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Bond graph modeling in view of the faults detection and localization in renewable energy systems

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localisation de défauts dans les systèmes d'énergie
renouvelable**

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Dedication

"وقتِ ربیٰ ارحمہما کما ربیانہی صغیرا"

This document is dedicated to my family.

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Abbreviations

ARR:	Analytical Redundancy Relations
BL:	Bridge-Linked
C:	Capacitive Elements
CEEG:	Engineering Company for Electricity And Gas
CSP:	Concentrating Solar Power
DFIG:	Doubly-Fed Induction Generator
DOE:	Department Of Energy
FDI:	Fault Detection And Isolation Method
GW:	Gigawatts
GY:	Gyrator Elements
HC:	Honey-Comb
I:	Inertial Elements
IGCC:	Integrated Gasification Combined Cycle
KTOE:	Thousand Tons of Oil Equivalents
KWH:	Kilowatt Hour
MPPT:	Maximum Power Point Tracker
MTF:	Modulated Transformer
MWP:	Megawatt Peak
MWT:	Megawatt Tone
MTOE:	Million Tons of Oil Equivalents
NEAL:	New Energy Algeria
OECD:	Organization for Economic Co-operation and Development
OPEC:	Organization of the Petroleum Exporting Countries
PCS:	Power Conditioning System
PMSG:	Permanent Magnet Synchronous Generators
PV:	Photovoltaic
PWM:	Pulse Width Modulation
R:	Resistive Elements

RES: Renewable Energy System

SE: Effort Sources

SF: Flow Sources

SP: Series-Parallel

SYMBOLS: System Modeling by Bond Graph Language and Simulation

TCT: Total Cross-Tied

TF: Transformer Elements

VSI: Voltage Source Inverter

WEC: Wind Energy Conversion

WTGS: Wind Turbine Generation System

General Introduction

0.1. Importance of the topic

Several definitions of sustainable development have been put forth, including the following common one: development that meets the needs of the present without compromising the ability of future generations to meet their own needs. A recent World Energy Council (WEC) study found that without any change in our current practice, the world energy demand in 2020 would be 50–80% higher than 1990 levels. According to a recent USA Department of Energy (DoE) report, annual energy demand will increase from a current capacity of 363 million kilowatts to 750 million kilowatts in 2020. The world's energy consumption today is estimated to 22 billion kWh yr⁻¹, 53 billion kWh in 2020. Such ever-increasing demand could place significant strain on the current energy infrastructure and potentially damage world environmental health by CO, CO₂, SO₂, NO_x effluent gas emissions and global warming. Achieving solutions to the environmental problems that we face today requires long-term potential actions for sustainable development. In this regard, renewable energy resources appear to be the most efficient and effective solutions since the intimate relationship between renewable energy and sustainable development.

Renewable energy is an important component of sustainable development because of their close relationship with economic growth, social progress and environmental protection. At the national level, this component is a major focus of the country's energy policy. Indeed, over the past twenty years, Algeria has established the institutional and regulatory framework of energy management in general and has launched a national program in this area focuses on the rational use of energy but also on the promotion of the renewable energies. Currently strengthening of this policy becomes increasingly necessary and urgent, given the energy dependence in which our country finds itself and which can be a constraint to economic development. This constraint is likely to increase in the future, with the potential for irreversible increase in international oil prices. At the international level, renewables currently enjoy an environment characterized by globalization, which strengthens the competitiveness requirements and supported by the global awareness on climate change issues and the need to fight against this phenomenon, whose energy consumption is primarily responsible.

Research and development efforts in solar, wind, and other renewable energy technologies are required to continue for improving their performance, establishing techniques for accurately predicting their output and reliably integrating them with other conventional generating sources.

Recently in Algeria we can find a lot of farms, situated in remote area, which electricity supply is not solved. One obvious solution for electrification of these regions is the installation of small-scale stand-alone solar and wind energy production systems. The importance of this topic is timely because we can find a lot of applications, which energy supplying is resolved by renewable energy sources. For a good performance application is necessary to realize a preliminary planning, a feasibility study, which indicate an optimal

technical solution for this application sites. Is necessary to elaborate one optimal model for which can be answered for this technical solution for the energy system.

0.2. Problem statement

In recent years, the problem of energy crunch has become more and more aggravating, resulting in increased exploitation and research for new power energy resources around the world. In particular, the use of natural energy, especially the solar and wind energy are increasingly emphasized and regarded as an important resources of power energy in the future.

