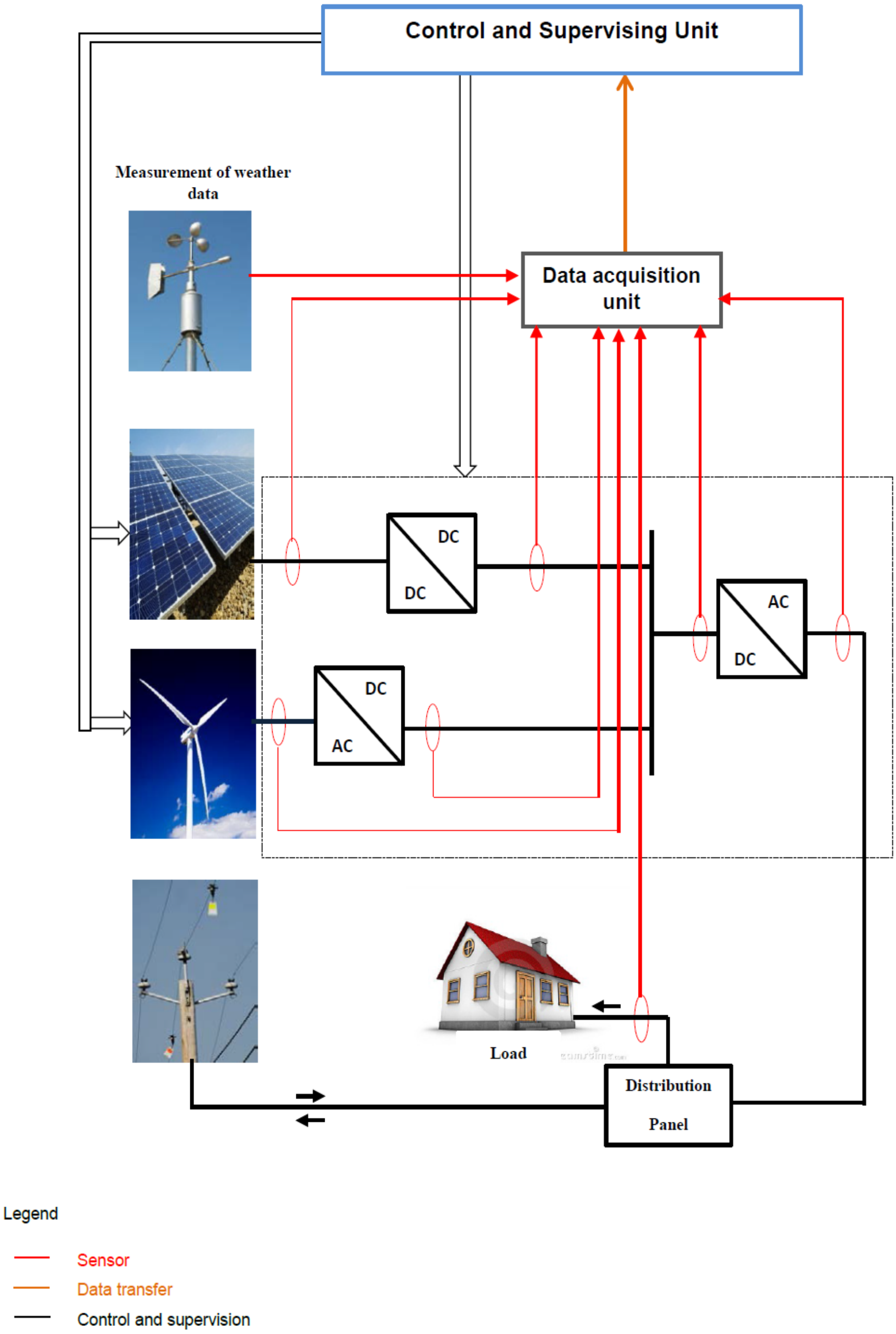


Figure 3.1 View of the proposed system

3.2.2.1 Subsystems description

3.2.2.1.1 Photovoltaic power subsystem

The photovoltaic subsystem consists of a set of photovoltaic panels and a DC to DC boost converter. The power generated by the solar photovoltaic panel is generally at a low voltage. A DC to DC boost converter is used to step up the photovoltaic output voltage to a higher level. The control of the DC to DC boost converter is assured by the supervisory and control unit.

3.2.2.1.1.1 Behaviour of the photovoltaic power subsystem

When the solar energy becomes available, the photovoltaic panels capture the sunlight and convert it into electric energy which flows to the DC to DC boost converter, converting the low voltage DC electrical energy produced to an adequate voltage. From the converter, the electricity travels to the DC bus.

3.2.2.1.2 Wind power system

The wind generation subsystem consists of a small wind power. Due to the variable nature of electrical power output of the wind power system, DC to AC converters are used to control the frequency of the electrical power.

In order to determine the wind power captured by the wind turbine, it is important to be aware of the weather data of the site considered. In our system, all weather data related to the wind power system will be captured by the wind speed sensor (anemometer).

3.2.2.1.2.1 Wind power subsystem behaviour

The first step in the wind power system operation is to check the orientation of the wind turbine relative to the wind. If the wind turbine is not facing the wind, the yaw system is then used to bring back the wind turbine to face the wind.

Once the wind turbine is facing the wind, the behaviour of the wind power system can consist of three different cases. These cases are related to the variation of the wind speed. The wind speed sensor measures the speed of the wind at every operating time for the control of that speed in order to avoid that the extremely high wind speed will cause the shaft to turn too fast and damage the turbine. The first case of the wind power system behaviour refers to the interval of the wind speed starting from the speeds greater than the cut in speed of the wind turbine to the speed less than the cut off speed of the wind turbine. In this interval, to ensure a constant output power from the wind power system, a pitch control system is applied to prevent the wind turbine from overloading. The energy from the wind is captured by the three blades of a wind turbine which are attached to a hub. The hub turns the shaft which is connected to the gear box and the gear box turns the rotor of the electrical generator producing an electrical power. The electrical power is then converted to DC through a rectifier. From the DC rectifier, the DC electrical power flows to a DC to DC converter so that the voltage can be converted to an adequate level of voltage. From the DC to DC converter, the electrical power travels to the DC bus.

The second case refers to the interval of wind speed less than or equal to the cut in speed of the wind turbine, in this interval the wind turbine is shut down.

The last case refers to the interval of wind speed greater than the cut off speed of the wind turbine. In this interval, the wind turbine is shut down.

3.2.2.1.3 Inverter

The inverter acts as an interface between the hybrid photovoltaic wind power systems and converts the DC power output from the hybrid system to AC. The grid connected inverter must present some characteristics such as:

- Response time which must be as fast as possible.
- Power factor; generally poor because of harmonics; however with the development of inverter technologies it is possible to keep it close to an acceptable value.
- Frequency control: The frequency of the inverter is imposed by the grid.
- Harmonic output
- Synchronization
- Fault current contribution
- DC current injection
- Protection

3.2.2.1.3.1 Behaviour of the inverter

The inverter receives the electrical power from the DC bus and converts it to AC. The inverter must produce a good form output sine wave and must follow the frequency and the voltage of the grid. In the event of a power cut from the electrical distribution network, the inverter must react and disconnect automatically.

3.2.2.1.4 DC bus

The DC bus is used to tie both the wind power and the photovoltaic power subsystems together. It is also used as an interface between the hybrid power system and the inverter and its main role is to transfer DC electricity generated by the hybrid power system to the inverter. In the chapter related to the modelling, the DC bus will not be considered fully, we will just introduce it in particular cases.

3.2.2.1.5 Supervising and Control Unit

The supervising and control unit has a role to organise and schedule the flow of power in the system. Its aim is to allow the optimal operation of the overall system. The supervising and control unit is used to manage and control all the main components of the system. These components are:

- Wind and photovoltaic generators;
- Rectifier;
- Converters (DC boost converter and inverter);
- Connection to the grid.

The supervising and control unit consists of two parts. The first part is related to the acquisition of data and is made up of sensors which capture and measure the weather conditions for the operation of wind and photovoltaic power generators. The second part of this unit can be considered as a piece of intelligence such as embedded software or a computer algorithm which aims to achieve the optimal operation of the system (IEA, 2012).

In this research, the supervisory and control unit has been assigned goals such as:

- To optimise the supply of the load from the power generated by the hybrid power system rather than by the power from the utility grid.
- Highter reliability
- Best quality of supply

In this system, the supervisory and control unit has three inputs:

- power generated by wind power system (PWR1out);
- power generated by solar photovoltaic system (PWR2out);
- power required by load (P_{load}).

In this system we have assumed that the first priority of an energy supply is assigned to the hybrid photovoltaic wind power system, meaning that before we can consider the remaining electrical supply system, we have to first ensure that the power generated from this hybrid power system is not available or not sufficient to supply the load. in this case, the priority of electrical energy supply is given to the utility grid through the electrical distribution system.

Therefore, in this system, we have considered four different operating modes, which are:

First operating mode

The first operating mode corresponds with the period of time when there is sufficient wind power and/or photovoltaic power to fulfil the load demand. Additionally, there is a surplus of electrical power generated by the hybrid power system. In this period of time, the load demand requirement is fulfilled by the hybrid wind photovoltaic and the exceeding power is fed to the grid through the electrical distribution system.

Second operating mode

This operating mode corresponds with the period of time when there is sufficient wind power and/or photovoltaic power to fulfil the load demand. In this period, the hybrid wind photovoltaic power subsystem operates and supplies the total load demand and in this operating mode, we assumed that there is no surplus of electricity from the hybrid power fed to the grid.

The system stays in these two operating modes until the total load demand exceeds the available wind and/or photovoltaic power. When this period occurs, the supervisory and control unit switches to the third operating mode which consists of involving the electrical utility through the distribution system for electrical energy supplied.

Third operating mode

As stated above, this operating mode corresponds with the period of time when the hybrid wind photovoltaic system does not generate enough electrical power to fulfil the load demand requirement. In this operating mode, in order to maintain the load demand requirement, both the hybrid wind photovoltaic power system and the utility grid through the electrical distribution system operate in parallel.

Fourth operating mode

The last operating mode corresponds to the period of time when neither wind nor photovoltaic power is available. During this period, the total load demand requirement is fulfilled by the utility grid through the electrical distribution system. The hybrid wind photovoltaic power system is then switched off.

3.3 Summary

This chapter was focusing on giving a description of the system in terms of its different elements as well as their behaviours in terms of the operating modes considered.

CHAPTER FOUR
MODELING OF THE PROPOSED SYSTEM

4.1 Introduction

This chapter is devoted to the modelling of the system shown in Figure 3.1. First of all, we will present the SysML modelling methodology adopted in this thesis. This modelling methodology consists of some of the important steps that need to be followed in order to perform the modelling process. These steps are listed below:

- Requirement modelling;
- Structure modelling;
- Behavioural modelling.

4.2 Modelling methodology

The modelling methodology adopted in this research is taken from (Klykken, 2009) and includes two main stages. Figure 4.1 shows the overview of this methodology.

The first stage is related to the system-level requirements specification phase where the environmental entities and assumptions, the system-level requirements, and the main functionality of the system are captured. The second stage consists of system architecture and design. This phase includes designing and developing structure models, behavioural models, and requirements. Some of the activities in these steps are dependent on diagrams developed in other activities.

When implementing a system, the environment under which the system will operate has to be taken into consideration, as elements in the environment will influence the system design. Inputs to the methodology are therefore (Klykken, 2009):

- Standards: such as official, governmental, or corporate need to be met to be able to be certified and be allowed to run.
- Domain models: The system will run in an environment with an existing terminology that the system engineers need to be familiar with.
- Requirements from stakeholder: analyse the wishes and needs of the stakeholder to be able to extract the requirements. These reflect what the system will be used for, what things will be important to take care of.

The methodology includes one or more iterations of the two primary stages:

1. **System- level requirement specification**

The system level requirement specification consists of different steps such as:

- Make a system context diagram to see the external entities that interact with the system.
- Capture system-level requirements and define the requirements category for each individual system-floor requirements.
- Identify main system functions in terms of use cases, and relate these use cases to the system-level requirements.
- Identify the constraints that the external entities impose on the system, and include these constraints as system requirements.

2. **System architecture and design**

This stage includes the following points:

- Create the structural perspectives of the system using block definition diagrams by identifying top-level system blocks and decomposing them into sub-cubes.
- Model the use-case scenarios using sequence diagrams to describe behavioural interactions between the top-level parts.
- Specify block-level requirements and trace these requirements to the system-level requirements. Establish traceability links between the block-level requirements and top-level blocks.
- Describe flows of physical items and/or logical data among the top-level system parts using internal block diagrams.
- Model the sequences of actions for each of the top-level parts using activity diagrams.
- Capture the constraints on the physical attributes of blocks using parametric diagrams.
- Decompose each activity in the top-level activity diagram into a chronological succession of more primitive actions performed by the sub-parts.
- Capture the behaviour of individual top-level parts with behaviour using state machine diagrams.

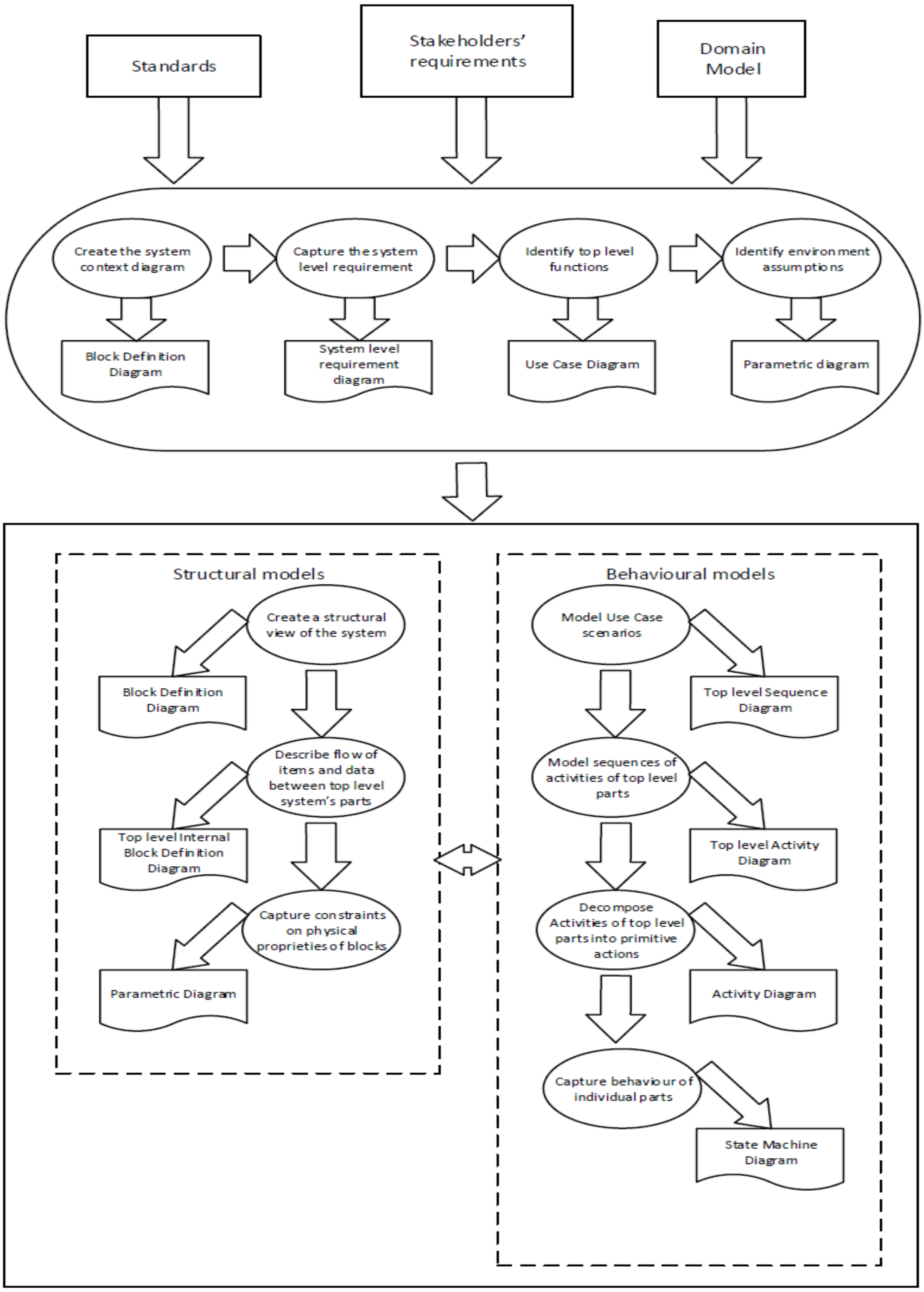


Figure 4.1 Block diagram of the modelling methodology

4.3 Modelling system level requirement

In order to make good decisions when analysing or designing a system, it is important to know the system, the environment in which it will operate, the different elements interacting with it as well as the restrictions and requirements that the system must satisfy.

4.3.1 System context diagram

The overview of the different entities in the environment/domain that interact directly or indirectly with the system of interest is given in the system context diagram. This context diagram is depicted in Figure 4.2 below and is made up of a block definition diagram using block constructs and the composition relation. In this figure, the system of interest consists of the hybrid photovoltaic wind power system. Besides this system of interest, the context diagram includes the blocks *EDS* (Electrical Distribution Network), *Load*, *Renewable Energy Sources*, the allocated block *Renewable energy sources* and three other stakeholders which are the *Regulatory Authority*, the *Hybrid Wind operator* and the *Distribution System Operator*.

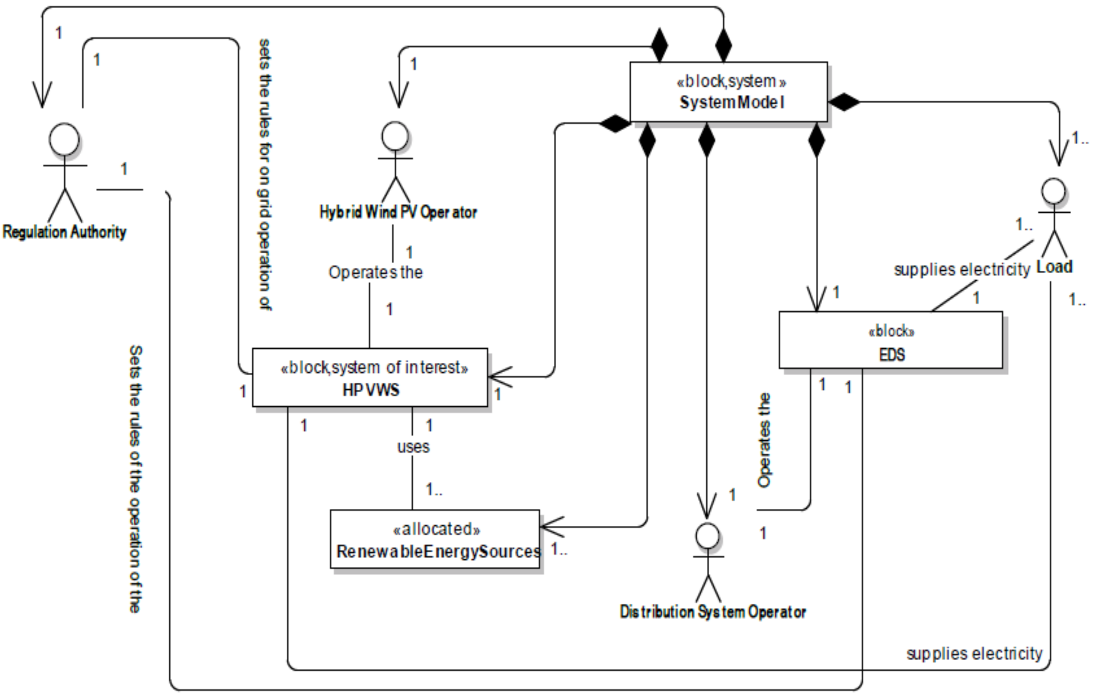


Figure 4.2 Block Definition Diagram of Model Domain

The context diagram in Figure 4.2 can be read as follows:

The *SystemModel Domain* is composed of one *hybrid photovoltaic wind system*, *one electrical distribution system*, one or more *loads*, one or more *renewable energy sources*, one *regulatory authority* and two *operators* (one for Hybrid photovoltaic wind system and the other one for the distribution system).

The *regulatory authority* sets the rules for the operation of the hybrid photovoltaic wind system as well as for the operation of the distribution system. The *distribution system operator* as well as the hybrid power system *operator,* operates the distribution system and the hybrid power system respectively and both supply the electricity to the load. The hybrid photovoltaic wind system uses renewable energy sources (solar and wind).

4.3.2 System level requirement

This step consists of capturing the system's requirements. Capturing the system's requirements mean capturing the main requirements such as the different stakeholders' needs, the standards that the system has to satisfy and the domain which are shown in the methodology figure as inputs.

The high level system requirements as we have considered is shown in appendix A.2 and include the main requirements such as the Government Regulations through the Regulatory Authority, the Hybrid Photovoltaic Wind System operator requirements, the Electrical Distribution System operator requirements and the load requirements. The diagram in Figure 4.3 shows these high level system requirements with further partitions.

The high level requirements in the system context diagram represent the set of rules and duties that the overall system has to adapt to and take into account the need of the different entities involved in the system. Obviously there are many different other requirements that can be taken into consideration depending on the objective that is being pursued. In this research we have just considered the requirements enumerated above.

In Figure 4.3, the requirements related to the system under study are included in the package "System specification" and as stated above, five main requirements have been considered which are: The Government requirements (*Regulatory Authority*), the requirements from the Hybrid Photovoltaic Wind System (*HPVWS*) to the Electrical Distribution System (*EDS*), the requirements from the Electrical Distribution System (*EDS*) to the Hybrid Photovoltaic Wind System (*HPVWS*) and the requirements from the load.

Each requirement contains an identification property known as requirement "*id*" and a text property known as "*text*" which shows what the entity has to satisfy. The relationships between the main requirements and the package "*System specification*" as well as the relationship between the main requirements and the requirements originating from each main requirement as represented in the requirement diagram are the containment relationships. All the requirements that originate from each main requirement will have the same identification property of its original plus another number. For instance the requirement "*HPVWS operator*" has "id=002" as identification property and the requirements originating from it which are "*Respect of the regulation by EDS*", "*Respect of technical standards by EDS*" and "*Power* *consumption*" have "id=0021", "id=0022" and "id=0023" as identification property, respectively.

The Regulatory Authority requirements with further partitions are shown in the Regulatory Authority requirement diagram in Figures 4.4 and 4.5 below. These requirements include two high level requirements which are the tolerance of frequency and the voltage deviation. These requirements can be further partitioned in much detail. In our case we have considered this level of detail.