As the power supplied by solar arrays depends upon the insolation, temperature and array voltage, it is necessary to implement a so-called maximum power point tracking (MPPT) technique to track the changes and extract the maximum power from the solar array. A MPPT for solar application is a control algorithm to force the impedance at the terminals of PV array to the value that produces maximum power out of the array. Some papers had proposed different maximum power point tracking control techniques in the past. The popularity of MPPT system was tempered to a large extent by operational problems, added complexity and unfavorable incremental costs.

0.3. Thesis motivations

Algeria plays a key role in world energy markets as a leading producer and exporter of natural gas and liquefied natural gas. Algeria's energy mix in 2010 was almost exclusively based on fossil fuels, especially natural gas (93%). However the country has enormous renewable energy potential, mainly solar, which the government is trying to harness by launching an ambitious Renewable Energy and Energy Efficiency Program.

The Program consists of generating 22,000 MW of power from renewable sources between 2011 and 2030, of which 12,000 MW will be meant for domestic consumption and the rest for export. The Program is focused on developing and expanding the use of renewable resources, such as solar and wind, in order to diversify energy sources and promote sustainable development of the country.

Solar energy: on account of its geographical location, Algeria holds one of the highest solar potentials in the world which is estimated at 13.9 TWh per year. The country receives annual sunshine exposure equivalent to 2,500 KWh/m². Daily solar energy potential varies from 4.66 kWh/m² in the north to 7.26 kWh/m² in the south.

Wind energy : Algeria has promising wind energy potential of about 35 TWh/year. Almost half of the country experience significant wind speed. The country's first wind farm is being built at Adrar with installed capacity of 10MW with substantial funding from state-utlity Sonelgaz. Two more wind farms, each of 20 MW, are to be developed during 2014-2013. Studies will be led to detect suitable sites to realize the other projects during the period 2016-2030 for a power of about 1700 MW.

0.4. Thesis objectives

The objective of this thesis is firstly to review different energy resources and describes methodologies to model renewable energy systems RES (photovoltaic and wind) components. Various modeling techniques are developed by researchers to model components of RES. Performance of individual component is either modeled by deterministic or probabilistic approaches; in this thesis we propose the graphical methods (bond graph) for modeling, fault detection and isolation of energy production systems. This thesis can be interesting to readers looking for a deeper knowledge in MPPT tracking or those looking for an introduction to PV power generation, because it includes a review of the general concepts related to PV power generation.

One of the original points is that this work treated the utilization of fault detection and isolation method (FDI). A new method is proposed to avoid the exploration of all the combinations for its application to the diagnostic of this system operation and to determine the gravity of a detected failure. The causal paths help us in this procedure in order to generating the analytical redundancy relations ARR at each step from constitutive and structural junction relations. This is shown through an algorithm for monitoring the system by sensors placements on the corresponding bond graph model. The performance of the developed algorithm is evaluated on a tow model of renewable energy systems: wind turbine and photovoltaic.

0.5. Thesis outline

This thesis is divided into three parts; each part contains two chapters as follows:

Part 1: in the first chapter, an overview is given on the world energy demand, electricity consumption and their development trend in the near future. The electric power generation technologies based on the different energy sources are also reviewed in the chapter

The second chapter presents the progress and efforts for the usage of the existing, on-going and planned projects of the renewable energy in Algeria over these last decades.

Part 2: Chapter three is mainly focused on methodologies for the modeling of wind energy conversion system. Details on the progress of the project are explained in this chapter.

The third chapter deals with the modeling and the control of wind turbine generation systems by bond graph approach for integration in power systems studies. The modeling of the wind phenomenon, the turbine mechanical system and the electrical machine, along with the corresponding converter and electrical grid is described.

Part 3: In the fourth chapter, a simple but efficient photovoltaic water pumping system is presented. It provides theoretical studies of photovoltaic (PV) and its modelling techniques. It also investigates in detail the maximum power point tracker (MPPT), a power electronic device that significantly increases the system efficiency. At last, it presents the Symbols simulations of the system and makes comparisons with the experimental results.

In the chapter five the problem of fault diagnosis in wind energy conversion (WEC) is addressed. The proposed method avoids the exploration of all the combinations for its application to the diagnostic of this system operation. The causal paths are used to generate

the analytical redundancy relations (ARR) at each computation step based on the components equation of the constitutive and the structural junction relations.

In the sixth chapter, we show a new methodology for automatic supervision and fault detection of the PV systems, based mainly on optimal sensors placement. This supposes the possibility to build a dynamic model of the system by using the bond graph tool, and the existence of a degradation model in order to predict its future health state.

Finally, this thesis presents the general conclusions.

Part 1: Energy Production

CHAPTER 1: Production of Energies Worldwide An Overview

CHAPTER 2: Renewable Energy in Algeria

***“Earth provides enough to satisfy every man's needs, but not every man's greed”
Gandhi.***

CHAPTER 1: Production of Energies

Worldwide: An Overview

Energy is a vital commodity and is closely intertwined with climate change and development. Energy is needed for basic human needs: for cooking, heating, lighting, boiling water and for other household-based activities. Energy is an essential factor to achieve sustainable development. So, countries striving to this end are seeking to reassess their energy systems with a view towards planning energy programs and strategies in line with sustainable development goals and objectives. As would be expected, the rapid expansion of energy production and consumption has brought with it a wide range of environmental issues at the local, regional and global levels. States have played a leading role in protecting the environment by reducing emissions of greenhouse gases. This chapter provides an overview of global energy use and renewable for clean and sustainable energy policies in the world.

1.1. INTRODUCTION

The processes of industrialization and economic development require energy [1]. The demand for energy is expected to increase at a faster rate in upcoming years [2], [3], partly due to the exponential growth of the world's population (figure 1.1) [4]. All the energy on earth is derived from the sun. However, it occurs in various forms that today, man has developed the technology to exploit and use for agricultural, industrial and personal advancement. Energy used to power our lives can be divided into three categories: fossil fuels, renewable resources and nuclear resources [5]. Renewable energy can play an effective role to meet energy demand. Among all, solar energy is most reliable and environmental friendly [6]. Nuclear energy can cause serious problems for the environment [7], [8] and human health [9], [10]; for example, those caused by nuclear accidents such as Chernobyl in 1986 and Fukushima in 11 March 2011.

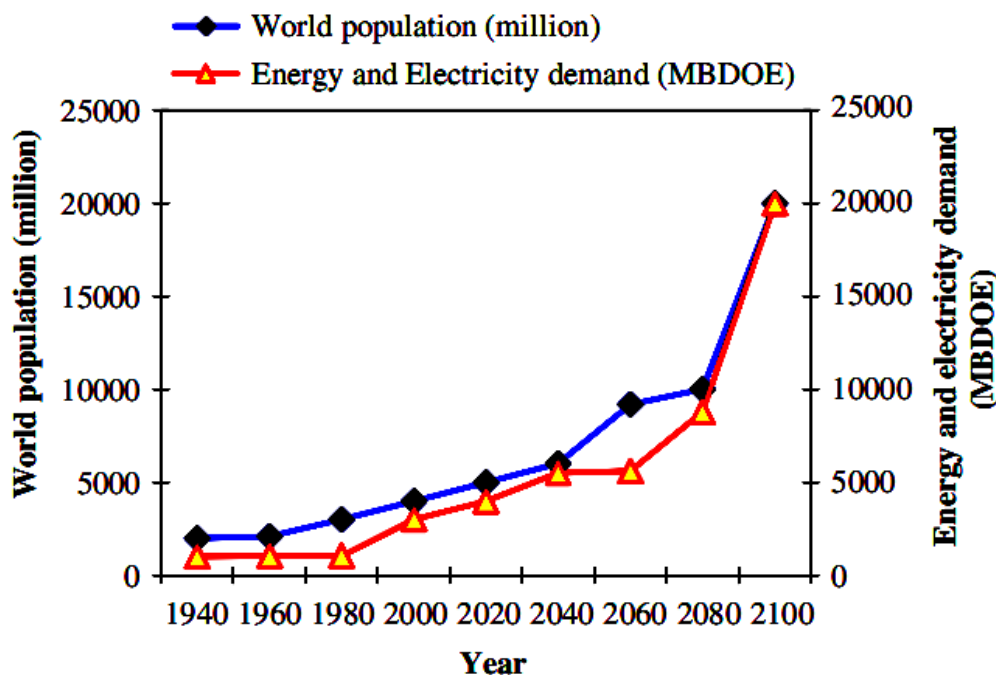


Figure 1. 1 Annual and estimated world population and energy demand. Millions of barrels per day of oil equivalent [4]

Combustible fuels are the world's main energy resource and are at the center of global energy demands [11]. However, the reserves of fossil fuels are limited, and their large-scale use is associated with environmental deterioration [12], [13]. Known negative effects of using fossil fuels include [14] acid rain, ozone layer depletion and global climate change. The result has been a rapid growth in the level of greenhouse gas emissions and an increase in fuel prices [15], which are the main driving forces behind efforts to use renewable energy sources [16].

A renewable energy source (RES) can be defined as a simple sustainable resource available over the long term at a reasonable cost that can be used for any task without negative effects [17]- [19].

Other researchers consider RESs as clean sources of energy and that the optimal use of these resources minimizes environmental impacts, produces minimum secondary wastes and is sustainable based on current and future economic and social needs [20].