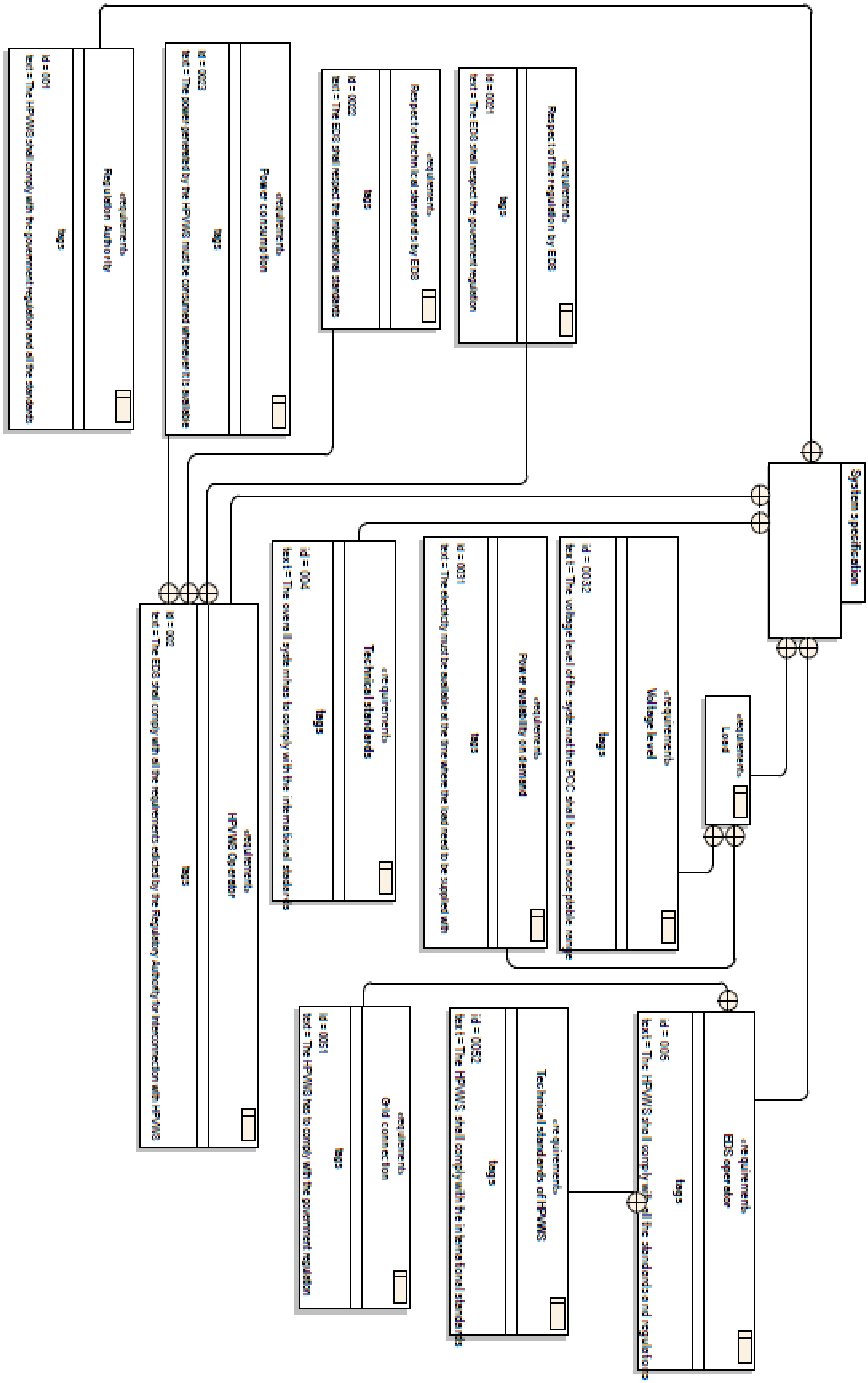
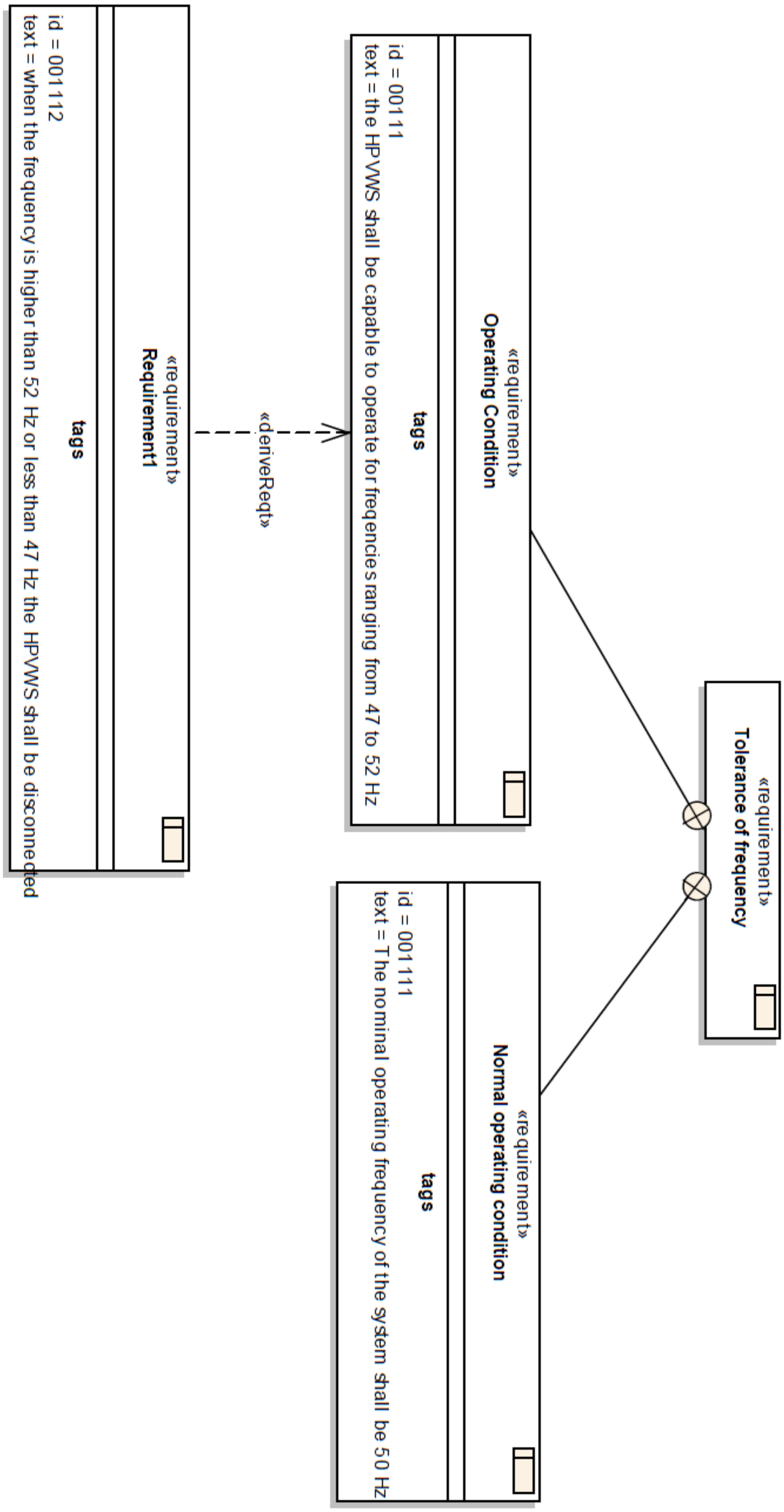


Figure 4.3 Requirement diagram of the system



id = 00111
text = the HPVWS shall be capable to operate for frequencies ranging from 47 to 52 Hz

id = 001111
text = The nominal operating frequency of the system shall be 50 Hz

id = 001112
text = when the frequency is higher than 52 Hz or less than 47 Hz the HPVWS shall be disconnected

Figure 4.4 System frequency tolerance requirements

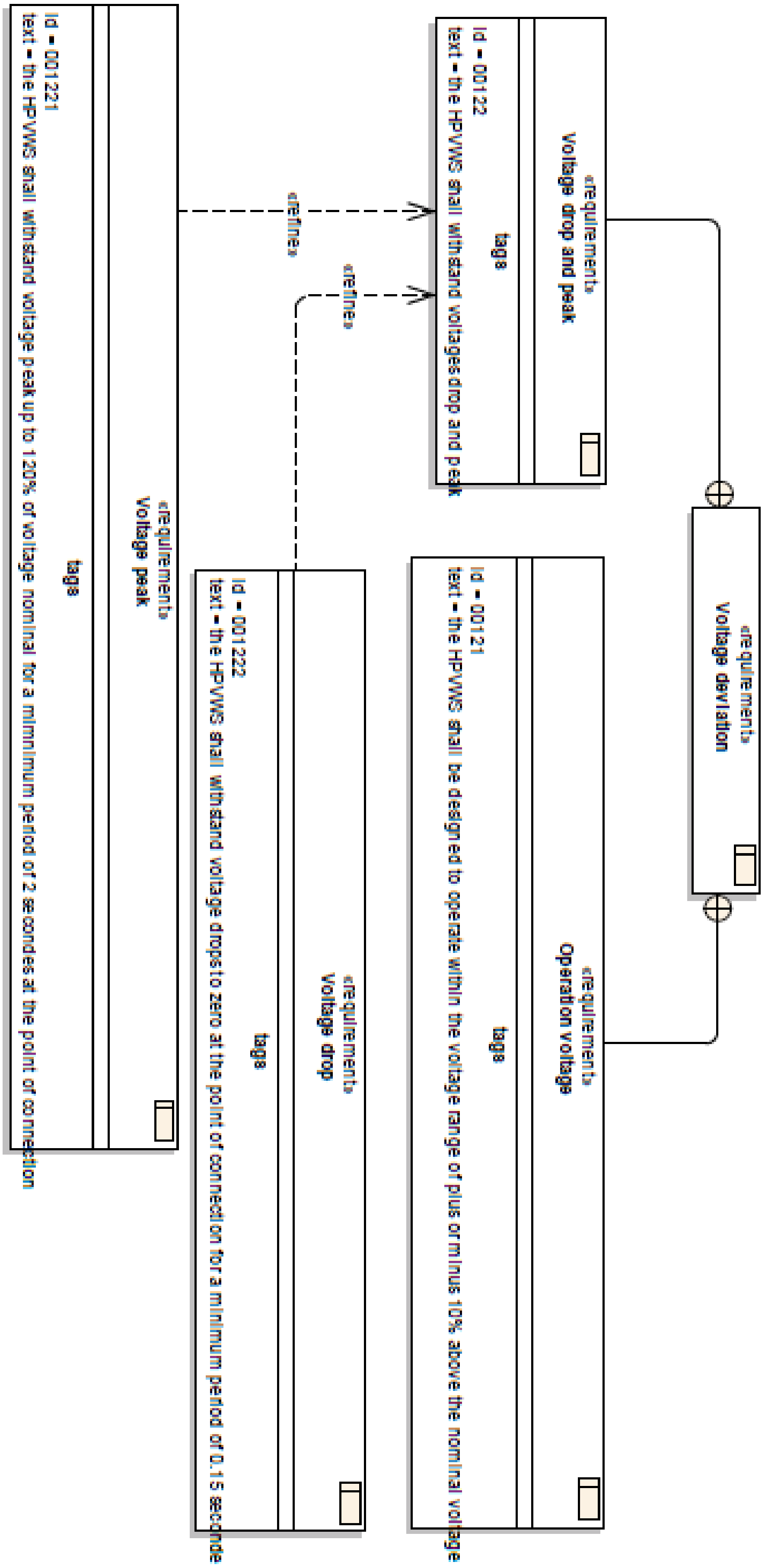


Figure 4.5 System voltage requirements

4.3.3 System level functions

The following step after capturing the system level requirement is the identification of the system function. This step consists mainly of identifying the main functions of the system by considering the system as a black box. These identified functions must reflect the goals that the users are expecting to get from the system as captured in the system level requirements.

Figure 4.6 shows the system use case diagram considering the different actors involved in the system. The Regulator actor has one use case which is "*Regulate the operation of HPVWS*". This use case consists of a set of rules for the operation of HPVWS and ensures that these rules are being followed.

The HPVWS operator has one use case which is "*Operate the HPVWS*". Operating the HPVWS includes generating the electricity, supplying the electricity to the load, controlling the on grid operation of the HPVWS and ensuring the sustenance of the HPVWS equipment. Furthermore, the operation of the HPVWS extends to selling any excess of electricity not used by the load to the EDS.

The EDS operator has one use case which is "*Operate the EDS*". This use case includes supplying the electricity to the load, controlling the operation of the EDS and ensuring the maintenance of the EDS equipment. The load has only one use case which is "*Use the electricity*".

Use case diagrams can be further detailed and described using textual representation and visually using a sequence diagram or activity diagram. In this research, we have adopted the visual representation using activity diagrams. Figures 4.7 and 4.8 show the activities of the power generation in the hybrid photovoltaic wind power system. The first figure refers to the activities during the generation of power in a photovoltaic power system and the second for the wind power system.

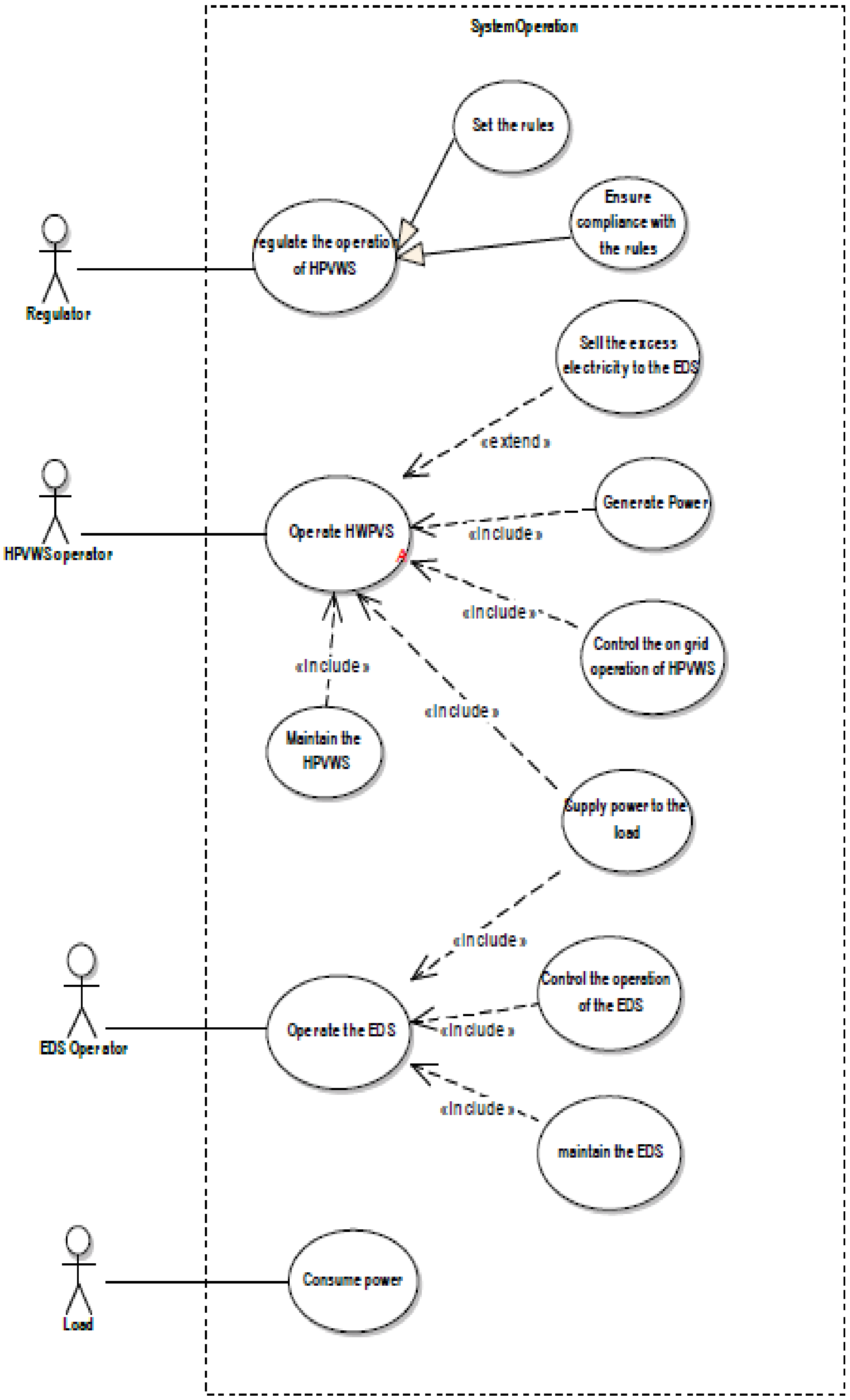


Figure 4.6 Use case diagram of the system (Main functions)

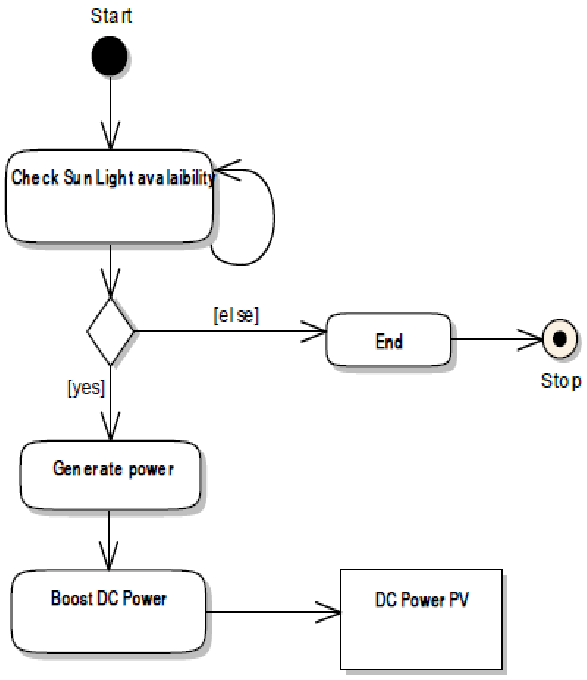


Figure 4.7 Photovoltaic activities power generation

For the photovoltaic activities (see Figure 4.7), after the initial step which is *Start,* the next step consists of checking the sunlight availability (represented by the activity "*Check Sunlight availability*" in the activity diagram in Figure 4.7. This step is repeated continuously as long as the photovoltaic system will operate. If the sunlight is not enough for the generation of electricity, the following activity will be the activity *End*, otherwise the system will keep operating by generating electrical power (see activity "*Generate power*" in the activity diagram in Figure 4.7) and then the DC electricity generated will be boosted up (see activity "*Boost DC Power*" in the activity diagram in Figure 4.7).The final object obtained from all these photovoltaic activities will be the DC electrical power which is represented in the activity diagram Figure 4.7 by a square.

Referring to the wind power generation activities (see Figure 4.8), after the initial step which is *Start,* the next step will consist of checking the wind availability (represented by the activity "*Check wind availability*" in the activity diagram in Figure 4.8). This step is repeated continuously as long as the wind power system will operate. If the wind is not available enough for the generation of electricity, the following activity will be the activity *End*, otherwise the next step will consist of checking the wind direction with respect to the turbine (see activity "*Check wind direction*" in the activity diagram in Figure 4.8)., This activity is also repeated continuously as long as the wind power system will be operating. If the turbine is in the direction of wind, the next activity will be to read the wind speed (see activity "*Read wind speed*" in the activity diagram Figure 4.8), otherwise if the turbine is not in the direction of the wind, the nacelle of the wind turbine will be aligned in the wind direction and the activity

“*Read the wind speed*” will be executed. This activity will also be continuously repeated as long as the wind power system will operate. After this stage, the next activity will consist of the execution of the activity “*Cut in speed <=wind speed <=Rated wind speed*”. This activity will also be continuously repeated as long as the wind power system will operate. If it is satisfied, then the power will be generated (see activity “*Generate Power*” in the activity diagram in Figure 4.8) and convert from AC to DC (see activity “*Convert AC power to DC*” in the activity diagram in Figure 4.8). The final object obtained from all these wind power generation activities will be the DC electric power represented by a square in the activity diagram Figure 4.8.

If the activity “*Cut in speed <=wind speed <=Rated wind speed*” is not satisfied, the following activity will be “*Rated speed <=wind speed<=cut off wind speed*”. This activity will consist of comparing the wind turbine rated speed and cut off wind speed and if it is satisfied, the electric power will be generated and converted from AC to DC, otherwise the system will be shut down.

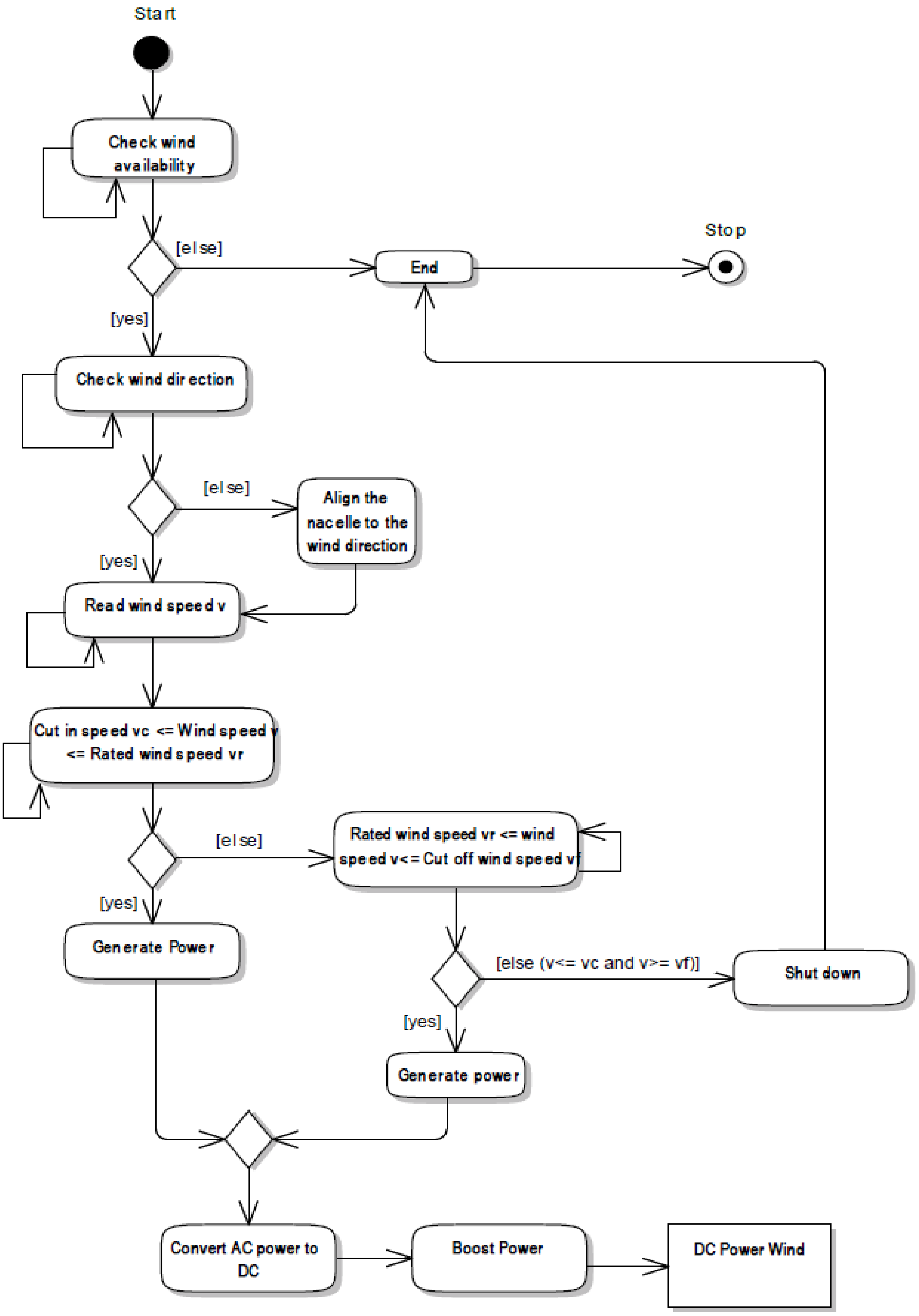


Figure 4.8 Wind power activities power generation

4.3.4 Recognition of environmental assumptions

In this step, the elements under consideration are the domain model, system context diagram and system level requirements. From these elements, more requirements can be added to the requirement diagram and some environmental constraints can also be represented using a parametric diagram. All the assumptions made in this step need to be discussed with a domain expert in order to assure that they are correct. In this research, we did not consider any environmental assumption.

4.4 System architecture and design

This step consists of two different parts which are the design and development of structure model parts and the behavioural models.

The first part which is the design and development of structure models consists of modelling the structure and interaction points of the blocks.

4.4.1 System architecture

The focus point in this step is on creating a structural representation of the system by decomposing it into its different components. The most important part which needs to be decomposed is the system of interest block consisting of the Hybrid Photovoltaic Wind System (HPVWS) (Figure 4.2).

After decomposition, the different parts are then represented using block constructs in a block definition diagram. Figure 4.9 shows the block definition diagram of the system as presented in Figure 3.1. The main block construct of this block definition diagram is the *System Model* block. This block definition diagram in Figure 4.9 can be read as follow:

The system model block (*System Model*) is built up of five block constructs namely *Hybrid PV Wind System*, *Distribution Panel*, *Electrical Distribution System, Control and Supervising Unit* and the *Load* blocks. Until this stage, the block constructs in Figure 4.9 can be considered as high level blocks due to the fact that their decomposition in the entities that are parts of them are not implemented yet. Therefore, the block definition diagram in Figure 4.9 represents a simplified variant of the system in Figure 3.1. Normally, when modelling the structure of a system, the decomposition needs to be done until we reach all the small parts of the system. The decomposition of block constructs will be further discussed in the coming pages.

Except the *System Model*, *Hybrid PV Wind System*, *Distribution Panel* and *Control and Supervising Unit* blocks, each of the remaining block constructs is made up of two or three different compartments. The first compartment gives the name of the block construct, the second one includes the main properties of the block and the third shows the different operations that the block is expected to accomplish.