Positive points in the use of RES are the increased diversity in energy supply options, both for developed and developing countries [17], [21], [22], less dependence on fossil fuels [17], the increase of net employment, the creation of export markets [22], [23] and a reduction in greenhouse gas emissions and climate change [17], [21], [23], [24].

1.2. GLOBAL ENERGY CONSUMPTION

Global energy consumption in the last half century has rapidly increased and is expected to continue to grow over the future. The past increase was stimulated by relatively “cheap” fossil fuels and increased rates of industrialization in North America, Europe and Japan; yet while energy consumption in these countries continues to increase, additional factors make the picture for the next five decades years more complex. These additional complicating factors include China and India’s rapid increase in energy use as they represent about a third of the world’s population; the expected depletion of oil resources in the near future; and, the effect of human activities on global climate change. On the positive side, the renewable energy technologies of wind, biofuels, solar thermal and photovoltaic are finally showing maturity and the ultimate promise of cost competitiveness [25].

Global primary energy supply has continued to grow, mainly fossil fuels, mainly coal. Fossil fuels supply was up 183 million tonnes oil equivalent (Mtoe) in 2013 while new renewable supply was up 45 mtoe from 2013 (figure 1.2).

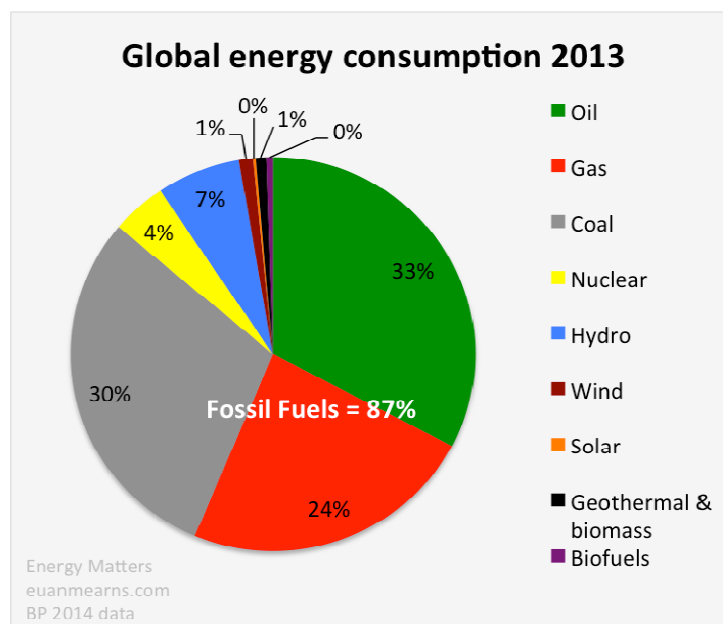


Figure 1. 2 Global energy consumption 2013 [26]

In 2003, fossil fuels accounted for 87% of global primary energy consumption. In 2013, fossil fuels accounted for 87% of global primary energy consumption. This is testimony to the absolute failure of energy policies aimed at reducing CO₂ emissions.

In 2003, new renewables (wind, solar, geothermal, biofuels etc) accounted for 0.82% of total primary energy and by 2013 this had grown to 2.69%. In 2003, nuclear power accounted for 6.01% and this fell to 4.40% in 2013. The 1.87% growth in share of new renewables almost matches the 1.61% fall in the share of nuclear power. On the CO₂ account, low emissions nuclear power has been replaced by low emissions renewable energy. The actual energy substitutions are a little more complex [26].

Oil consumption has been on a gently rising plateau since 2005 (Figure 1.3) and oil is declining in importance in the global energy mix. The fall in oil's share has been picked up by coal and the only simple way for this substitution to occur is for oil fired power generation to close. Once all oil fired generation has been closed, expect severe upwards pressure on the oil price.