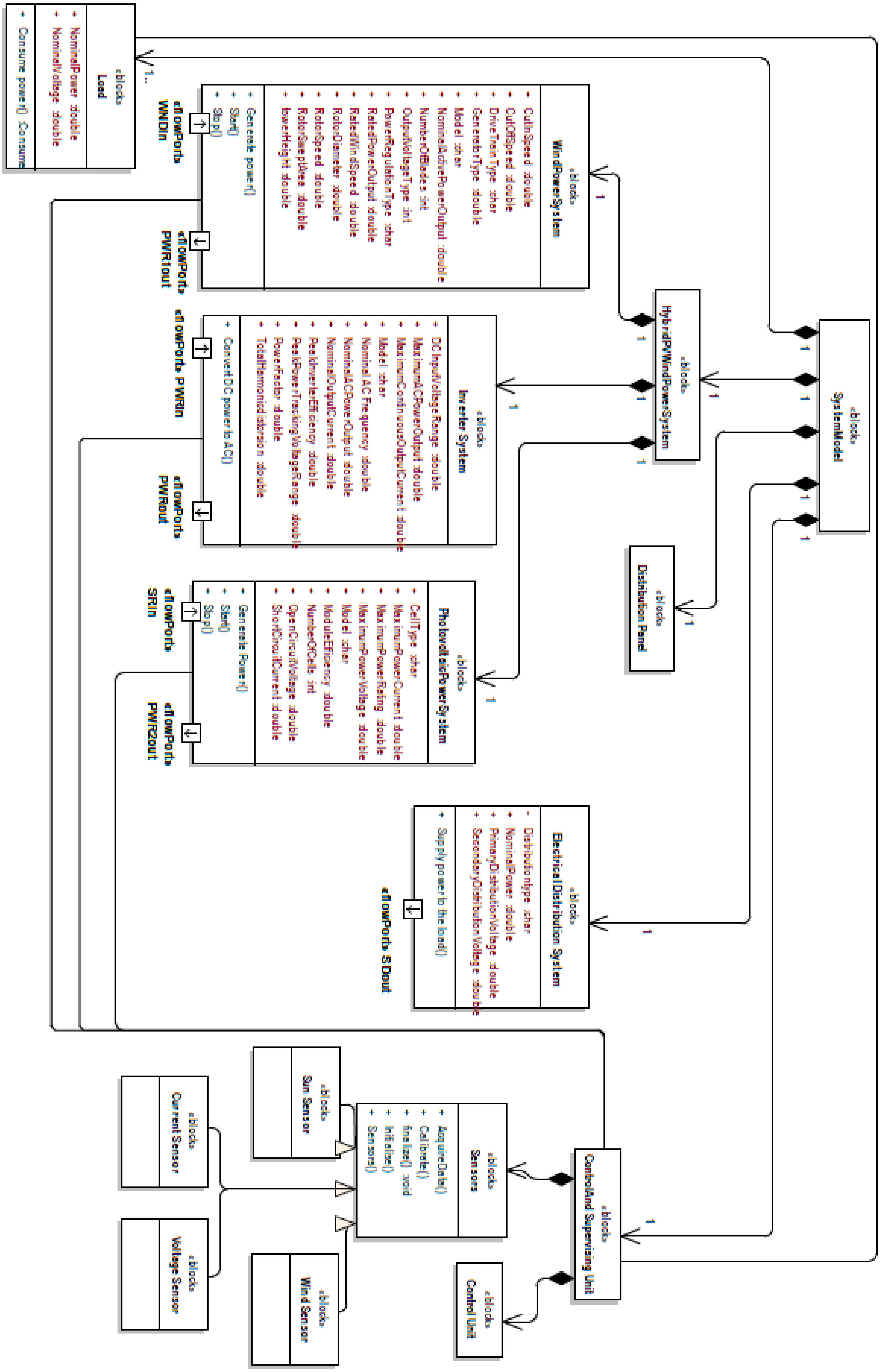


Figure 4.9 System Architecture

4.4.1.1 Hybrid PV Wind System architecture

The hybrid PV Wind system represents the system of interest in the domain model (Figure 4.2) and the structure of the hybrid is shown in Figure 4.9. Referring to this figure, this hybrid power system includes three main parts, namely Wind Power system, photovoltaic power system and the inverter.

4.4.1.1.1 Wind power system features

The wind power system block definition diagram is presented in Figure 4.10 and consists of all the main parts of a wind power scheme. These parts are the tower, the drive train, the aerodynamic system generally known as blades, the pitch angle controller and the electrical generator. The relationships joining the wind power system block and the blocks representing its different parts are a composition relationship, meaning that all these parts are compulsory in a wind power system. Besides these parts, the wind power system in Figure 3.1 includes a rectifier and a DC to DC boost converter. These two parts are also included in the block definition diagram in Figure 4.10. The relationship between the wind power system block construct and these two parts are an aggregation relationship which means that these elements are part of the system, but they are not compulsory in a wind power system. One more significant factor that demands to be noted is the flow port. In Figure 4.9 the wind power system includes two flow ports namely *WND in* and *PWR1 out* flow ports. The *WND in* flow port represents the flow of wind energy going through the wind turbine whereas the *PWR1 out* represents the electrical power generated by the wind power system.

As expressed in section 4.4.1, the wind power system block as well as some other block constructs in Figure 4.9 includes three different compartments. The first compartment shows the name of the block, the second gives the block's main properties or attributes whereas the third gives the block operations. In the properties compartment (see Figure 4.9), some of the most important wind power system properties as given by the manufacturer are shown. Depending on their types, these attributes are characterized as *double*, *char* (character) or *int* (whole number).For instance, the cut in wind speed which is normally given by a numerical decimal value is characterised as double whereas model or again the number of blades are characterised by char and *int,* respectively. It should be noted that these different types of characteristics are given referring to the Java programming language.

In the operation compartment (see Figure 4.10), three wind power system main operations are likewise presented. These operations are: start the wind power system, generate electrical power and stop the wind power system. The operations in a block construct are normally used in an activity diagram. For instance, the wind power system operations as shown in the block definition diagram in Figure 4.10 can be seen in the activity diagram in Figure 4.8.

Concerning the rectifier and the DC to DC boost converter, their main operations are *«convert the AC power to DC»* and *«boost the DC power»,* respectively.

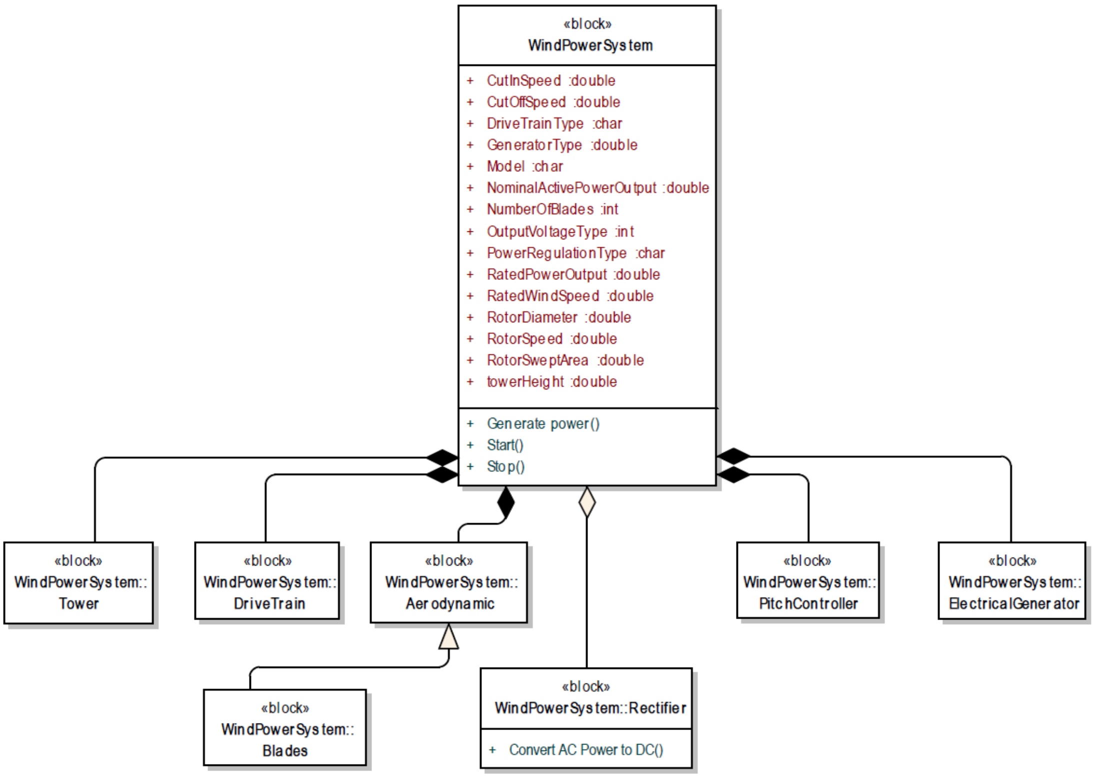


Figure 4.10 Wind Power system block definition diagram

4.4.1.1.2 Photovoltaic power system

The block definition diagram of the photovoltaic power system is shown in Figure 4.11 and includes the main parts such as the solar panels, the controller, the MPP Tracker, the Limiter and the boost converter.

Besides the photovoltaic panels, the rest of the entities that are part of the system are not compulsory elements and therefore they are represented by an aggregation relationship.

As for the wind power system, the different characteristics of the photovoltaic power system as given by the manufacturer are shown in the properties compartment, whereas the operations of the photovoltaic power are shown in the operation compartment. Referring to this operation compartment, it can be seen that the main operations of the photovoltaic power systems are: start, generate electrical power and stop. These main operations are likewise recorded in the photovoltaic activity diagram (see Figure 4.7).

From Figure 4.11, it can be seen that the block construct of the photovoltaic power system also includes two flow ports. These flow ports are *SRin* and *PWR2out*; the *SRin* flow port is used to represent the flow of solar energy hitting the solar panel, whereas the *PWR2out* represents the electrical energy generated by the photovoltaic system.

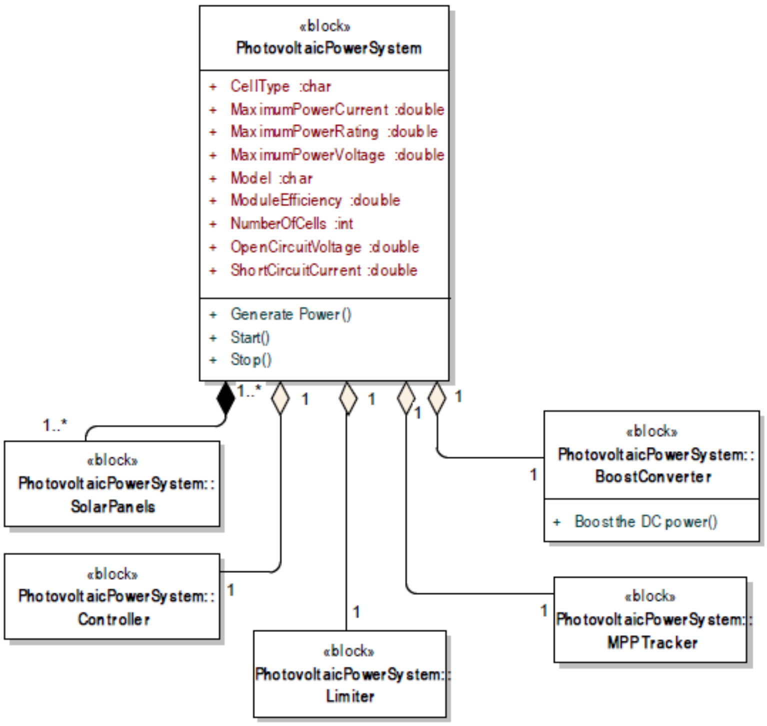


Figure 4.11 Photovoltaic system block definition diagram

4.4.1.1.3 Inverter

Another element which is part of the hybrid photovoltaic wind power system shown in Figure 3.1 is the inverter. The block definition diagram giving the details about this inverter is shown in Figure 4.11. This block construct consists of two main blocks which are the inverter itself and the control system applied on it. The inverter control system consists of three block constructs, namely the *Signal Conditioning Unit*, the *Controller* and the *PWM* blocks. The *Signal Conditioning Unit* has four properties or attributes which are the grid *voltage* and *frequency,* the *photovoltaic* and *wind power outputs.* These attributes are the type which stand for integer as stated earlier and are used as reference for the control strategy. Therefore, the inverter system block definition diagram in Figure 4.11 can be interpreted as follow:

The *Inverter* block construct is linked to the control system block and the *Control System* block is composed of a *Signal conditioning Unit*, *Controller* and *PWM* block constructs.

Assumption

In this block definition diagram, we did not specify the type of link between the *Inverter* block construct and the *Control System.* This aspect will be shown in the inverter system internal block diagram in the coming pages.

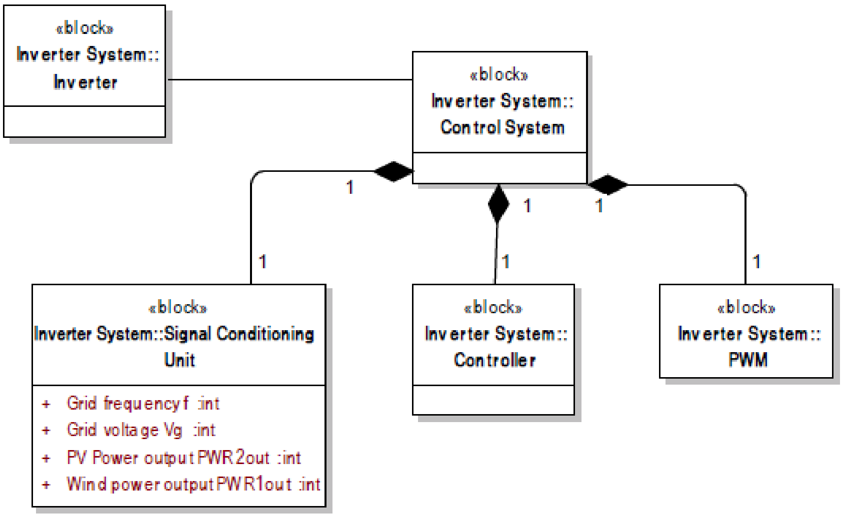


Figure 4.12 Inverter System BDD

4.4.1.2 Control and monitoring unit

Another important part of this system and which needs to be discussed is the control and supervising unit. As can be seen in Figure 4.9, the control and supervisory unit consists of a set of sensors and a control unit. The role of these sensors is to read the values of important parameters of the system such as the wind speed, the voltage and the current.

4.4.1.3 Electrical distribution system

The block definition diagram in Figure 4.13 shows the different entities which are part of the electrical distribution system that we have considered. This block definition diagram refers to a radial distribution system and includes six blocks, namely, *Primary Feeder, NC1* and *NC2 switches* which are normally closed switches, *Fuse1* and *Fuse2, and a Distribution Transformer*. This distribution system has some attributes such as *distribution type, nominal power, Primary* and *Secondary distribution voltages* and the operation that the system is expected to perform is to *supply power to the load*. More attributes and operations can be added to the system depending on the purpose of modelling.

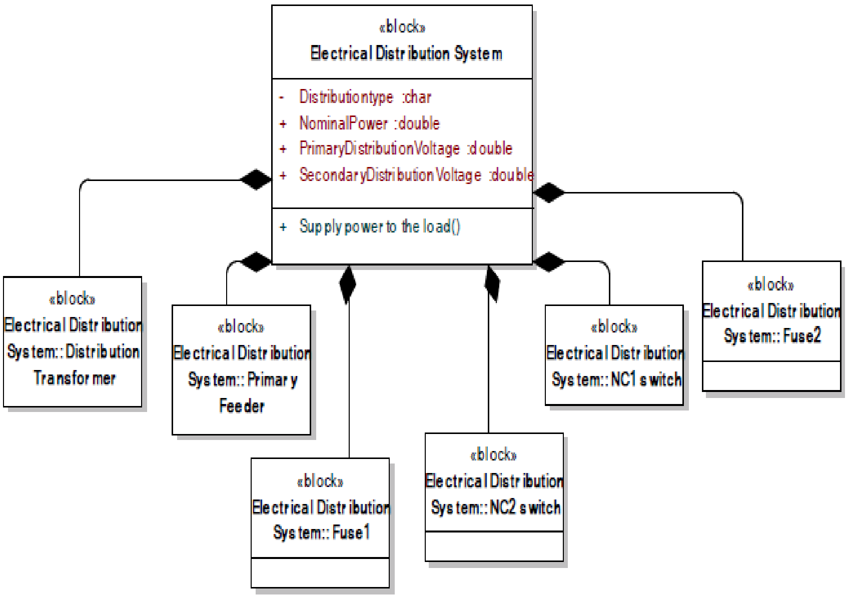


Figure 4.13 Electrical distribution system BDD

4.4.2 Communication and flow of items between block construct

This step consists of connecting the parts of the overall system and describing the interaction between them. This is done using an Internal Block Definition Diagram (IBD) introduced in chapter 2, section 1.

4.4.2.1 System Internal Block Diagram

The IBD (Internal Block Diagram) of the system can be seen in Figure 4.14. This IBD is characterized by three different types of elements which are: the part properties, the item flows and the ports.

As can be seen in this figure, part properties represent the different subsystems which constitute the overall system. These subsystems are the Hybrid PV Wind System, the Control and Supervising Unit, the inverter, the distribution panel, the electrical distribution network, the load, the wind energy as well as the solar energy. It should be noted that the last two subsystems cited above have not been considered in the block definition diagram but they are also part of the system.

Another element that can be seen in the internal block definition diagram in Figure 4.14 is the item flow. Item flows are the dashed lines joining the subsystems. As their names suggest, item flows simply represent the flow of an element from one subsystem to another. In our study, item flows are the wind and solar energy, the electrical power as well as the control signal strategy applied to the system.

The role of these item flows is as follows:

- “wind energy” item flows represents the flow of wind energy moving toward the wind power system for electricity generation;
- “solar energy” item flows represents the flow of solar radiation going through the solar panels;
- “DC power” item flows represent the electrical Direct Current from the hybrid PV wind power system to the inverter;
- “AC power” item flows represent the Alternative Current from the inverter to the distribution panel;
- “Power” item flows represent the electrical power from the distribution panel to the load;
- “Control strategies” item flows: There are three control strategies item flows applied in this system. These item flows represent the data exchange and the control strategies from the control and supervising unit to the hybrid PV wind system, the inverter and the load.

The last types of elements that can be seen in the Internal Block Diagram of the system are the flow ports. These flow ports can be seen as the interaction points between the different subsystems. They also describe the type of items that may flow between the different subsystems as well as their direction. These directions can be either *in, out or inout*. For instance, if we consider the hybrid PV wind power system, the wind and solar energy (*SRin* and *WNDin*) flowing into this power system are represented visually in the flow ports with a *in* direction to the hybrid PV wind system whereas the DC power from the hybrid PV wind system (*PWR1out* and *PWRout2*) are represented with an *out* direction from the hybrid PV wind system. In the hybrid PV wind system, the item flow going into the *CnStH* flow port is represented visually with an *inout*, meaning that items can flow in both directions, either an *in* direction or an *out* direction. The flow port with only one direction is known as an atomic flow port whereas the flow port with *inout* direction is a composite flow port. Composite flow ports require a flow specification in order to specify the type of element flowing as well as its direction. This is done using flow specification block definition diagrams. These flow specifications can be seen in the appendix A.3.

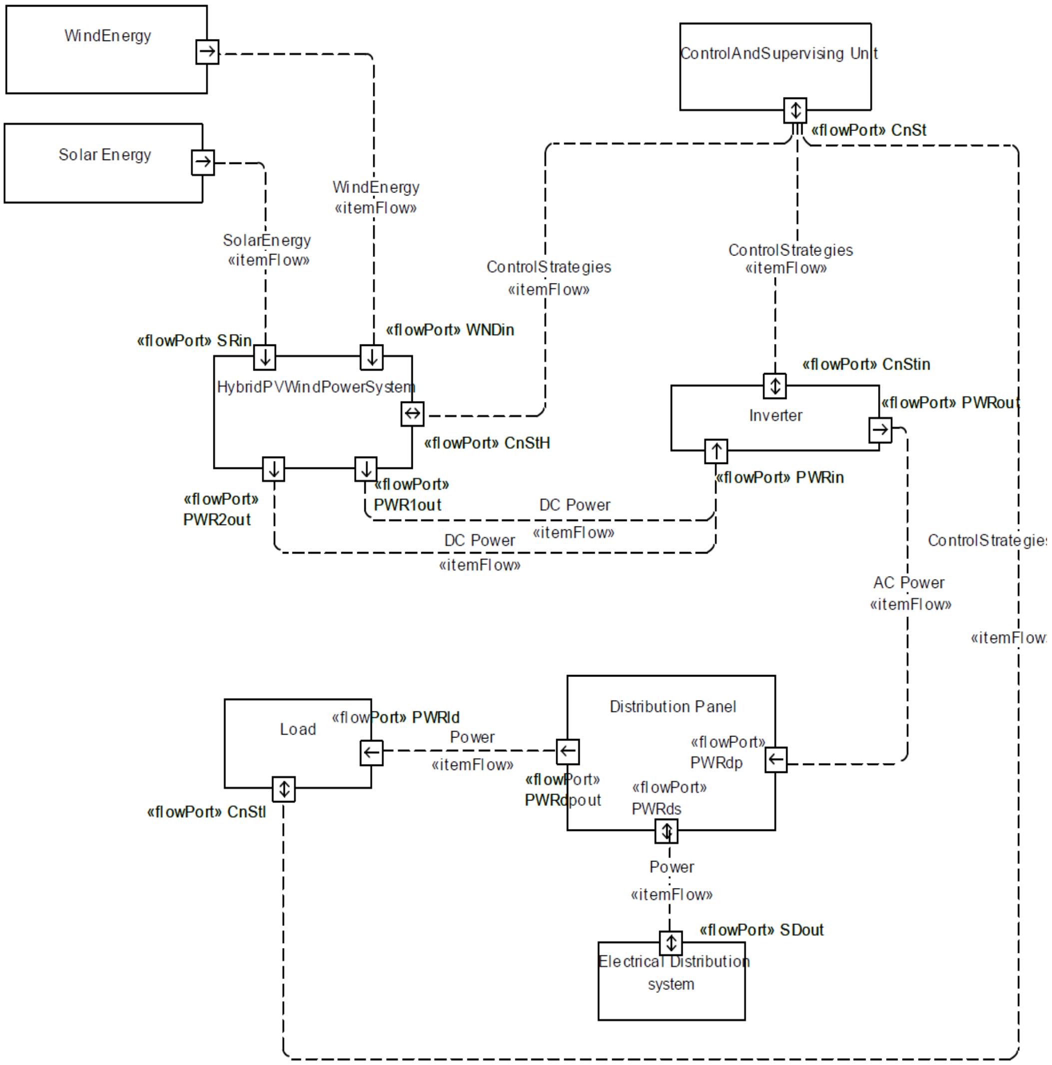


Figure 4.14 Internal Block Diagram of the system

4.4.2.2 Hybrid PV wind power Internal Block diagram

The internal block definition in Figure 4.15 shows the flow of items as well as the interaction points between the different subsystems in the hybrid PV wind power systems without considering all the internal details such as the internal parts and item flows and flow ports within the different subsystems. More details will be shown in the following sections where we will be considering some of the subsystem part properties.

The IBD in Figure 4.15 consists of five part properties, namely *WindPowerSystem*, *PVPowerSystem*, *DCBus*, *Inverter* and “Load” part properties. These part properties represent the different subsystems of hybrid PV wind power systems as shown in Figure 4.10. Notice that the part property *DCBus* has not been taken into consideration in the Block Definition Diagram in Figure 4.10, but we have represented it in the hybrid PV wind power system IBD in Figure 4.15. Depending on the type of items flowing between the different part properties, the flow ports used are *PWRout1*, *PWRout2*, *PWRin* and *PWRld*. The flow ports *X1* and *X2* are the connecting points in the *DCBus* part property and the type of items flowing in these flow ports are DC power. The flow specifications for all the composite flow ports which are part of this internal block diagram are shown in the appendix A.3.

As can be seen in the IBD in Figure 4.15, we did not specify the different items flowing in or out of some of the part properties such as *WindPowerSystem, PVPowerSystem, Inverter* and *Load* through *WNDin, SRin, CnStin* and *CnStl* flow ports, respectively. However, as said in section 4.4.1.1.1, the flow port *WNDin* is used as an interaction point to model the wind energy flowing into the wind power system whereas, *SRin* represents the interaction point for the flow of solar energy. The composite flow ports *CnStl* and *CnStin* are used for control strategy purposes through the supervisory and control unit. Their role is to capture data from the load and the inverter to the supervisory and control unit and send back the command from the supervisory and control unit to the load and the inverter for system control and management in order to meet the requirements of all the stakeholders.

The item flow *DC Power* is used to model the flow of DC electrical power from the hybrid power system to the DC bus and then from the DC bus to the inverter whereas the item flow *AC Power* represents the flow of AC electrical power from the inverter to the load.