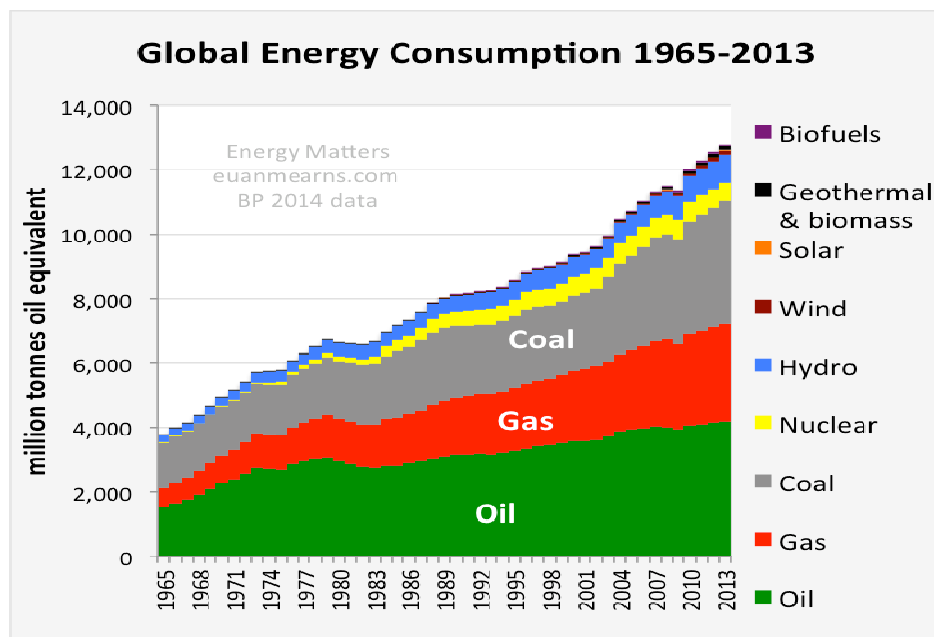


Figure 1. 3 Global energy consumption 1965-2013 (source: *Energy Matters euanmearns.com, BP 2014 data*)

1.3. GLOBAL ENERGY PRODUCTION

The generation of electricity worldwide is heavily dominated by the use of fossil fuels. The combustion of these fuels releases large amounts of carbon dioxide and pollutants to the atmosphere. Fossil resources are also ultimately limited, with finite amounts in existence. While coal reserves are still abundant, the excessive consumption of coal by the electricity sector is responsible for the greatest share of carbon dioxide emissions globally, as well as emitting large amounts of pollutants, such as NO_x, SO₂, CO, particulate matter and air toxics to the environment.

World electricity production by fuel is shown in figure (1.4) indicating coal contribute to over 35% of the world electricity generation, with fossil fuels in total accounting for over 75% of the electricity generated in 2010.

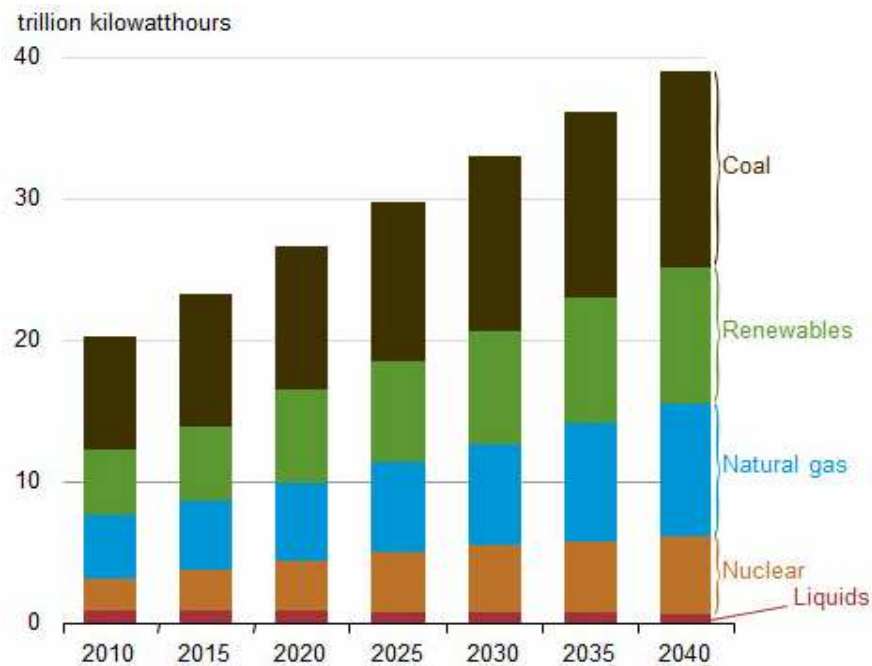


Figure 1. 4 World net electricity generation by fuel 2010-2040 [26]

Renewable energy sources are rapidly increasing in usage, however current market shares, excluding hydropower, are so low that it will be some time before a significant percentage of world electricity is produced by non-hydro renewable energy sources [26]. For example, in 2010 solar accounted for only 0.038% of the world's electricity production [27], despite its 33% market growth between 1997 and 2005 [28], [29].