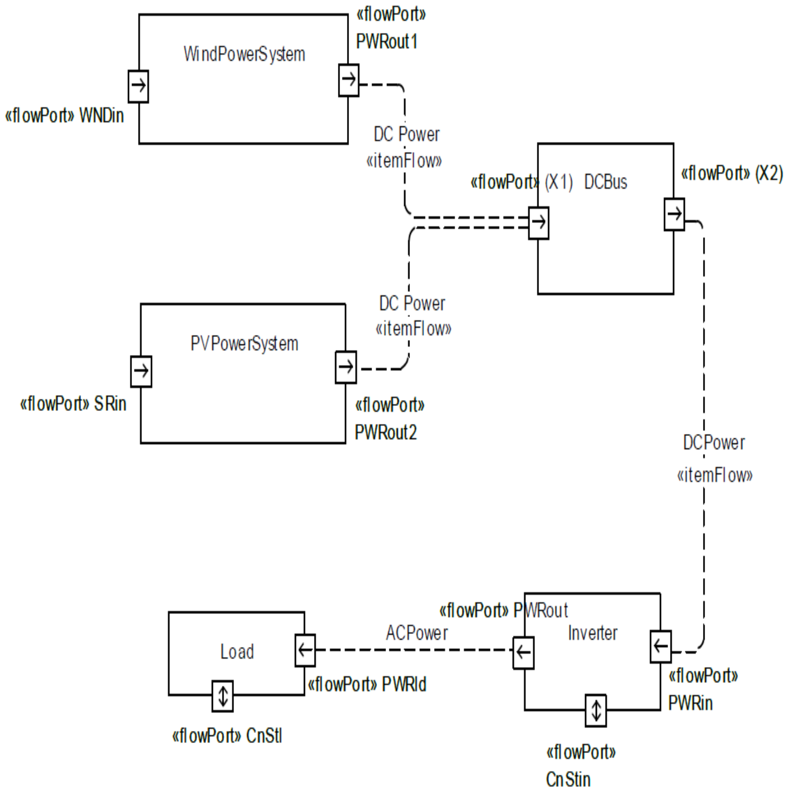


Figure 4.15 Hybrid PV wind power system IBD

4.4.2.2.1 Wind power system IBD

The wind power system IBD as shown in Figure 4.16 represents the interaction between the different elements of the wind power system on the block definition diagram in Figure 4.10, except the tower which is not included in this IBD and consists of part properties, namely *PitchController*, *Aerodynamic*, *DriveTrain*, *ElectricalGenerator*, *Rectifier* as well as *Wind*. We have included this diagram to show how the wind power system parts are connected internally. Besides the interaction between the different part properties, the internal block diagram as represented in the figure also includes the control strategies applied in the wind power system subsystem under study. Three control strategies are applied: the pitch control; the wind turbine rotor position and speed control; and the generator speed.

The pitch control is done through the pitch controller which consists of three flow ports (*PWRref, PWRmea* and *F1*). The flow ports *PWRref* and *PWRmea* are used as input for power generated measurement and the power reference input to the pitch controller whereas the flow port *Flow1* is used as output from the controller to send the commands to the aerodynamic part.

Regarding the rotor position and speed control, this is done through the wind part property. This part property consists of three flow ports namely *WND*, *F14* and *AverageWindSpeed*. The flow ports *F14* are used to sense the rotor position whereas the *AverageWindSpeed* flow port is used to set the wind speed average in order to control the wind speed that will drive the *aerodynamic* part property.

The part property *Wind* is not represented in the block definition diagram in Figure 4.10. However, in the internal block diagram we have shown that wind energy can be modelled as part property in the wind power system.

The generator control strategy as it can be seen in the internal block diagram in Figure 4.16 depends on the pitch control, the rotor speed and position control as well as the drive train control.

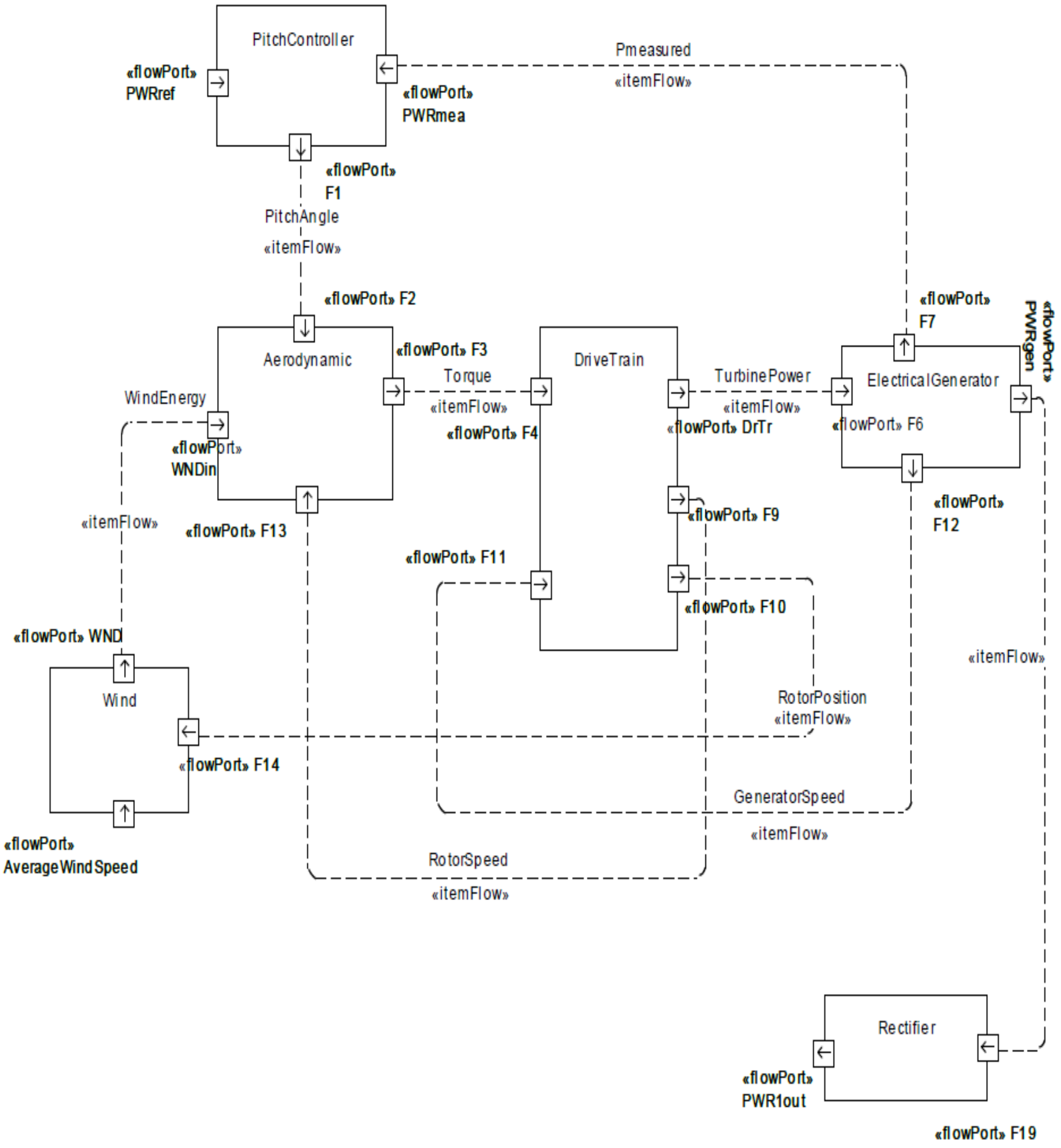


Figure 4.16 Wind power IBD

4.4.2.2.2 Photovoltaic system IBD

The photovoltaic system internal block diagram as shown in Figure 4.17 depicts the interaction between all the entities of the photovoltaic power system as described in the block definition diagram in Figure 4.11. This internal block diagram consists of part properties namely *SolarPanels*, *DCBoostConverter, MPP Tracker, Limiter* and *Controller*.

The type of flow port used in this internal block diagram is an atomic flow port showing the flow of items from one part property to another. Besides the solar panels and the DC boost converter which are the main entities of the photovoltaic power systems, this internal block diagram also shows the interaction between the different part properties for the control strategy. For instance, the solar panels have interaction with the *MPP Tracker* through *Ipv* and *FP4* flow ports, respectively. The item flowing between these two part properties is *Ipv measured* which is the current generated by the solar panels. On the other hand, the *MPP Tracker* and the *Limiter* part properties have interaction through *FP5* and *FP6,* respectively and the item flowing between these two part properties is the Maximum Power Point values whereas the *Limiter* and the *Controller* part properties have interaction through *FP7* and *FP8* flow ports, respectively and the type of item flowing between the two part properties is the *MPP range Tracking*.

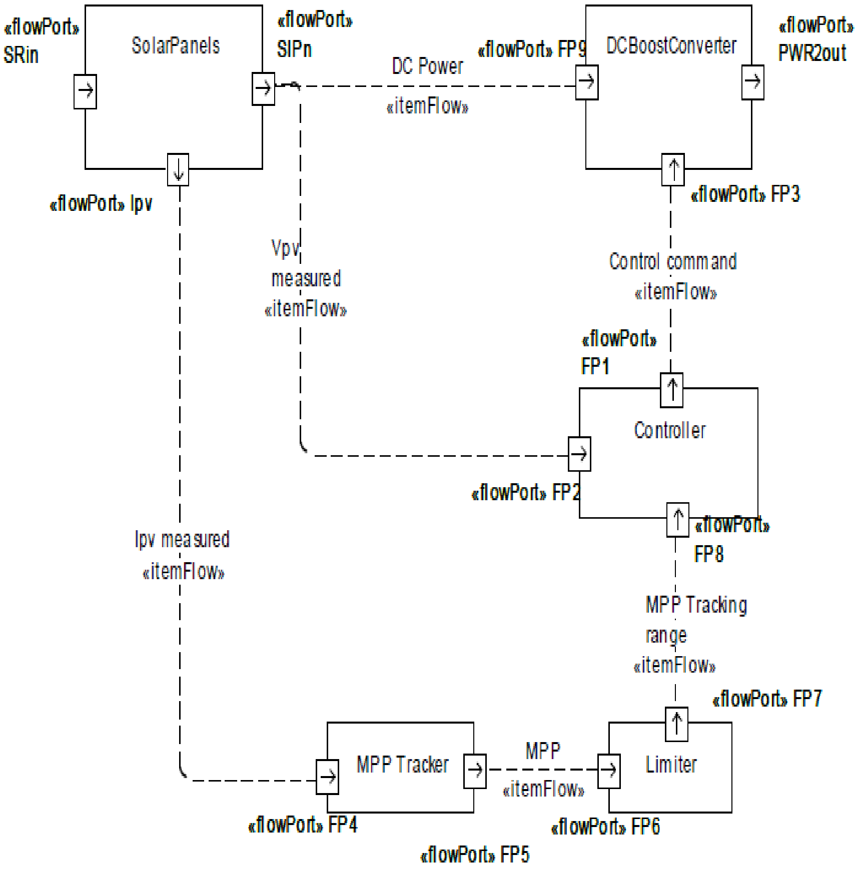


Figure 4.17 Photovoltaic power system IBD

4.4.2.2.3 Inverter System IBD

The inverter system internal block diagram as shown in Figure 4.18 is based on the block definition diagram depicted in Figure 4.12. This Internal block diagram shows how the different entities of the *Inverter System* interact together and the type of flow ports and items flowing between them. This inverter includes two flow ports which are *PWRin* and *PWRout*. The flow port *PWRin* refers to the DC power from the hybrid system flowing to the inverter for conversion to alternative current, whereas the *PWRin* flow port is the AC power converted by the inverter. The inverter control system consists of three part properties namely *Signal Conditioning* system, *PWM* and the *Controller.*

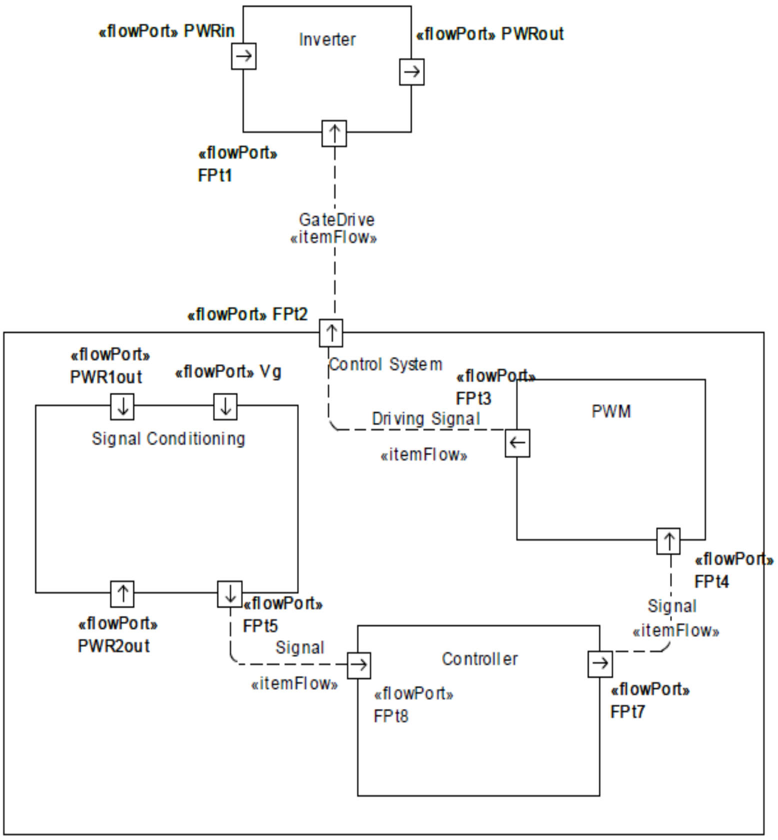


Figure 4.18 Inverter IBD

The *Signal Conditioning* system includes four flow ports: *PWR1out, Vg, PWR2out and FPt5*. The first three flow ports mentioned are used as interacting points to the *Signal Conditioning* system from the wind power system, the electrical distribution network and the photovoltaic power system, respectively. They are used to inset the values of the voltage and current of the wind power system through *PWR1out,* the voltage and current of photovoltaic system through *PWR2out* and the voltage and frequency of the electrical distribution network through *Vg.* The last flow port of the *Signal Conditioning* system which is *FPt5* is used as an interacting point to the *Controller* through *FPt8* in order to transmit the signal from the *Signal Conditioning* system to the *Controller* and generate the signal for the *PWM* to drive the inverter gate.

4.4.2.2.4 Electrical distribution system IBD

The internal block definition shown in Figure 4.19 depicts the internal composition of a radial distribution system and also the flow of items between the part properties. This internal block diagram is based on the block definition diagram in Figure 4.13 and consists of five part properties, namely *Primary Feeder, NC1 switch, NC2 switch, Distribution Transformer, Fuse1* and *Fuse2.* The type of item flowing between all these parts properties is the electrical current.

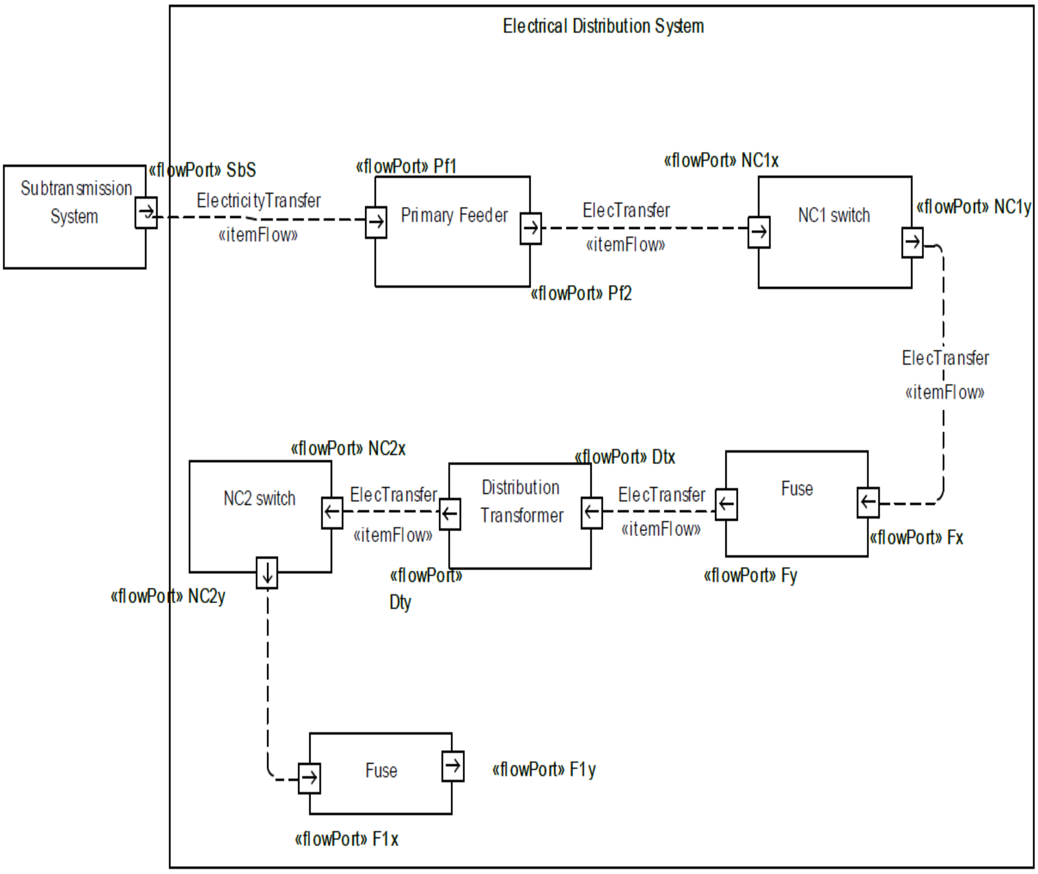


Figure 4.19 Electrical distribution system IBD

4.5 System activities diagrams

The system activities diagrams as presented in this section are based on the four operating modes described in chapter three, section 3.2.2.1.5. These operating modes consist of the control strategies applied to the *Supervisory and Control Unit*. As stated in chapter three, the *Supervisory and Control Unit* has three input parameters which are the electrical power generated by the wind power system (PWR1out), the electrical power generated by the photovoltaic power system (PWR2out) and the power demanded by the load (P_{load}). Additionally, we have assumed that the first priority of energy supply to the load is assigned to the hybrid photovoltaic wind power system. In order to consider the remaining electrical power supply subsystem which is the utility grid through the electrical distribution system, we have to ensure that the power generated from this hybrid power system is not available. The utility grid can only be used for energy supply when the HPVWS does not generate enough power to supply the load or when the power generated is equal to zero.

The overall activities of the system are shown in the activity diagram in the appendix A.4

4.5.1 First operating mode activity diagram

This operating mode consists of supplying the total load demand by only operating the hybrid wind photovoltaic power system. In this operating mode, the hybrid wind photovoltaic power system is operating in islanded mode without any contribution from the utility grid through the electrical distribution systems and there is no surplus of energy to be injected to the grid. It should be noted that when operating as islanded, no particular control strategy is required to ensure the system stability compared to when the system is operating as grid connected. The corresponding activity diagram for this operating mode is shown in Figure 4.20.

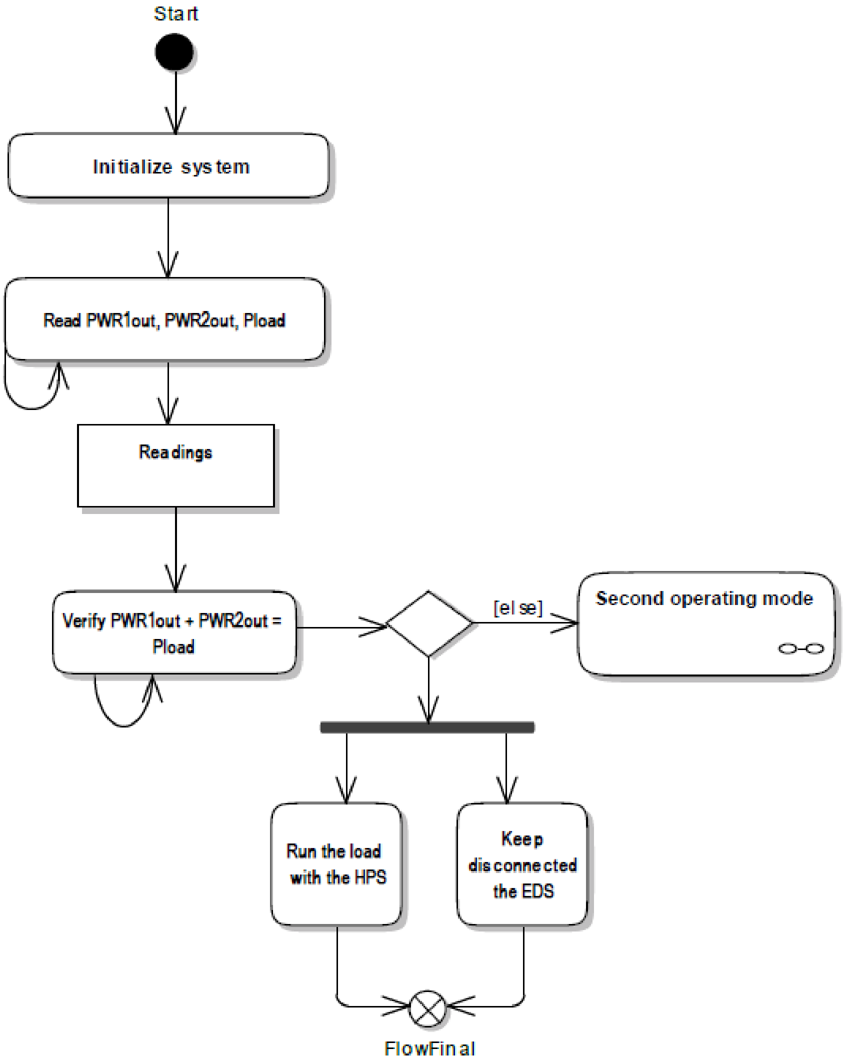


Figure 4.20 First operating mode activity diagram

4.5.2 Second operating mode activity diagram

The second operating mode consists of supplying the load demand by operating the hybrid wind photovoltaic power system. In this mode we have assumed that the load demand requirement is fully met by the hybrid power system and the exceeding electrical power is fed into the utility grid through the electrical distribution system. The activity diagram for this operating mode is depicted in Figure 4.21.

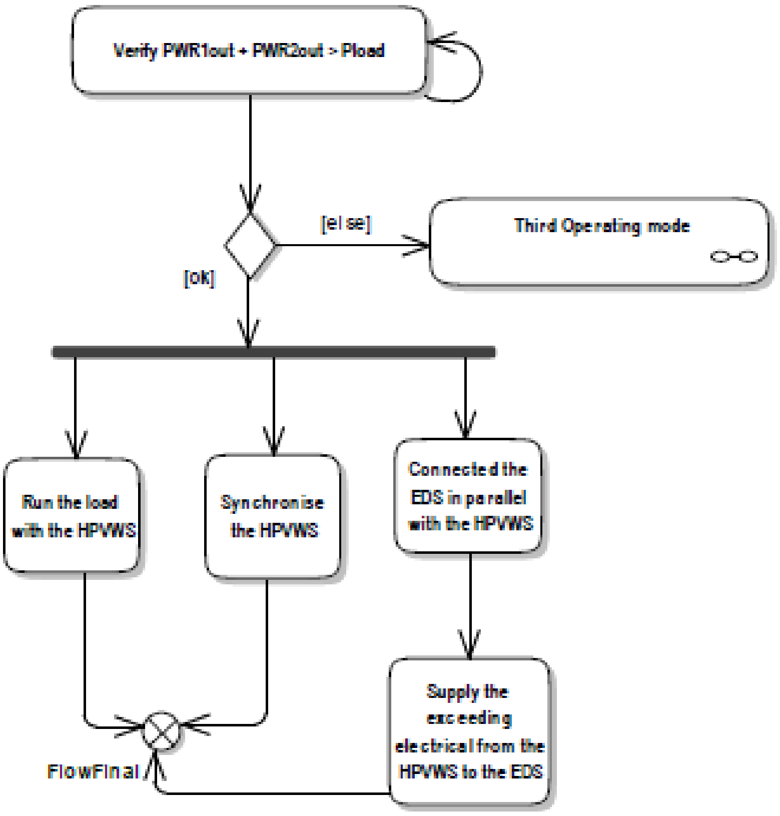


Figure 4.21 Second operating mode activity diagram

4.5.3 Third operating mode activity diagram

In this operating mode, in order to maintain the load demand requirement, both the hybrid wind photovoltaic power system and the utility grid through the electrical distribution system operate in parallel. In this case, the priority of electrical energy supply to the load is set to the hybrid photovoltaic wind power system while the electrical distribution system plays a secondary role by supplying only the deficit of electrical energy that the load needs. In this operating mode we assume that the hybrid photovoltaic wind power system is generating electrical power, but this power is not enough to fulfill the load requirement. The corresponding activity diagram of the system in this operating mode is shown in Figure 4.22.