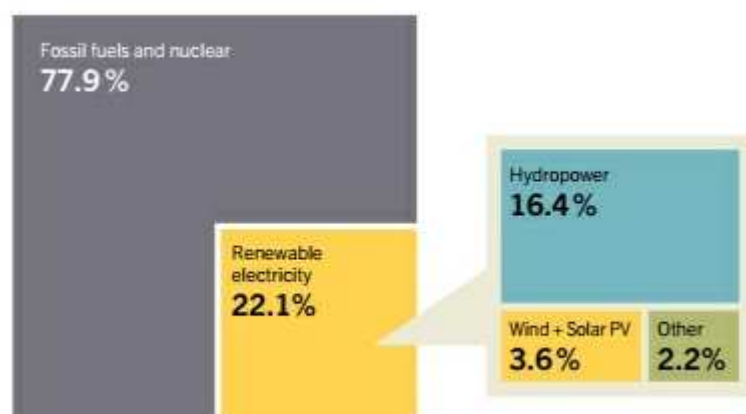


Figure 1. 5 Power generation from renewable energy in the world [30]

Increased electricity demand strengthens the need for reduced impacts from electricity generation per unit produced. Demand for electricity increased at an average of 1.8% per year between 1990 and 2013.

Overall last year, renewable sources accounted for more than 56% of net additions to global power capacity.

Hydropower rose by 4% to approximately 1,000 GW in 2013, accounting for about one-third of renewable power capacity added during the year. Other renewable sources collectively grew nearly 17% to an estimated 560 GW.

Renewable energy provided 19% of global final energy consumption in 2012, and continued to grow in 2013. Of this total share in 2012, modern renewable sources accounted for 10% with the remaining 9% coming from traditional biomass the share of which is declining.

IEA predictions show that, if the current coal dependence is not reduced, coal fired power stations in developing countries alone will produce more greenhouse gas emissions than the entire OECD power sector in the year 2030 [31], [32]. The impacts of developing nations working to achieve better standards of living, compounded by the number of people in these nations will cause electricity consumption rates to keep increasing [33].

In order to meet increasing energy requirements with minimal environmental impact, changes to the current energy generation practices are essential. Changes need to include increased energy efficiency from fossil fuel combustion technologies through introduction of oxyfiring and IGCC technologies, as well as increasing the share of alternative energy generation technologies, including hydropower, wind energy, geothermal, biomass combustion and gasification, solar and tidal power. Renewable energy sources provide freedom from the price fluctuations; trade and transport issues associated with uranium, gas and coal, and can potentially improve energy security to countries deficient in mineral resources.

However, traditional coal and gas based technologies offer high reliability and low prices. Careful evaluation of the sustainability of each technology is needed to direct future investment and policy.

1.4. ENERGY SOURCES

There are five ultimate primary sources of useful energy:

1. The sun.
2. The motion and gravitational potential of the Sun, Moon and Earth.
3. Geothermal energy from cooling, chemical reactions and radioactive decay in the earth.
4. Human-induced nuclear reactions.
5. Chemical reactions from mineral sources.

Renewable energy derives continuously from sources 1, 2 and 3 (aquifers). Finite energy derives from sources 1 (fossil fuels), 3 (hotrocks), 4 and 5. The sources of most significance for global energy supplies are 1 and 4. The fifth category is relatively minor, but useful for primary batteries, e. g. dry cells.

1.4.1. RENEWABLE ENERGY

The term renewable energy source (RES), which is closely linked to sustainable development, is defined as any sustainable resource available in the long term in a simple long-lasting manner, found at a reasonable cost and applicable for any task without causing negative effects [34], [35] and [36]. Several technologies are available for the production of clean, efficient and reliable energy from long-term RES, such as wind, sun, water, biomass and biogas, tides and waves, hydrogen and geothermal energy [36], [37]. Also, it is further demonstrated that RES can increase the diversity of energy supply options in both developed

and developing countries, and that doing so makes a strong contribution to the reduction of global and local air pollution [34], [38]. Svensson et al. [39] point out that RES systems and nuclear energy have a low impact on climate change. Rodrigues et al. [40] believe that the increase in RES demand responds to the need of an increased share of carbon-neutral energy as an aid in the mitigation of climate change, and to the search of heightened energy independence.

RESs include biomass, hydropower, geothermal, solar, wind and marine energies [41]. Today, RESs supply 14% of the total world energy demand [20], [41], [42], and the share of RESs is expected to increase significantly (30–80% in 2100) [20]. One of the factors that can foster the development and use of RESs is research. The analysis of research efforts and trends can be accomplished by examining the number of indexed scientific journals [43]–[49]. The number of scientific publications on renewable energy has been evaluated for biomass in 1992 [50]. It has recently been evaluated using Scopus data base: for Europe during the period 2000 to 2007 [51], without differentiating the type of renewable energy or the research institutions most involved in the research of these energies; and worldwide during the period 2003 to 2008 [50], also without differentiating the type of renewable energy.