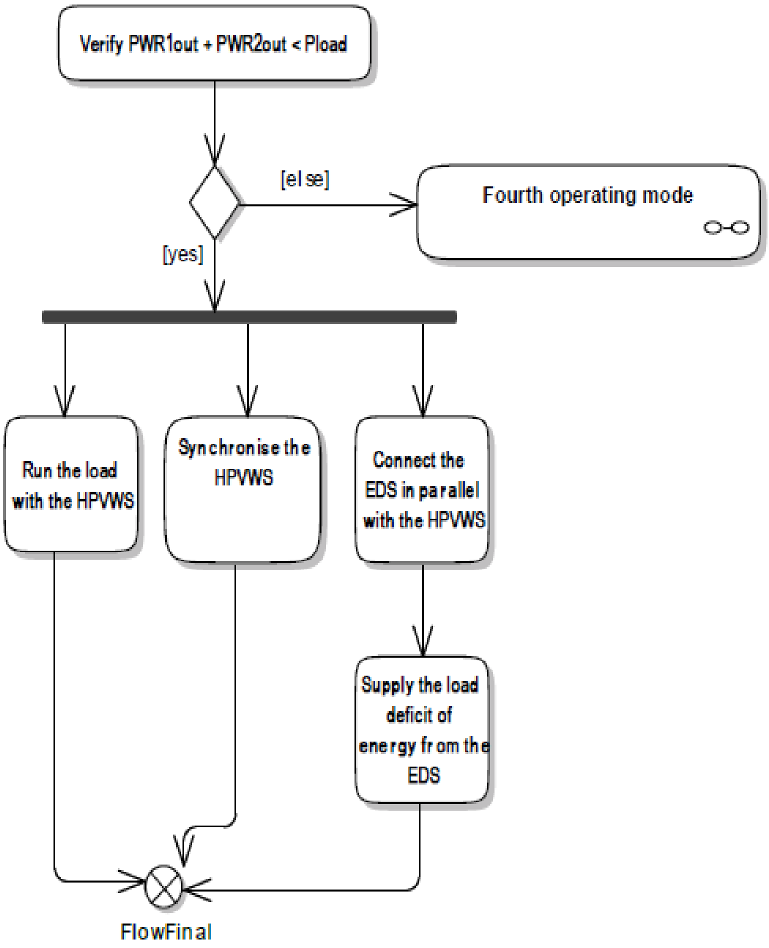


Figure 4.22 Third operating mode activity diagram

4.5.4 Fourth operating mode

This operating mode refers to the period of time when neither wind nor photovoltaic power is available. The total energy load demand requirement is fulfilled by the utility grid through the electrical distribution system. The hybrid wind photovoltaic power system is then switched off and not operating. The corresponding activity diagram for the system in this operating mode is shown in Figure 4.23.

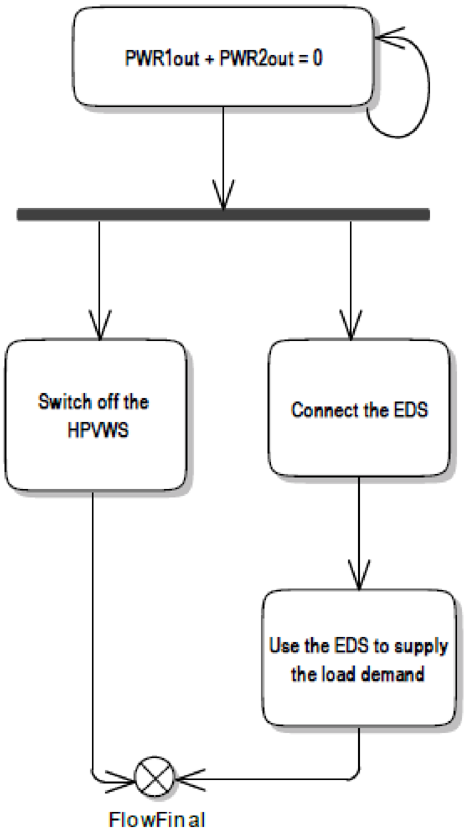


Figure 4.23 Fourth operating mode activity diagram

4.6 Constraint on physical properties of blocks

The study of the constraint on physical properties of the blocks of the system normally considers as input the system requirements as well as the block definition diagram. The output obtained in this case will be the constraint block definition diagrams and the parametric diagrams.

Modelling the system constraint using parametric diagrams starts by defining the physical constraints on the system's blocks. This is done using a block definition diagram called a constraints block. After defining the constraint proprieties of the block, a parametric model can be implemented and depending upon the advantages of the software used, the simulation of the parametric diagram can be configured and ran.

This section deals with the modelling of the physical constraints of the wind and photovoltaic power systems as well as the expected output voltage and current. We also present a comparison between SysML based tools and Matlab (Simulink).

4.6.1 Wind power system parametric diagram

The wind power system parametric diagram as modelled is shown in Figure 4.24. This wind power system parametric diagram is based on a wind power system model presented in the equation (2.12).

The constraint block definition diagrams related to this parametric diagram as well as the scripts to run the simulation are shown in the appendices A.5 and A.6, respectively.

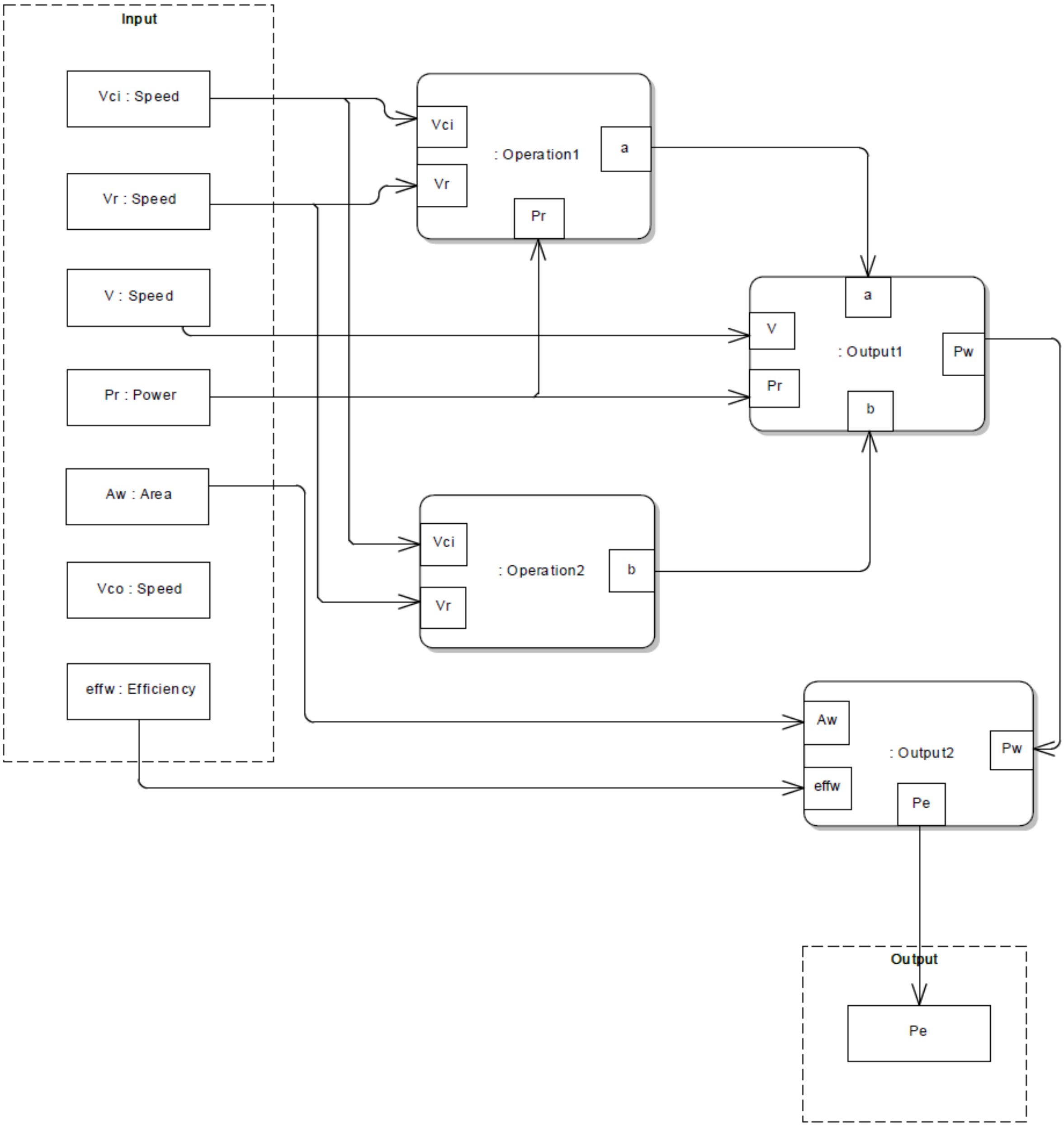


Figure 4.24 Wind power system parametric diagram

The inputs considered in the parametric diagram in Figure 4.24 are: the cut-in speed (V_{ci}), the cut-off speed (V_{co}), the rated speed (V_r), the rated power (P_r) and the area of the wind turbine, the wind speed (V) and the efficiency of the wind power system (eff_w), whereas the output of the system is the electric power (P_e).

The constraint property "*Operation1"* in this parametric diagram (see Figure 4.24) refers to the computation of the value of *a* (refer to the equation 2.13), while the constraint property *"Operation2"* computes the value of *b* (refer to the equation 2.14).

The constraint property *"Output1"* computes the value of the wind turbine generator P_w (see equation 2.12), whereas, the constraint property *"Output2"* computes the electric power output from the turbine.

4.6.2 Photovoltaic system parametric diagram

The photovoltaic parametric diagram model as shown in Figure 4.25 is based on the photovoltaic model given in the equation 2.29.

The constraint block definition diagrams as well as the scripts to run the simulation are shown in the appendices A.7 and A.8, respectively.

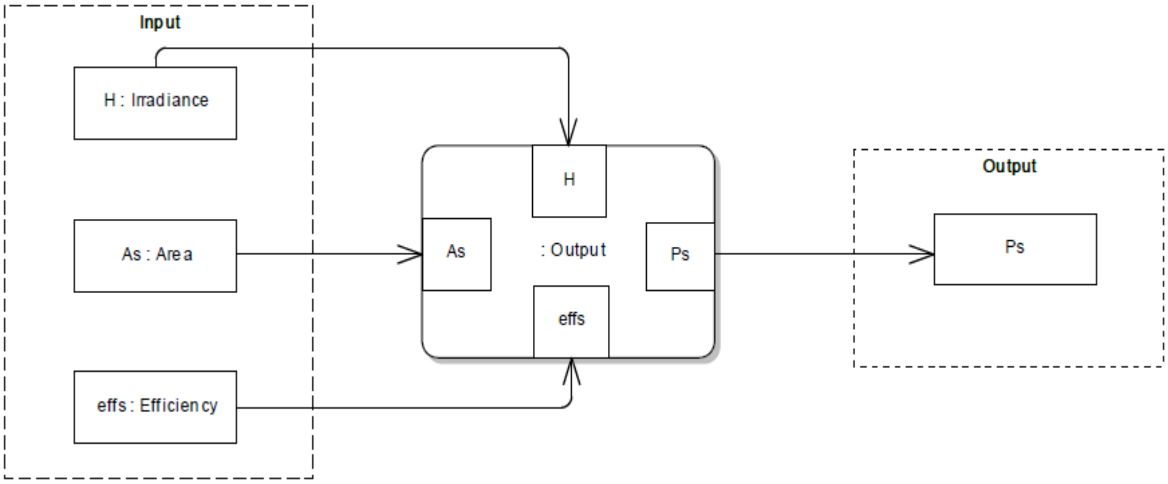


Figure 4.25 Solar Photovoltaic parametric diagram

As can be seen in the photovoltaic parametric diagram in Figure 4.25, three input parameters are considered. These inputs are the irradiance (H), the area and the efficiency of the photovoltaic panel. The computed output in the photovoltaic parametric diagram represents the power output of the photovoltaic system (P_s).

The constraint property *"Output"* represents the computation of the equation 2.29.

4.6.3 Output voltage and current parametric diagrams

The parametric diagrams of the output voltage and current as modelled and shown in Figures 4.24 and 4.25 are based on the three phase voltage and current by assuming that the voltage and the current are three phase sinusoidal and balanced systems.

The constraint block definition diagrams corresponding to both parametric diagrams as well as the scripts can be found in the appendices A.9 and A.10, respectively.

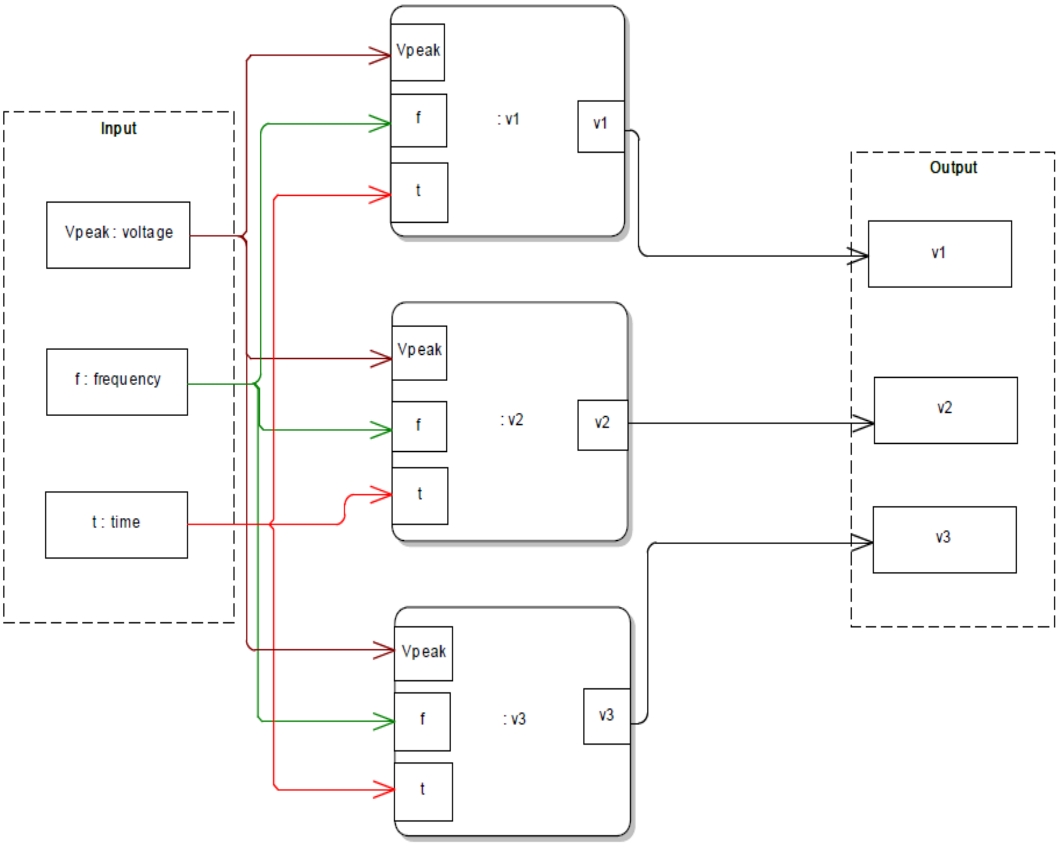


Figure 4.26 Voltage output parametric diagram

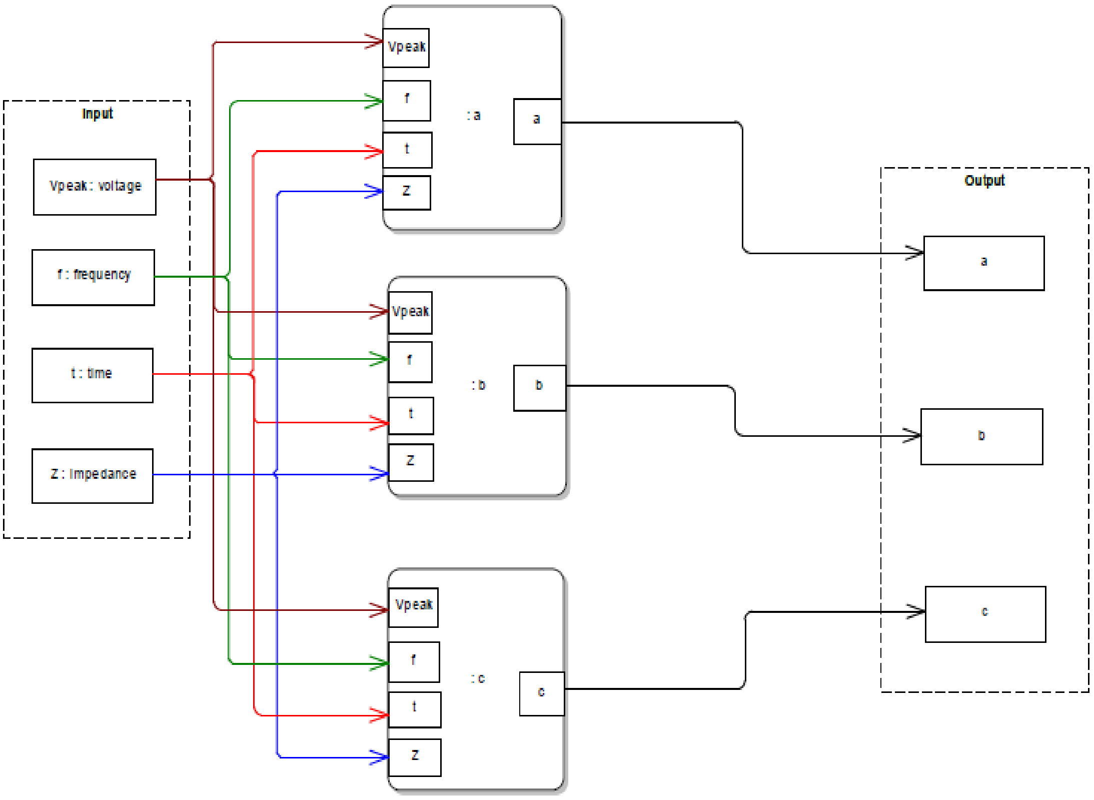


Figure 4.27 Output current parametric diagram

4.6.4 Simulation of the parametric diagrams

The System Modelling Language has been developed to support communication between the different engineering disciplines involved in the development of a system and does not include a particular language for specifying the state transitions, meaning that by default it does not include any executable model. It is therefore the choice of the tool vendor to provide an appropriate SysML platform which may include an executable model for the simulation. Different SysML tools can be found on the market such as Artisan Studio, MagicDraw, Rapsody IBM, AltovaUModel, Enterprise Architect, etc. Most of these tools provide a code generation from SysML models that can be used in interactive simulation using a simulation platform supporting the code generated. Others, such as Enterprise Architect which is the SysML tool used in this project, also include a simulation platform based on parametric diagrams. This simulation platform operation is based on mathematical constraint of the constraint blocks.

Due to the limitation of the SysML tool used, we did not perform the simulation of the parametric diagrams represented in Figures 4.24 and 4.25. The SysML tool used does not support the script for the equation 2.12 which includes conditional statements such as *if* or *else*.

Another problem occurred when performing the simulation of the photovoltaic parametric diagram represented in Figure 4.25, which is based on equation 2.29 as stated previously. The problem faced here was the configuration of input values of the solar radiation. Knowing that the solar irradiation during a day varies, the SysML tool used did not support a particular type of interval value, such as [0 1000 0] that we used as data in order to set the solar irradiation variation values.

These SysML tool limitations did not allow us to perform all the simulations planned and only two simulations were performed without issues. These simulations are related to the parametric diagrams represented in Figures 4.26 and 4.27 and represent the expected output voltage and current and the data configuration used for the simulation can be seen in appendix A.9 and A.10 for the voltage and the current parametric diagrams, respectively.

The simulation curves for both parametric diagrams are shown in Figures 4.28 and 4.29 for the output voltage and current, respectively.

Figure 4.28 represents the expected three phase sinusoidal output voltage from the hybrid photovoltaic wind power system.

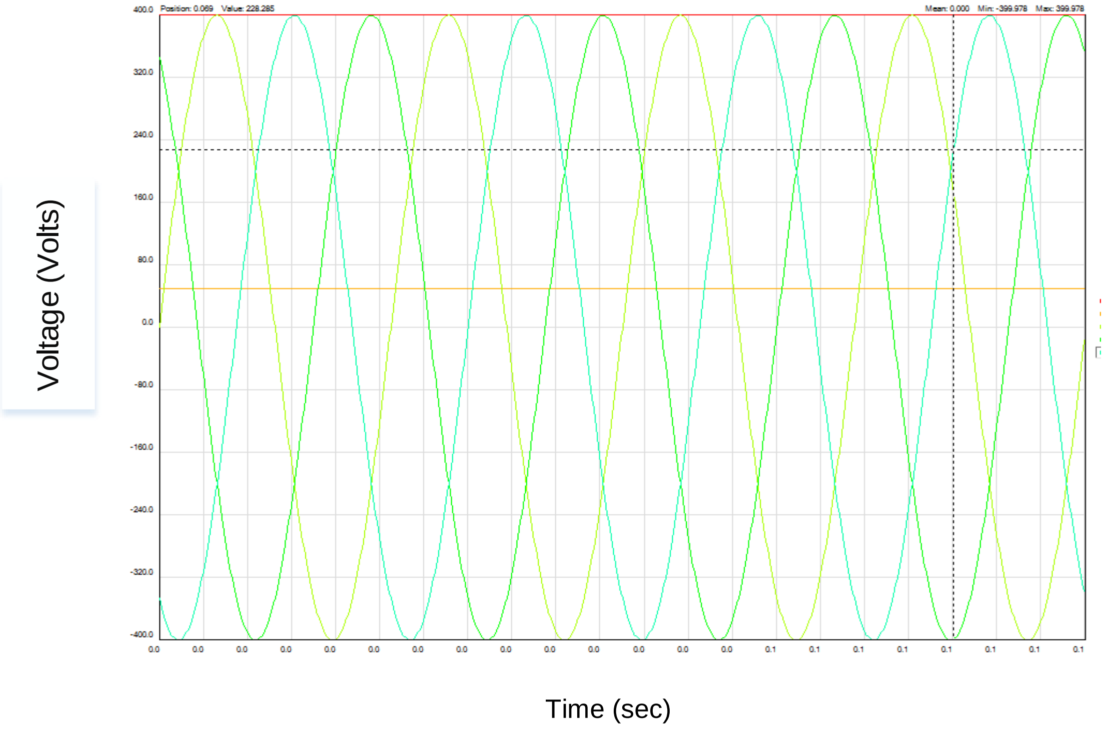


Figure 4.28 Hybrid photovoltaic wind power systems output voltage

The type of electrical load considered for the simulation of the expected output current (see Figure 4.29) is resistive impedance. Different other types of load can be considered such as capacitive or inductive loads etc. However, due to some modelling tool limitations, we did not consider all these types of loads.

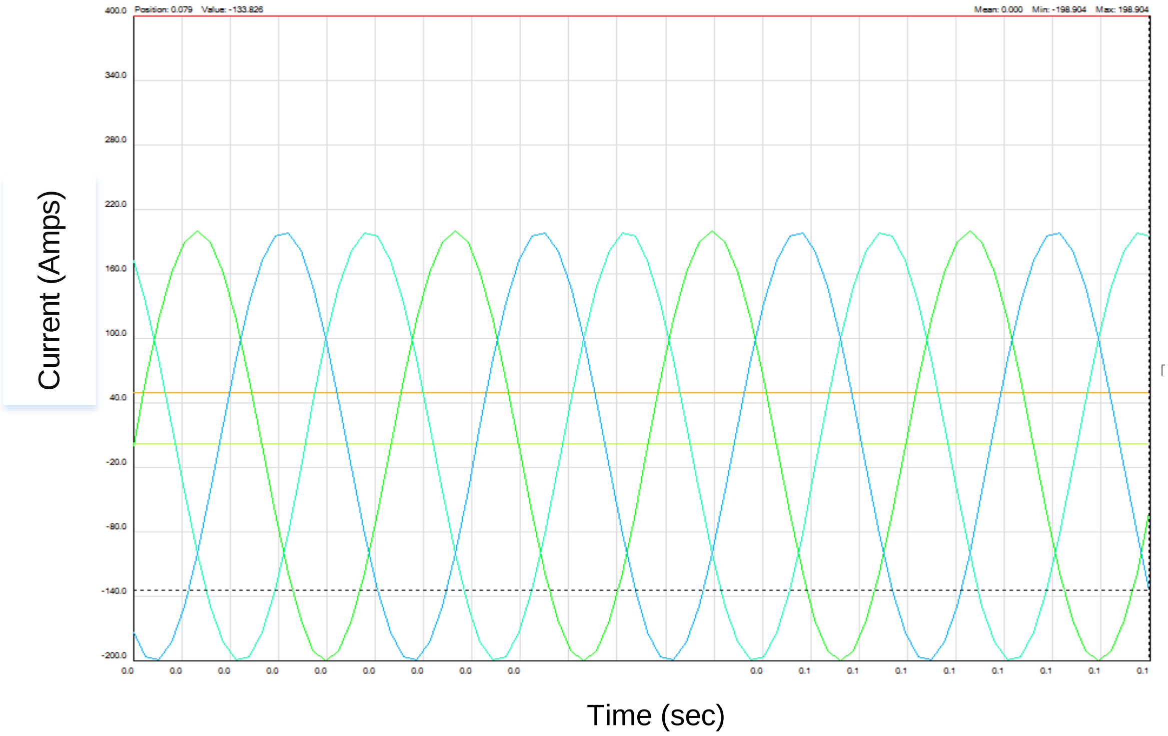


Figure 4.29 Hybrid photovoltaic wind power systems output current

4.6.5 Simulation with Matlab Simulink

When comparing SysML and Matlab-Simulink, which is the widely used platform in the industry for modelling and simulation of systems, it appears that SysML has a standardized general purpose graphical notation for modelling different views including requirement, structure behaviour and constraints of the system, whereas Matlab-Simulink does not have a standardized graphical notation. Additionally, Matlab-Simulink is based on the block-oriented paradigm, which always forces a causal dependence between input and output values of a block when solving equation systems Matlab-Simulink does not support inheritance-concepts for classification of components in order to enable their reuse. However, Matlab-Simulink presents the advantage of allowing the modelling and simulation of dynamic systems whereas SysML parametric diagrams are based on mathematical equations. Figure 4.30 shows the Matlab-Simulink corresponding model of the hybrid photovoltaic wind power system considered.

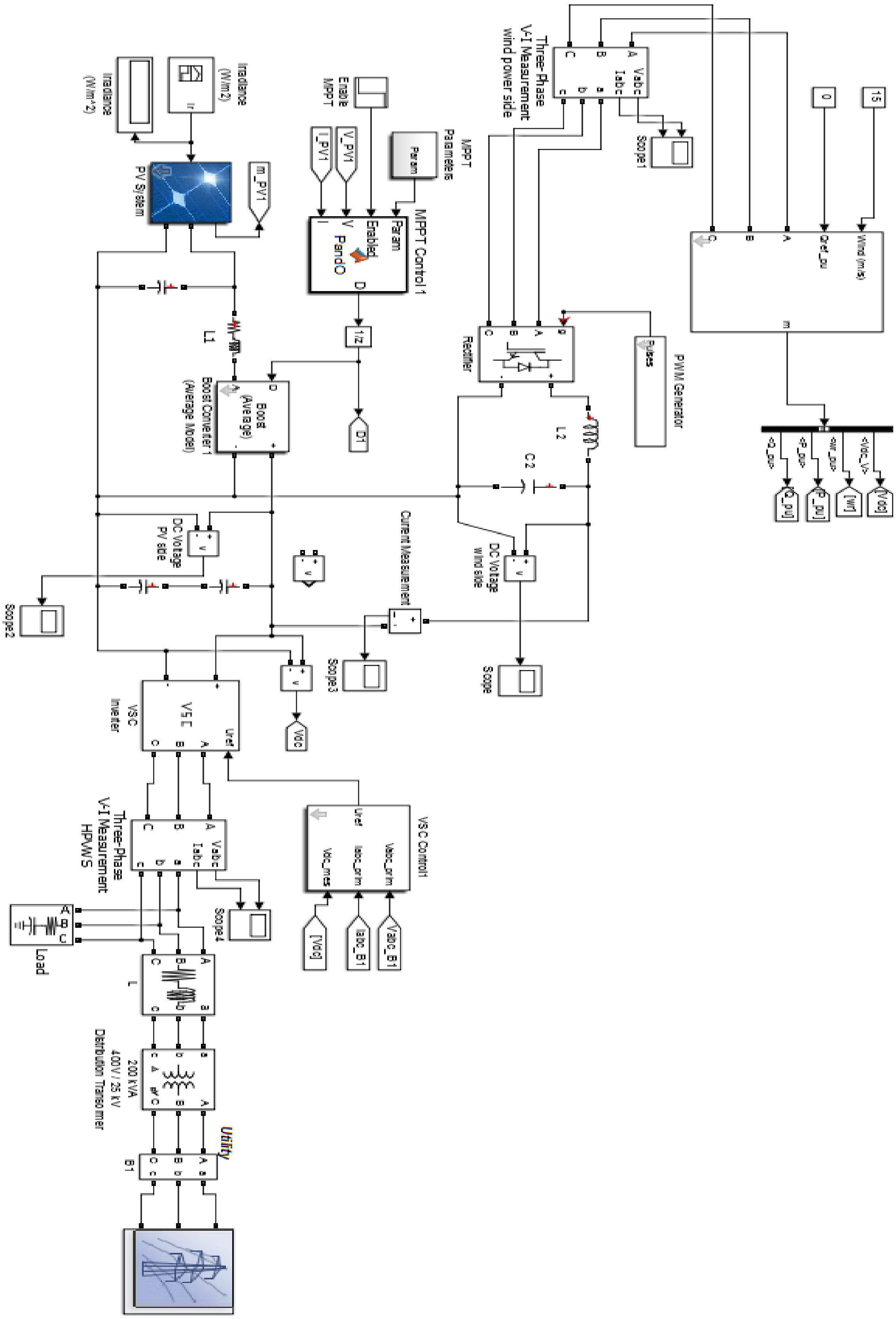


Figure 4.30 Matlab-Simulink model of HPVWS integrated to the electrical distribution system

As shown in Figure 4.30, the model implemented includes a HPVWS connected to the utility grid through the distribution network. The parameters of the HPVWS used for the simulation are shown in Table 4.1. Besides the parameters in Table 4.1, the other parameters used are provided by Matlab-Simulink.

Table 4.1 HPVWS model simulation data

Wind Generator PMWG	
Power (W)	4500
$V_{Phase\ to\ Phase}$ (V)	440
Frequency (Hz)	50
Wind Turbine	
Nominal Mechanical Power (kW)	2000
Wind speed at nominal speed (m/s)	11
PV System	
Module type	SunPower SPR 305 WHT
Module specification under STC	
V_{oc} (V)	64.2
I_{SC} (A)	5.96
V_{mp} (V)	54.7
I_{mp} (A)	5.58
Number of series connected modules per string	5
Number of strings in parallel	4
Rectifier	
Type of electronics device	IGBT
Generator mode	3 arms bridge (3 pulses)
Carrier frequency (Hz)	1080
VSC Inverter	
Power electronics device	Average model based VSC
Number of bridge arm	3
Nominal Power (kVA)	200
Nominal Frequency (Hz)	50
Nominal Primary and Secondary Voltage (V)	35000and 400 respectively
Nominal DC bus voltage (V)	640
Load	
Nominal Power (kW)	200
Frequency (Hz)	50
$P_{Phase\ to\ phase}$ (V)	400

Figures 4.31 and 4.32 show the output voltages waveforms for the photovoltaic power and the wind power systems, respectively after the simulation of the model in Figure 4.30. As can be seen, both output voltages are in Direct Current (DC). However, at the beginning both waveforms are not completely continuous. These areas simply correspond to the system

start up region. It should be noted as well as that the DC voltage from the wind power system is measured after the rectifier.

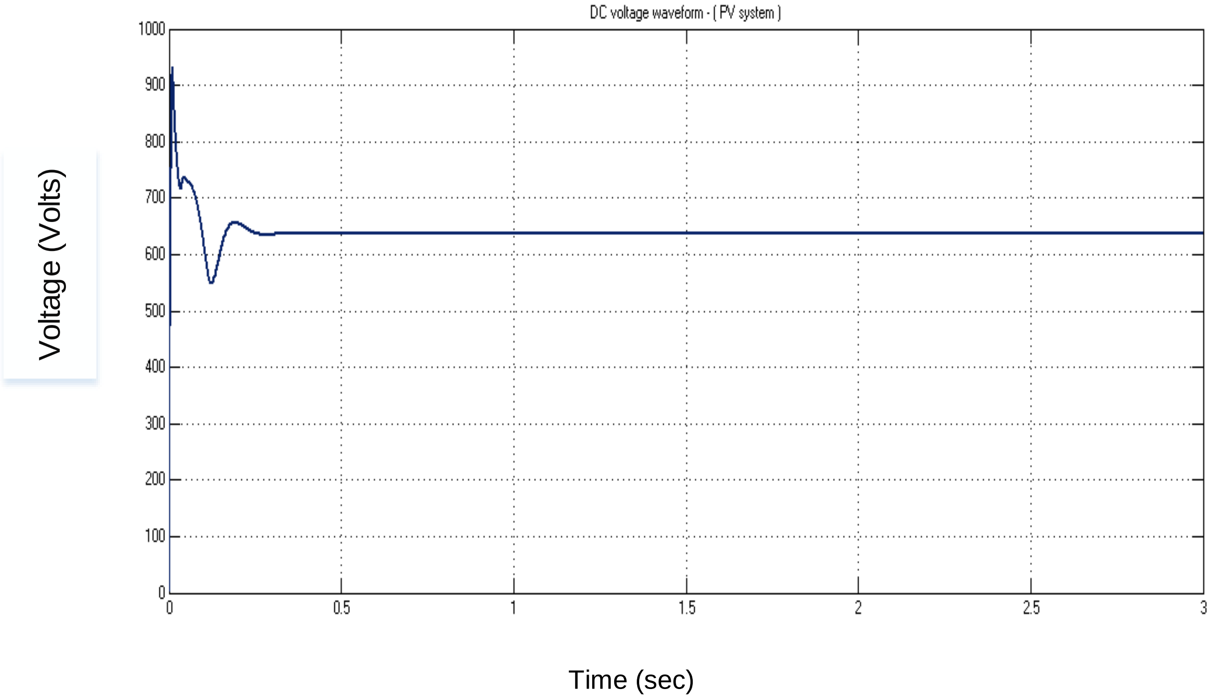


Figure 4.31 PV DC voltage

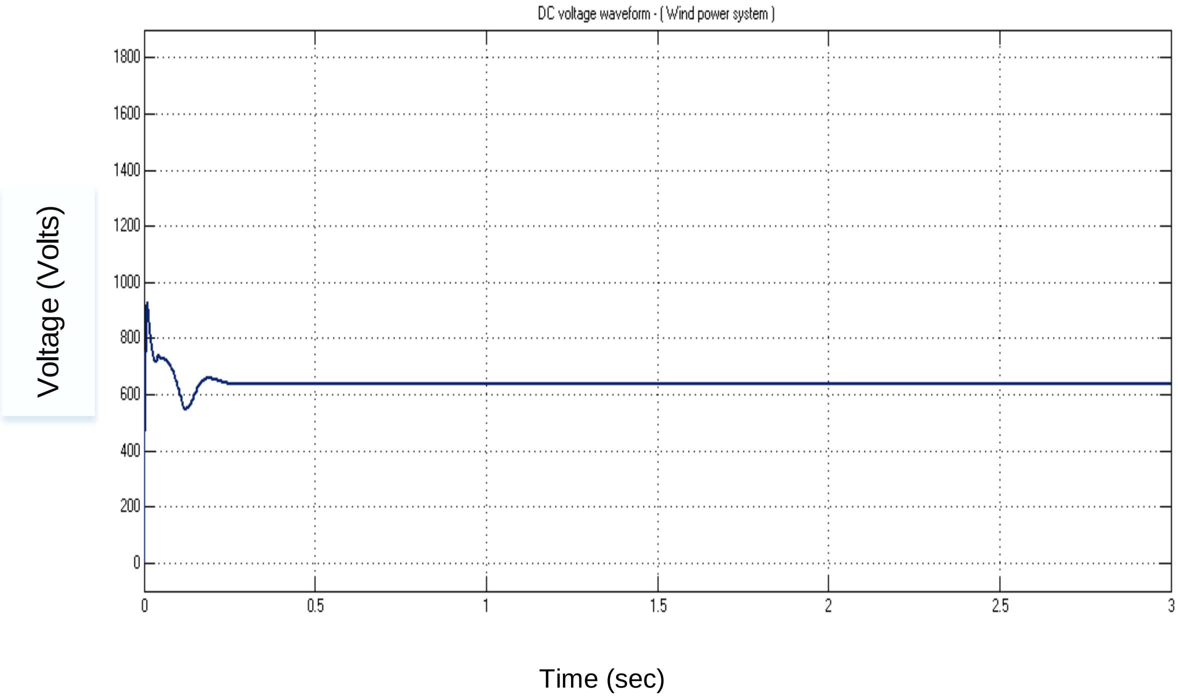


Figure 4.32 Wind Power DC voltage

Figures 4.33 and 4.34 represent the curves for output voltage and current respectively. These curves are measured at the output of the inverter after the simulation of the model in Figure 4.30. As can be seen from these two figures, the waveforms are totally sinusoidal and reflect the reality. The type of load considered for the simulation is a pure resistive load. The output voltage corresponding to the RL and RC loads are shown in Figures 4.35 and 4.34 respectively. In both these figures we have considered the reactive power as well as the capacitance power as being equal to 200 kvar.

For Figure 4.35, the voltage and the current waveforms show that the voltage is lagging behind the current according to the reality in a RL circuit whereas in Figure 4.36, the current is lagging behind the voltage.

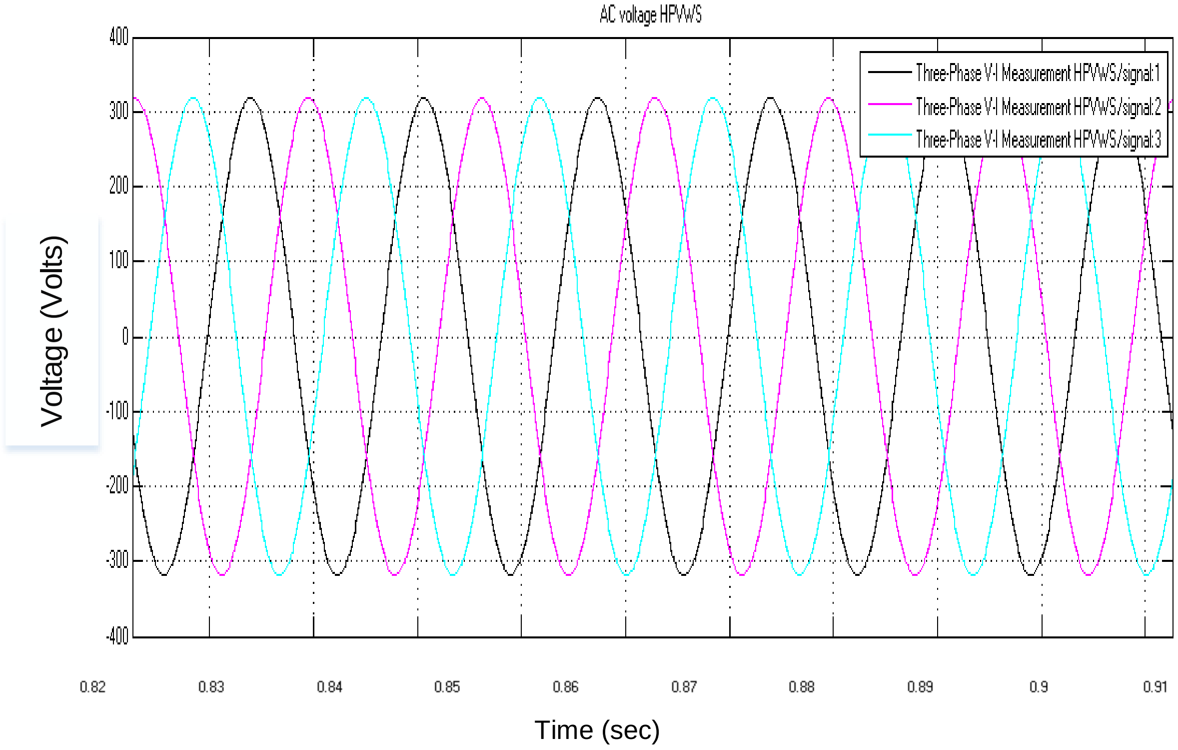


Figure 4.33 HPVWS AC output voltage

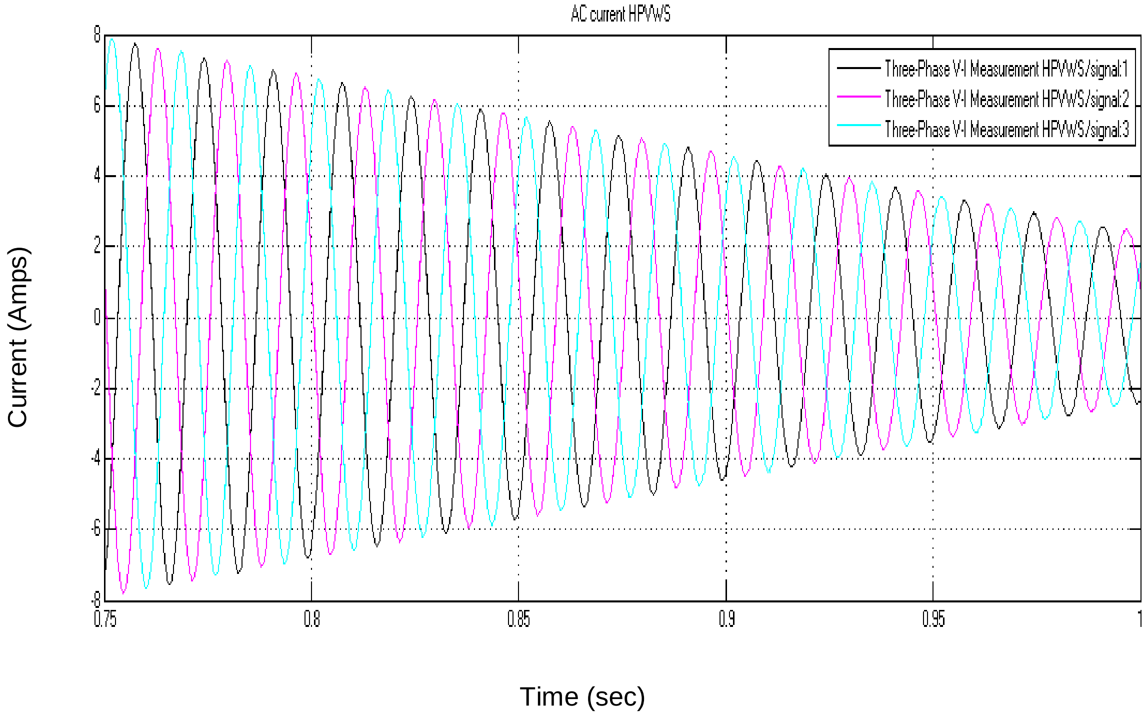


Figure 4.34 HPVWS AC output current

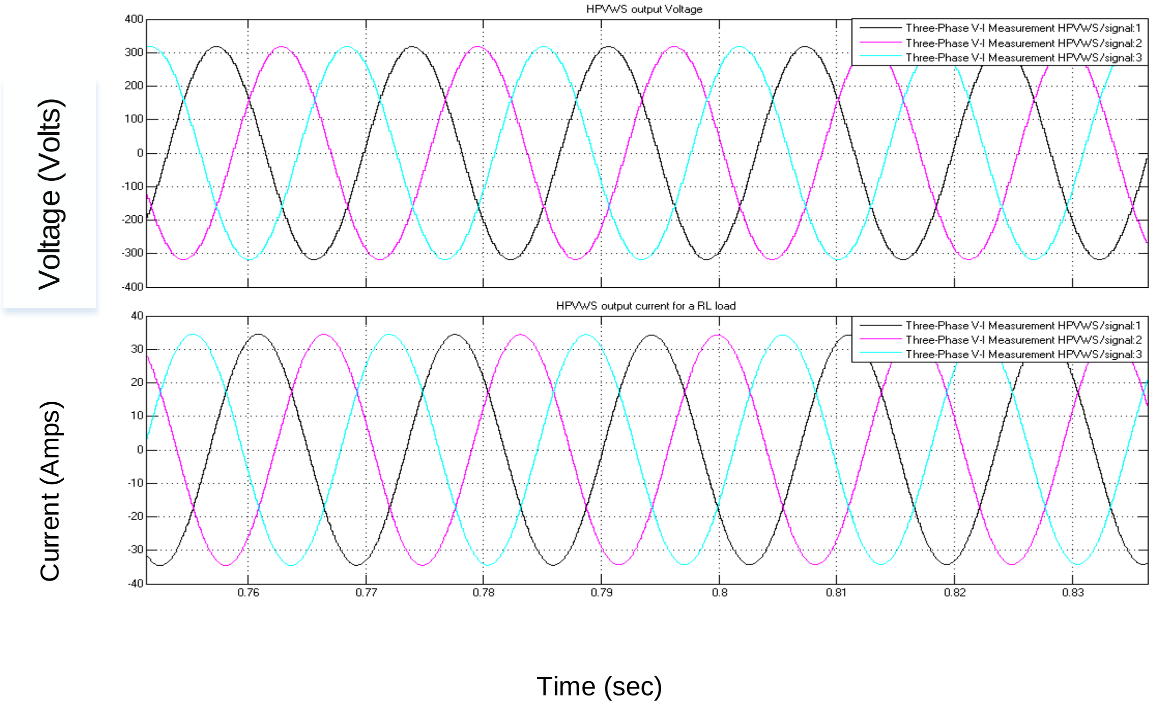


Figure 4.35 HPVWS voltage and current for a RL load

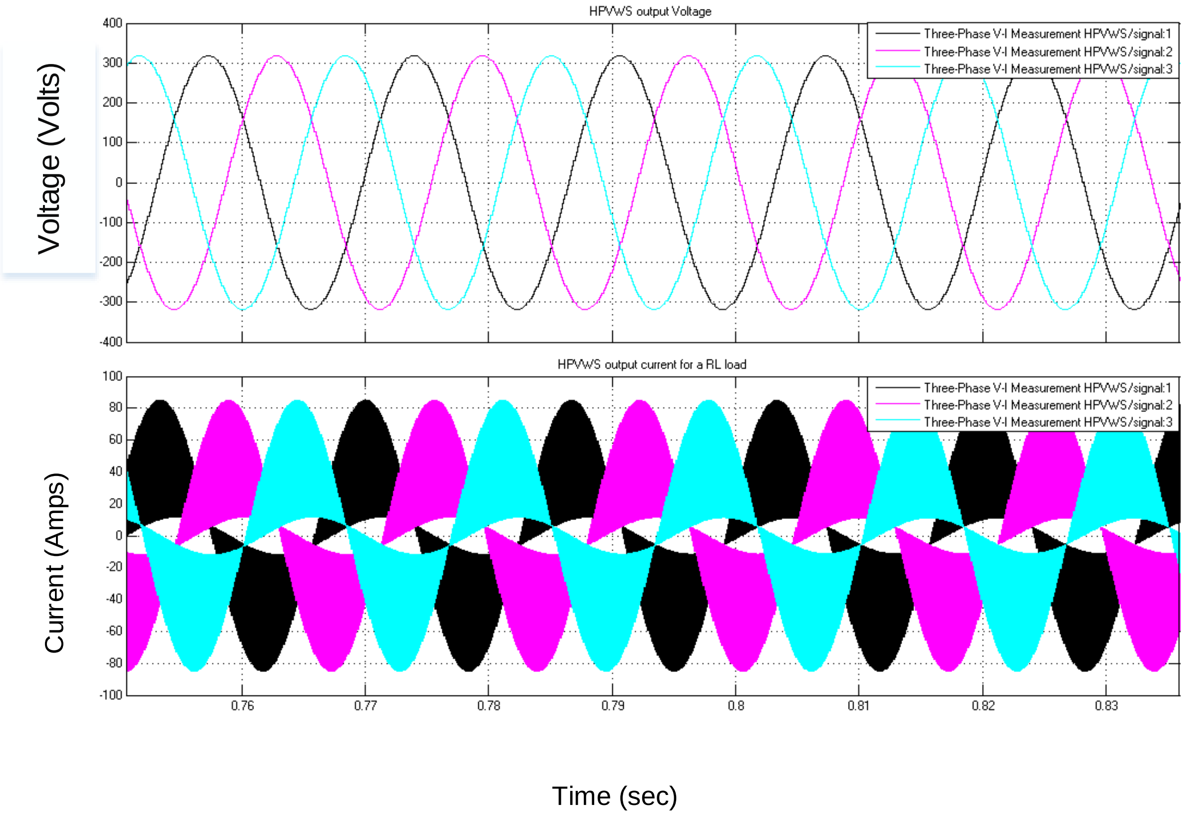


Figure 4.36 HPVWS Voltage and current for a RC load

4.7 State machine diagram of the system

The state machine diagram is implemented by considering the structure and the activity diagrams. For this we need to identify the block diagrams which present some behaviours and capture these behaviours by creating a state machine diagram for each of them.