In 2010, the contribution of different renewable energy sources to the overall energy production was estimated to be [48], [49] 16.6% hydropower (large and small), 2.56% wind, 1.95% biomass, 0.67% geothermal, 0.13% solar (PV and Solar thermal) and 0.01% marine.

Figure (1.6) presents percentages of all scientific journals in the ISI data base related to renewable energies during the period from 1979 to 2009. It is noted that in the last 30 years, more than half of the global research effort (56%) has been in related to the use of biomass as renewable energy, followed by solar energy, which was more than double (26%) of wind power (11%). These data draw attention to the relatively low (2%) focus on hydropower research, which, as seen, is the renewable energy that produces more energy. The explanation for this low percentage can be found in two factors: this source is limited to very specific areas of the planet with water resource availability [50]; and hydropower technology is regarded as the most mature of all considered RESs [53].

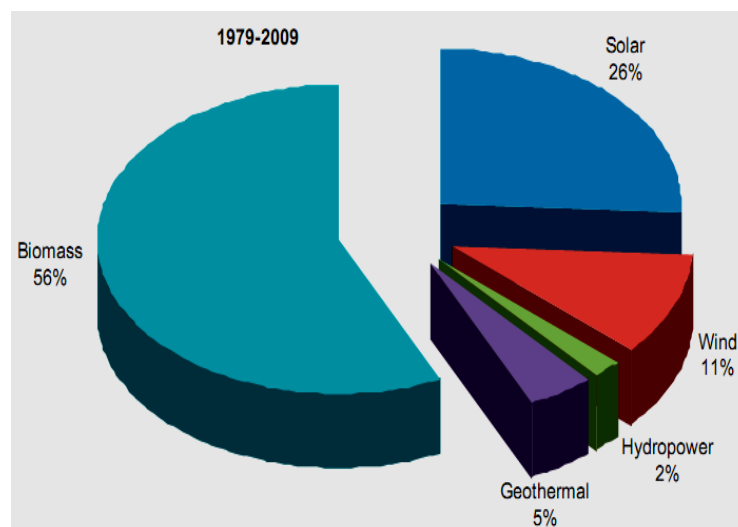


Figure 1. 6 Distribution of scientific publications (1979–2009) per renewable energy [52]

1.4.1.1. WIND ENERGY

Wind power harnesses the power of the wind to propel the blades of wind turbines. These turbines cause the rotation of magnets, which creates electricity. Wind towers are usually built together on wind farms. Wind power is growing at the rate of 21% annually, with a worldwide installed capacity of 336327 MW by the end of June 2014, out of which 17613 MW were added in the first six months of 2014 [54]. This increase is a substantially higher than in the first half of 2013 and 2012, when 13,9 GW respectively 16,4 GW were added. All wind turbines installed worldwide by mid-2014 can generate around 4 % of the world's electricity demand.

The global wind capacity grew by 5,5% within six months (after 5 % in the same period in 2013 and 7,3 % in 2012) and by 13,5 % on an annual basis (mid-2014 compared with mid-2013) [55]. In comparison, the annual growth rate in 2013 was lower (12,8 %). Reasons for the relatively positive development of the worldwide wind markets are certainly the economic advantages of wind power, after all its increasing competitiveness, and the pressing need to go for emission free technologies in order to mitigate climate change and air pollution [56]. Wind power market penetration is expected to reach 3.35 percent in 2013 and 8 percent in 2018.

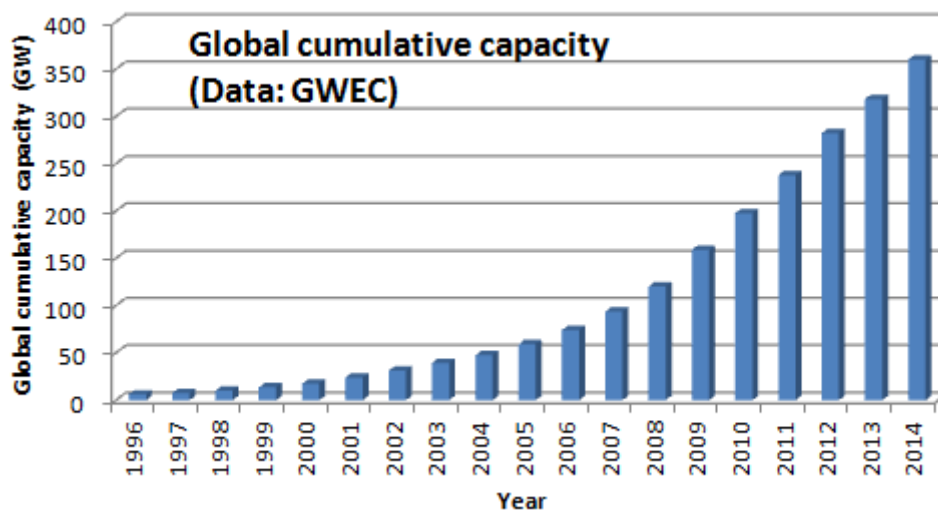


Figure 1. 7 Global wind power cumulative capacity [57]

1.4.1.2. SOLAR ENERGY

Solar energy applies energy from the sun in the form of solar radiation for heat or to generate electricity. Solar powered electricity generation uses either photovoltaic or heat engines (concentrated solar power).