The state machine diagram depicted in Figure 4.37 shows the system in its states and includes all the activities as presented in the activity diagrams. This state machine diagram can also be seen as the representation of the different operation modes presented in chapter three, section 3.2.2.1.5. As can be observed, in this state machine diagram it is shown that the system can transit from one operating mode to another when the condition to pass this operating mode is satisfied.

Two major states have been considered: one state called *HPVWS Operation* refers to the state where the HPVWS is operating, whereas in the other one called *F4 mode,* the HPVWS is shut down. The state *HPVWS Operation* consists of a composite diagram and includes three states: *F1 mode, F2 mode* and *F3 mode.* As for the *HPVWS Operation* state, the states *F1, F2 and F3 modes* also consist of composite diagrams including different states which will be described in the following sections of this chapter.

As shown in Figure 4.35, after reading the *Pload, PWR1out* and *PWR2out;* power of the load; power generated by the wind power system; and power generated by the photovoltaic system, respectively and evaluating *P=PWR1out* + *PWR2out,* which is the total power of the HPVWS, four events can occur depending on *Pload* and *P*. These four events are *P>Pload, P=Pload*, P<*Pload* and *P=0.*

In the event of *P>Pload*, the HPVWS will be in state *F1 mode.* Once the event passes to *P=Pload* the HPVWS will be in state *F2 mode.* If the event *P=Pload* occurs, the HPVWS will be in state *F3 mode* and if *P=0*, the system will be in state *F4 mode* where the HPVWS will be shut down and the system will switch to the EDS to supply power to the load. In this state machine, the HPVWS can transit from one state to another whenever the event for that state occurs. For instance, the HPVWS can pass from state *F1 mode* to *F2 mode once P* becomes equal to *Pload* and from state *F2 mode* to *F1 mode* once *P* becomes greater than *Pload*.

4.7.1 F1 mode state diagram

As mentioned earlier, the state *F1 mode* consists of a composite diagram and includes some other states. This state "*F1 mode"* is shown in Figure 4.38 representing the F1 mode state machine diagram. After the initial step, two states can be seen in this state machine diagram. These states are "*Synchronising"* and "*Operating".*

The operation in the state called "*Synchronising"* consists of synchronising the HPVWS frequency and voltage in order to connect it in parallel with the EDS. After the "*Synchronising"* state, the following state is called the "*Operating"* state. This state will happen after the event called "*Operate"* has occurred.

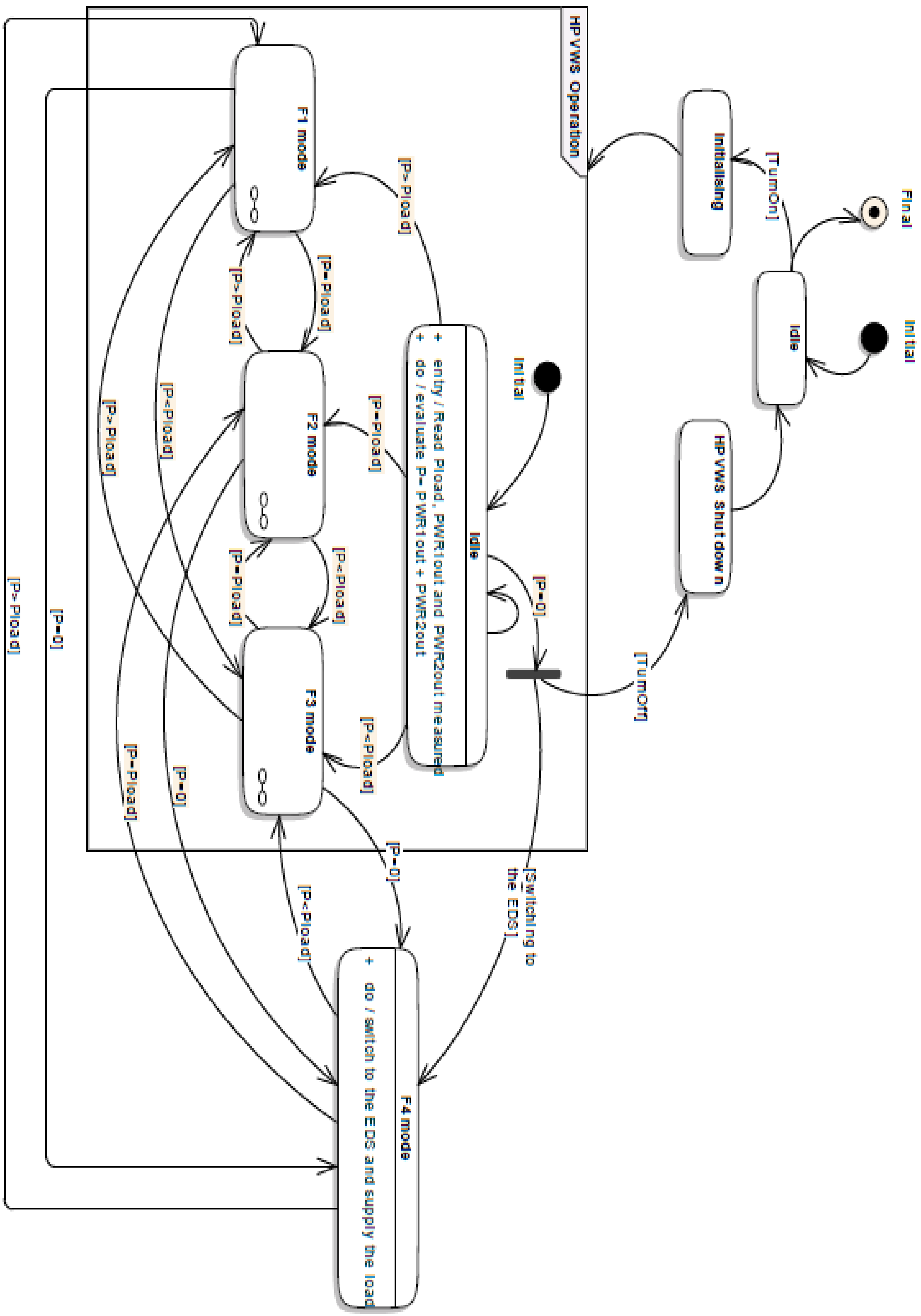


Figure 4.37 HPVWS state machine diagram

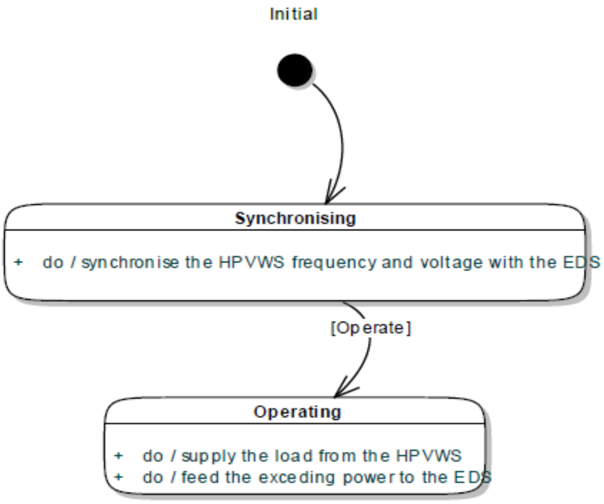


Figure 4.38 F1 mode state machine diagram

4.7.2 F2 Mode state diagram

The state machine diagram for "*F2 mode"* is shown in Figure 4.39. This state machine diagram consists of one state which is "*Operate"* and the operation to be accomplished by this state is "*disconnect the EDS and supply electricity to the load from the HPVWS".*

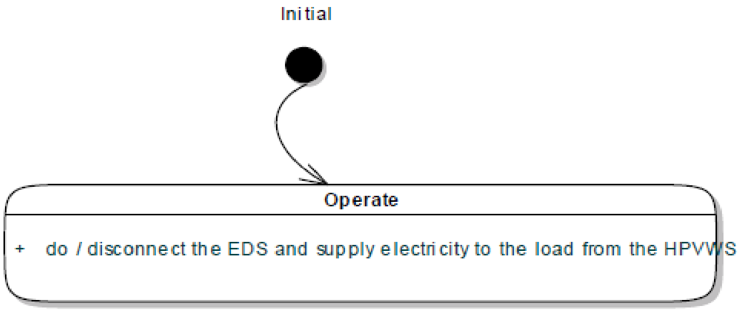


Figure 4.39 F2 mode state machine diagram

4.7.3 F3 mode state diagram

The*"F3 mode"* state diagram consists of two operations which are *"supply the load with electricity from the HPVWS"* and *"connect the EDS and supply the deficit electricity to the load".* This state machine diagram is shown in Figure 4.40 below.

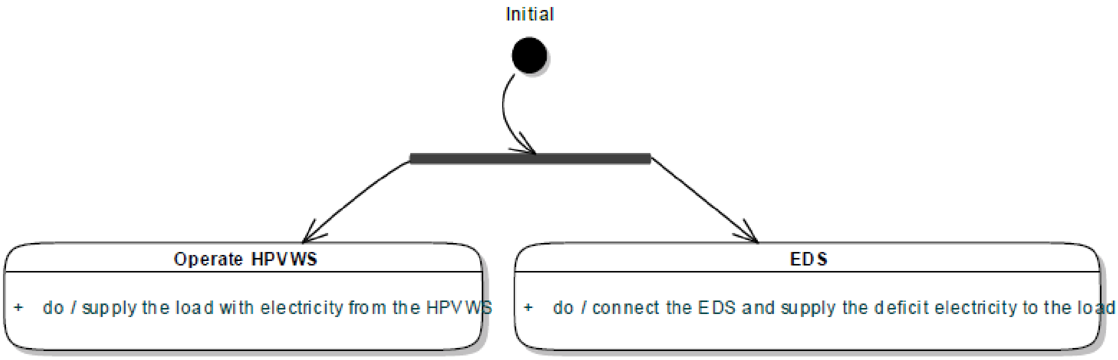


Figure 4.40 F3 mode state diagram

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

5.1 Conclusions

The modelling of hybrid photovoltaic wind integrated generation systems in an electrical distribution network has been presented in this thesis. This modelling framework is based on the approach of Model Based Systems Engineering (MBSE) and used SysML as the modelling language. The system architecture considered for this research includes a Permanent Magnetic Wind Generator, a photovoltaic system and the power electronics interfaces including a rectifier used to convert to DC the AC power generated by the wind generator, a DC to DC boost used to boost the DC power generated by the photovoltaic system and an inverter used to convert the DC power from the hybrid power system to AC power in order to connect it to the electrical distribution system.

A review of the literature on the modelling of power systems in general and the modelling of grid connected and stand-alone hybrid photovoltaic wind power systems in particular, has revealed that all the models use the modelling tools such as Matlab-Simulink, Power World, DigSilent, etc. These tools are based on different approaches and allow modelling of the system considering only a particular point of view, depending on the objective that is being pursued, while SysML offers the advantage of modelling the system by considering different aspects such as specifications and requirements, structure, behaviours and constraints.

5.1.1 Evaluation of the modelling language used in this thesis

Compared to the tools normally used to model power systems, there are some advantages when using SysML as modelling language, due to the fact that SysML provides different modelling viewpoints of a system. In this thesis, we modelled a hybrid photovoltaic wind power system integrated in an electrical distribution network capturing the system's requirements, the system's structure in terms of the relationship between the different elements, the system's behaviour in terms of activities in the different cases considered and transition from one state to another as well as the system's interaction with all the stakeholders.

5.1.2 Evaluation of the SysML tool used

SysML tools are now widely available on the market. The modelling tool used in this thesis is the Sparx System Enterprise Architect version 9 with SysML. This tool is easy to install and easy to use. However, as new users of this tool and being novices in the modelling of systems, we faced some problems which are described in chapter 4 and gained valuable experience.

5.2 Recommendations for further research

Further research should focus on the following aspects:

- Extend the models of this system in terms of greater complexity;
- Add additional behaviour of the system in terms of operating modes;
- Generate executable codes from the model and run them with a supporting simulation platform;
- Implement the complete mapping of SysML models to Matlab Simulink models;
- Compare the simulation results obtained from SysML executable codes and the simulation results from Matlab Simulink.

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APPENDICES

A.1 System Context Diagram

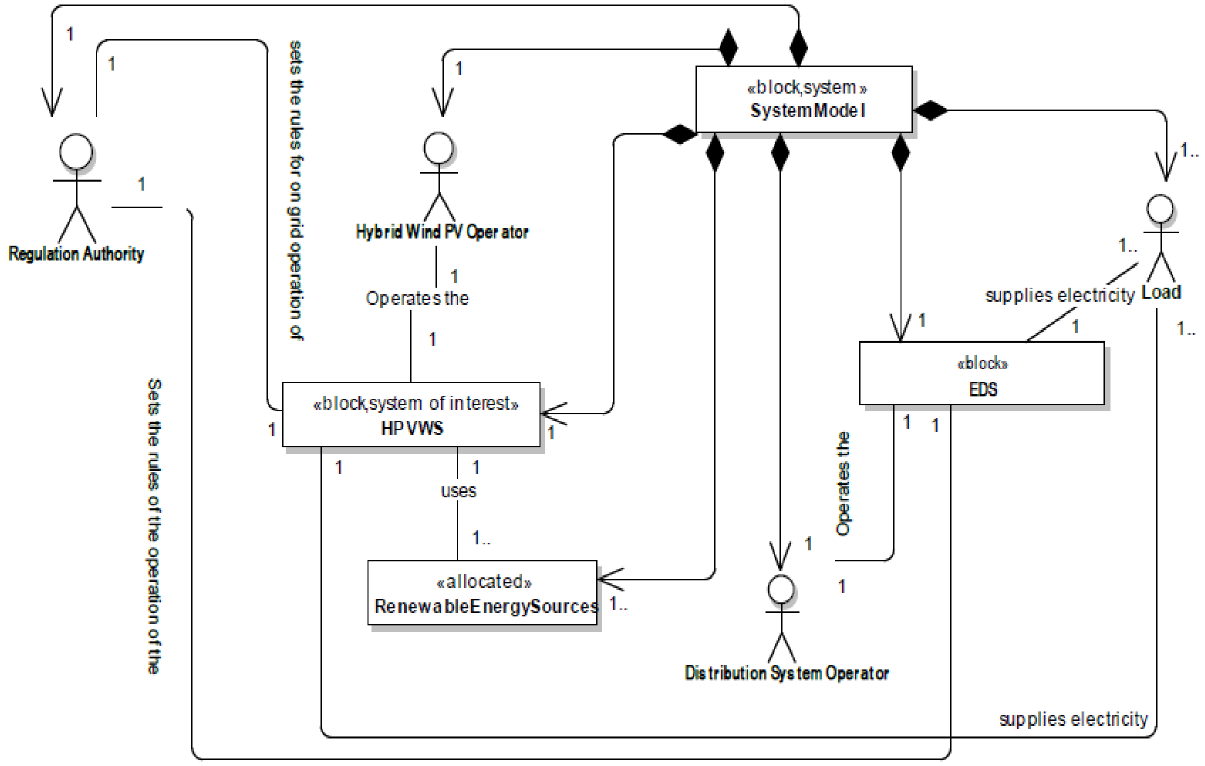
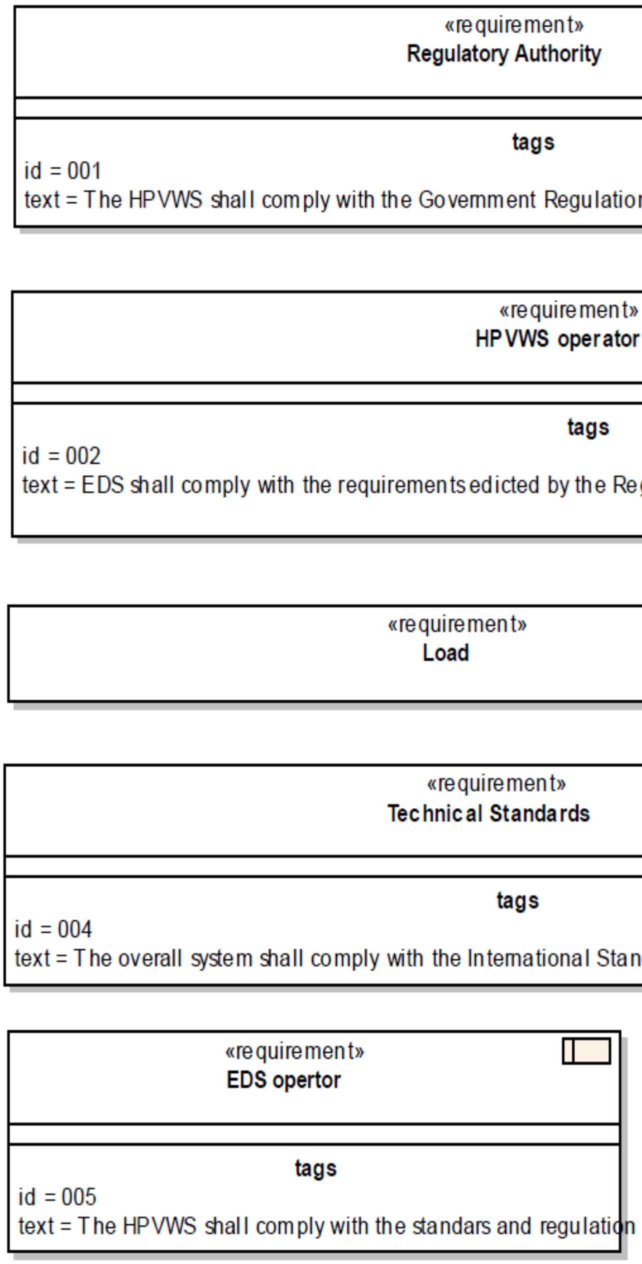


Figure 5.1 Domain model

A.2 High level system's requirements



«requirement»
Regulatory Authority

tags
id = 001
text = The HPVWS shall comply with the Government Regulation and all the International standards

«requirement»
HPVWS operator

tags
id = 002
text = EDS shall comply with the requirements edicted by the Regolatory Authority for interconnection with the HPVWS

«requirement»
Load

«requirement»
Technical Standards

tags
id = 004
text = The overall system shall comply with the International Standards

«requirement»
EDS opertor

tags
id = 005
text = The HPVWS shall comply with the standars and regulation

Figure 5.2 High level system's requirements

A.3 Flow specifications in the system

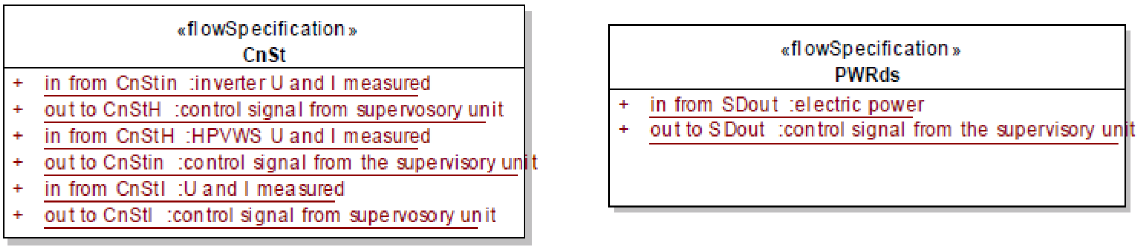


Figure 5.3 System flow specifications

A.4 System’s activity diagrams

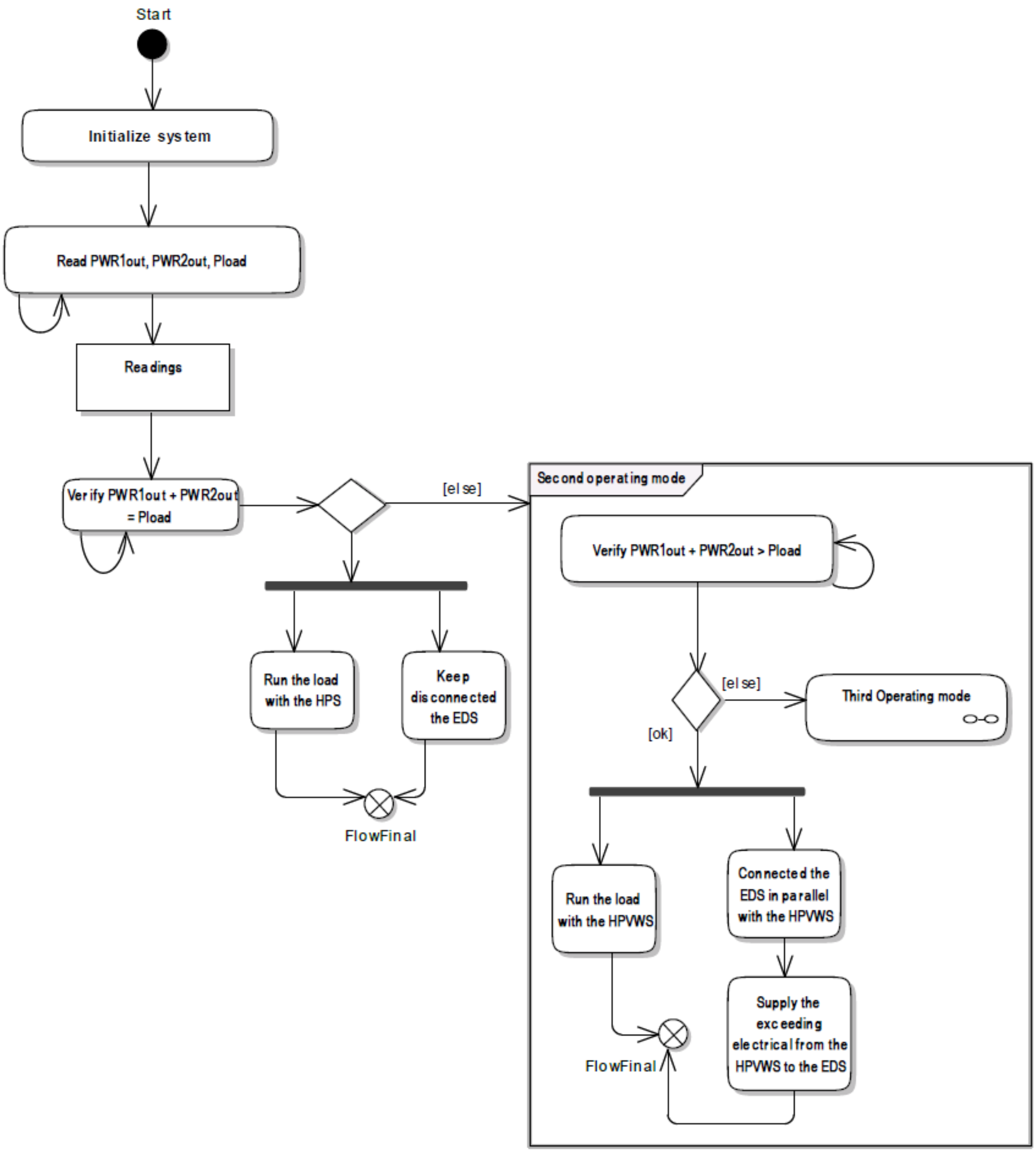


Figure 5.4 F1 and F2 mode activity diagram

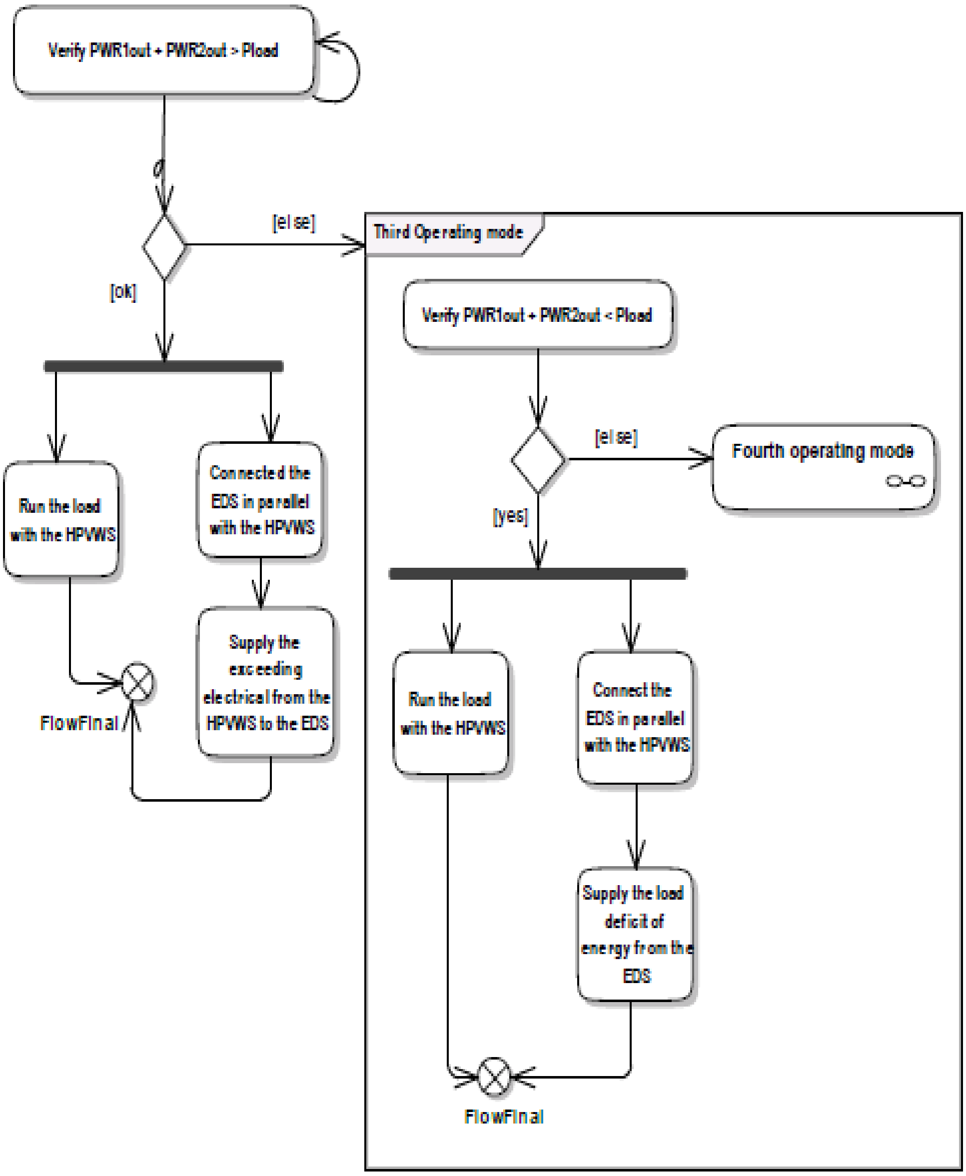


Figure 5.5 F2 and F3 mode activity diagram

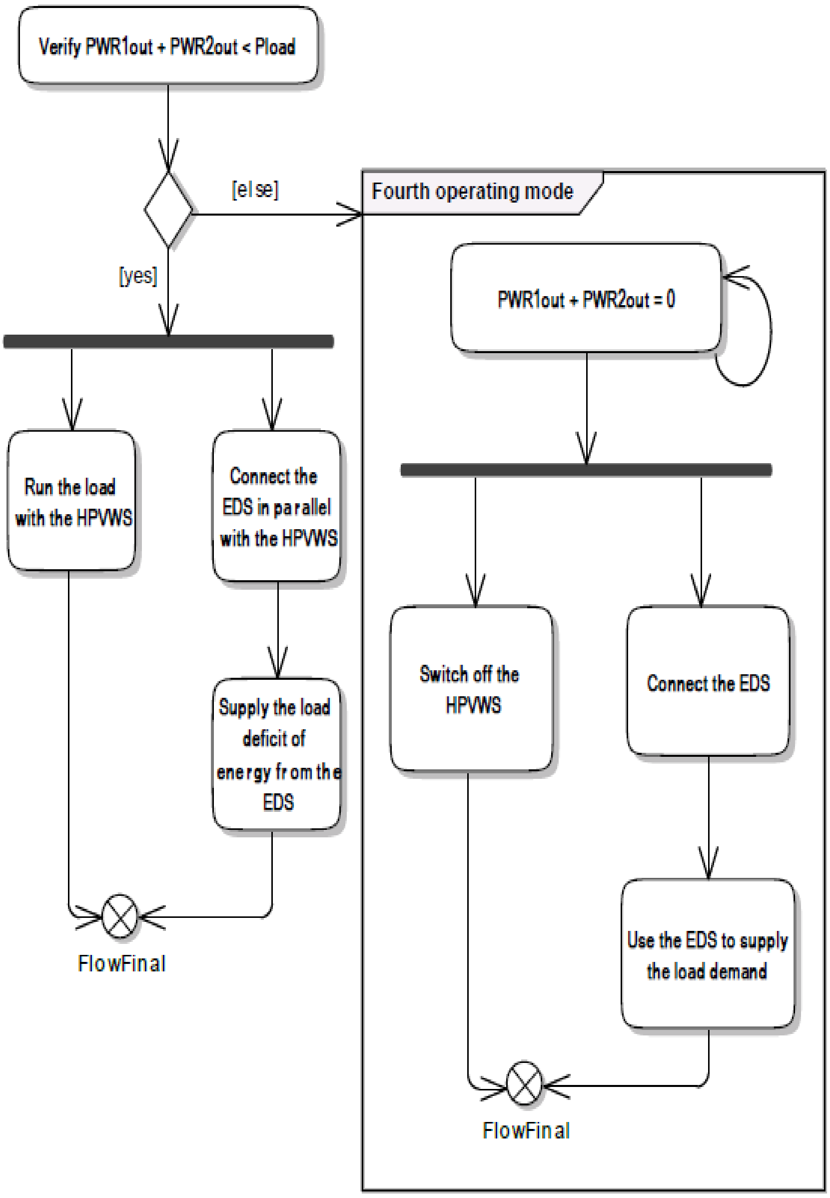


Figure 5.6 A. 4.3 F3 and F4 mode activity diagram

A.5 Wind Power system constraints block diagrams

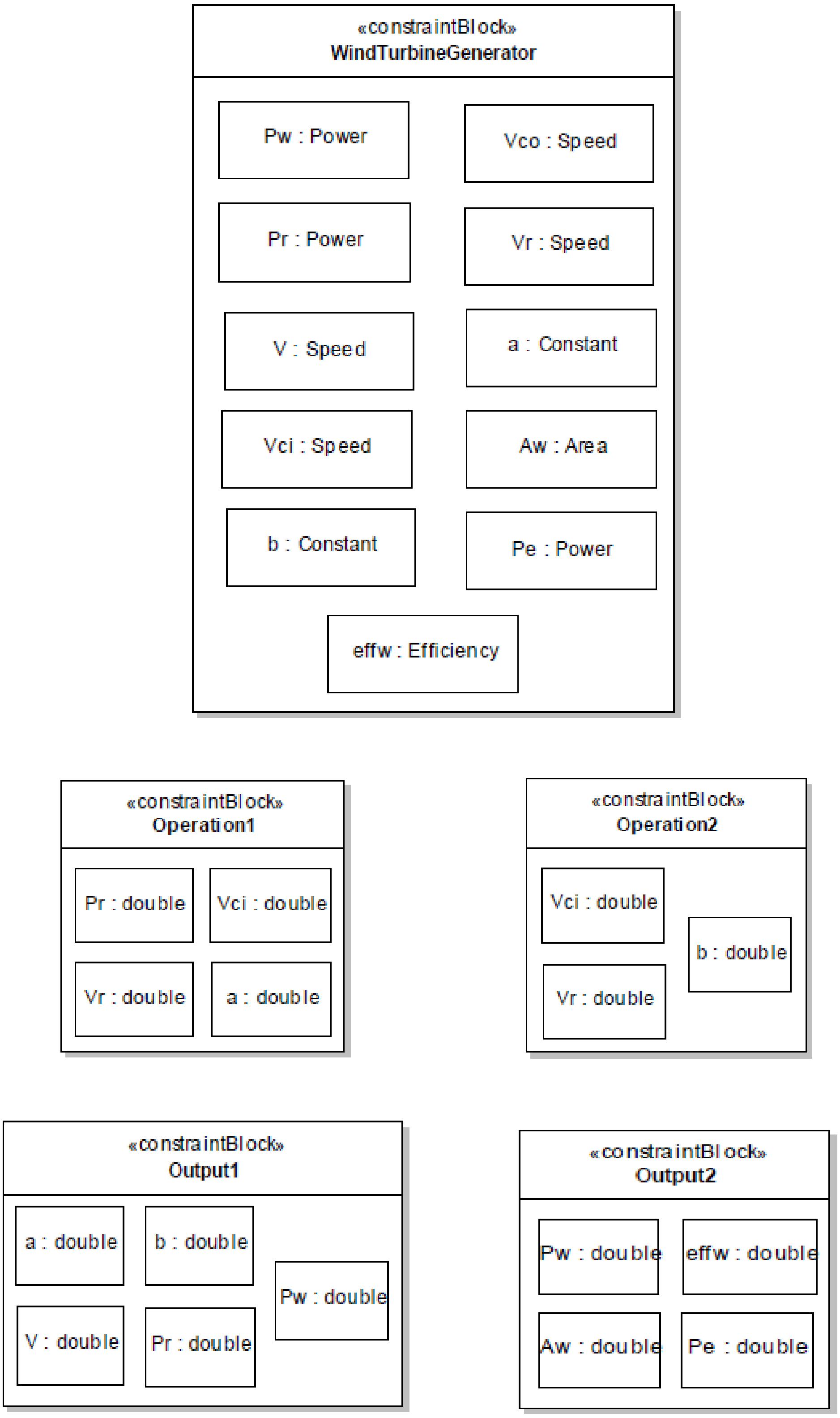


Figure 5.7 Wind power system constraints block diagrams

A.6 Script for the wind power system constraints block diagrams

```
/*
This method computes the value of the coefficient a

*/
functioncompute_a(Pr, Vr, Vci){
        return (Pr/((Vr*Vr*Vr) - (Vci*Vci*Vci)));
}

/*
This function computes the value of the coefficient b
*/

functioncompute_b(Vr, Vci){
        return ((Vci*Vci*Vci)/((Vr*Vr*Vr) - (Vci*Vci*Vci)));
}

/*
This function compute the output power PW
The variables Pr, Vci, Vr, Vco are the rated power, cut-in, rated and cut-
out wind speeds respectively
*/
functioncompute_pw( V,  Vci,  Vr,  Vco,  Pr){

        a = compute_a(Pr, Vr, Vci);
        b = compute_b(Vr, Vci);

        if(V <Vci){
                PW = 0;
        }
        else if(V >Vci&& V <Vr){
                PW = a*(V*V*V) - b*Pr;
        }
        else if(V >Vr&& V <Vco){
                PW = Pr;
        }
        else{
                PW = 0;
        }
        return PW;
}

/*

The next function here compute the value of Pe,w which is the real
electrical power
effw : Is the efficiency of the WTGs
Aw : The total swept area of the WTGs

*/

functioncompute_Pew( Vci,  Vr,  Vco,  Pr,  Aw,  effw){
        Pw = compute_pw(V, Vci, Vr, Vco, Pr);
        Pew = PW*Aw*effw;
        return Pew;
}


//vari;

functioncompute_a(varPr, varVr, varVci){
        return (Pr/((Vr*Vr*Vr) - (Vci*Vci*Vci)));
}
```

A.7 Photovoltaic system constraints block diagrams

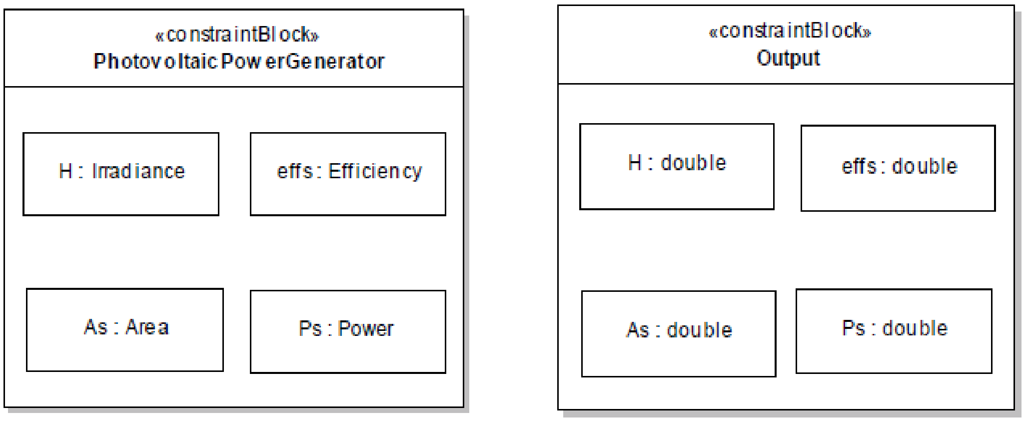


Figure 5.8Photovoltaic system constraint block diagrams

A.8 Script for the photovoltaic system constraints block diagrams

```
functioncreate_H(){
        H = [];
        var p = 2;
        for(vari = 0; i<= 100; i++){
                H[i] = i;
        }
        for(var t = 101; t <= 201; t++){
                        H[t] = t - p;
                        p = p + 1;
        }
}

//varH_arr = create_H();

functioncompute_PS(AS, effs){
        var H = create_H();
        PS = [];
        for(vari = 0; i<= 201; i++){
                PS = H*AS*effs;
        }
        return PS;
        // return sum(PS);
}
```

A.9 Voltage output constraints block diagrams

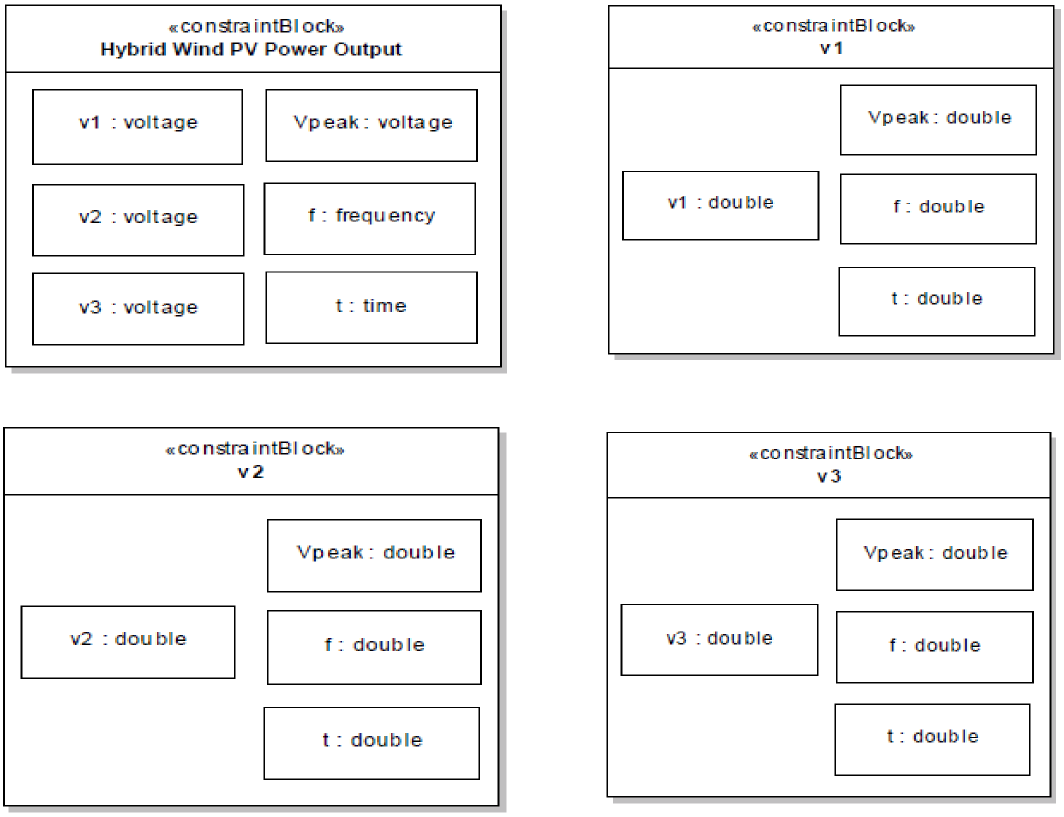
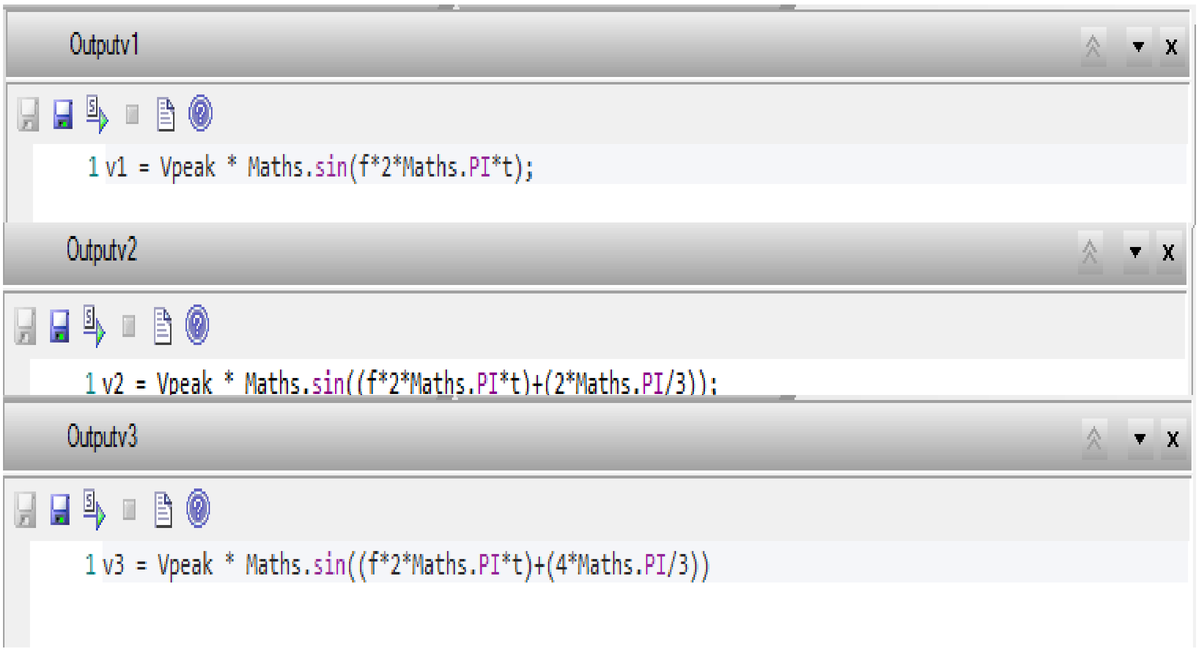


Figure 5.9 Voltage output constraints block diagrams



```
v1 = Vpeak * Maths.sin(f*2*Maths.PI*t);
```

```
v2 = Vpeak * Maths.sin((f*2*Maths.PI*t)+(2*Maths.PI/3));
```

```
v3 = Vpeak * Maths.sin((f*2*Maths.PI*t)+(4*Maths.PI/3))
```

Figure 5.10 Script for the voltage output constraints block diagrams

A.10 Current output constraints block diagrams

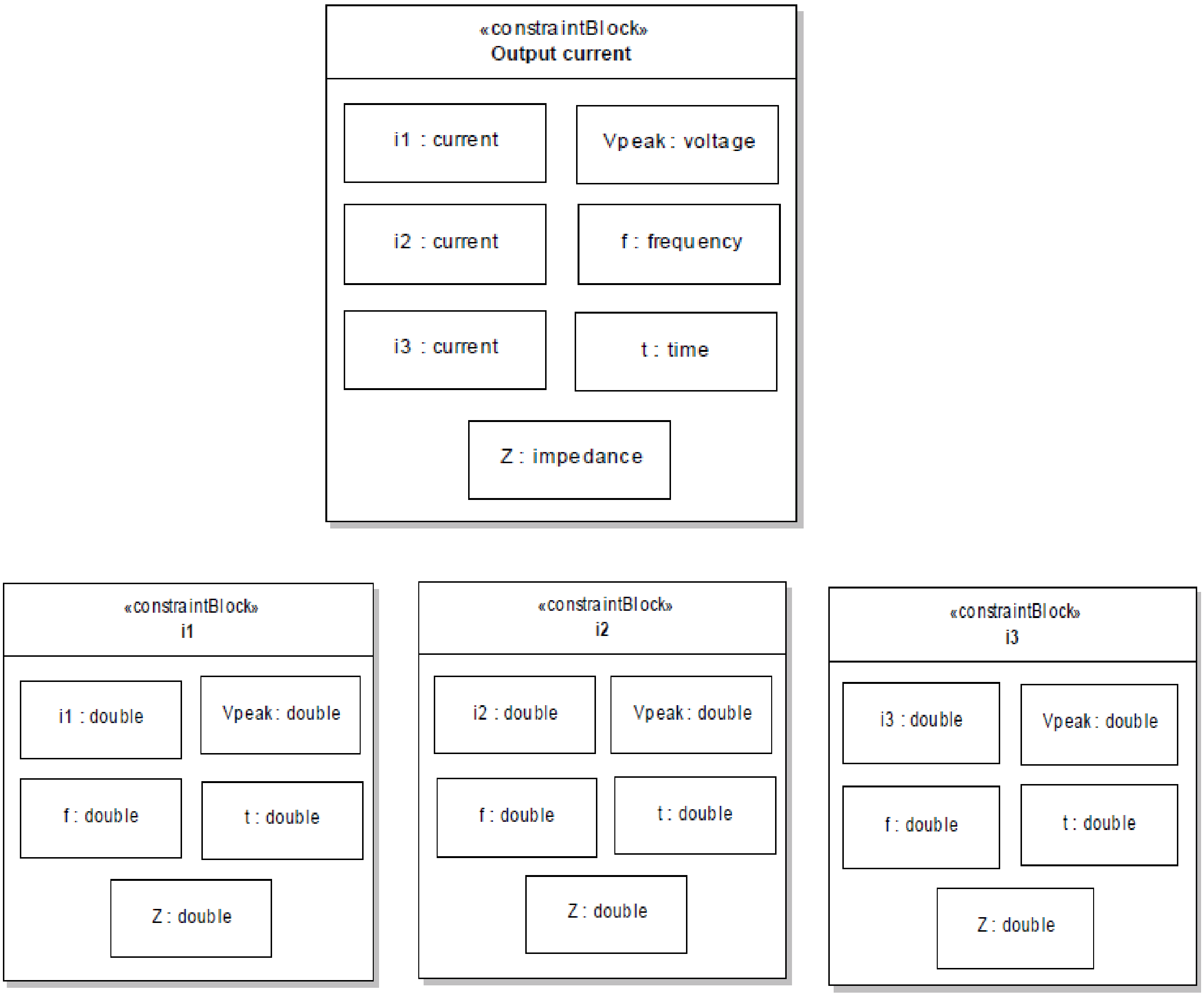
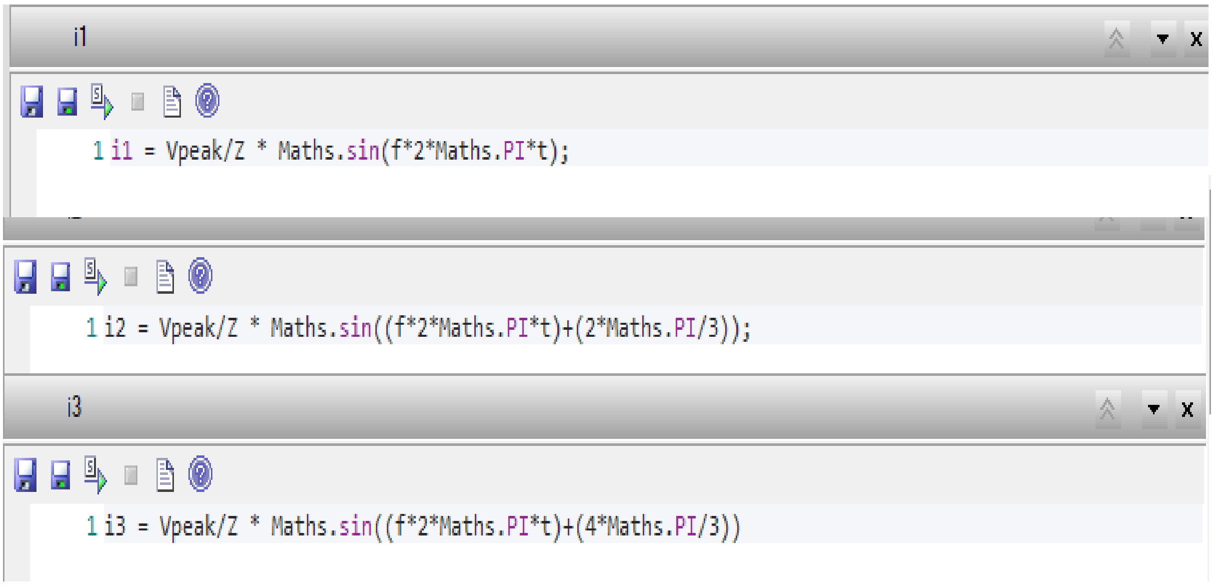


Figure 5.11 Current output constraints block diagrams



```
i1 = Vpeak/Z * Maths.sin(f*2*Maths.PI*t);
```

```
i2 = Vpeak/Z * Maths.sin((f*2*Maths.PI*t)+(2*Maths.PI/3));
```

```
i3 = Vpeak/Z * Maths.sin((f*2*Maths.PI*t)+(4*Maths.PI/3))
```

Figure 5.12 Script for the voltage output constraints block diagrams