Solar photovoltaic is a sustainable energy source [58], [59]. By the end of 2012, a total of 99.69 GW had been installed, sufficient to generate 118.5 TWh/year and in end of 2013, the 136.69 GW installed capacity milestone was achieved [60]. Solar photovoltaic is now, after hydro and wind power, the third most important renewable energy source in terms of globally installed capacity.

More than 100 countries use solar PV. Installations may be ground-mounted (and sometimes integrated with farming and grazing) or built into the roof or walls of a building (either building-integrated photovoltaic or simply rooftop).

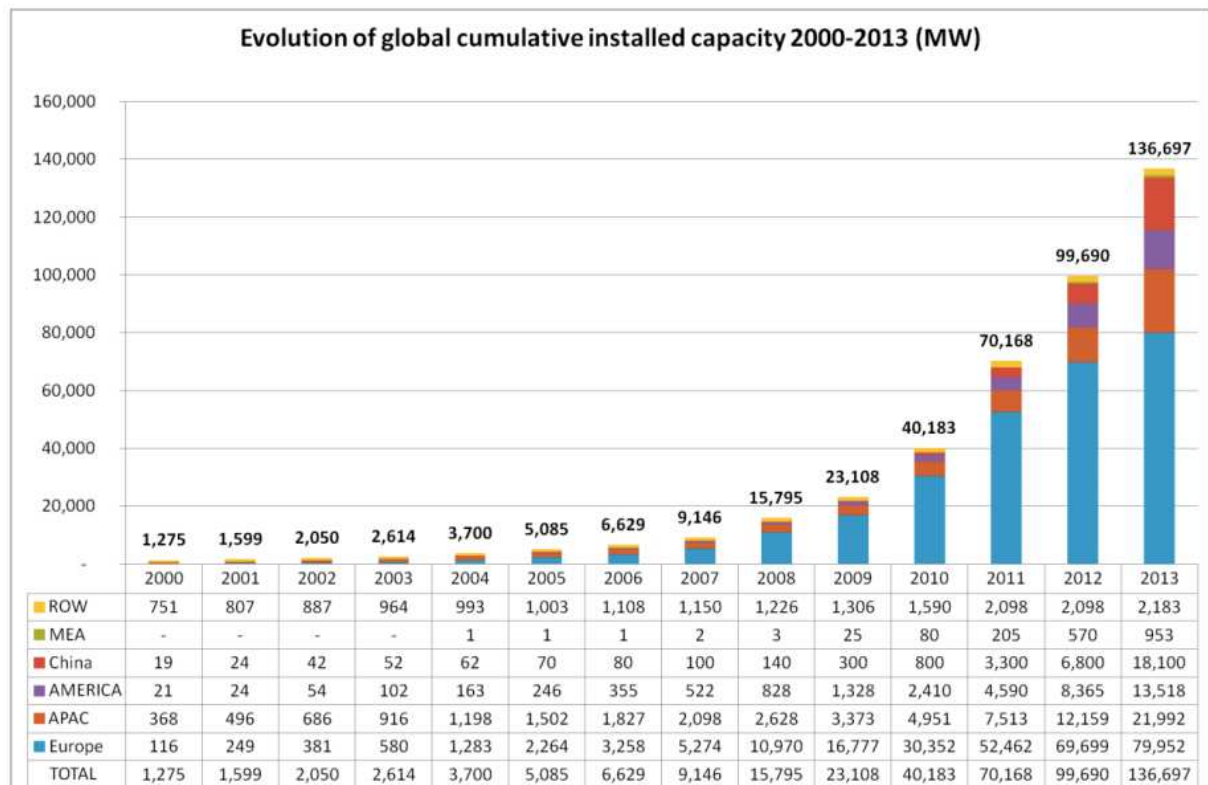


Figure 1. 8 Evolution of global cumulative installed capacity (MW) 2000-2013[61]

Driven by advances in technology and increases in manufacturing scale and sophistication, the cost of photovoltaic has declined steadily since the first solar cells were manufactured, and the levelised cost of electricity from PV is competitive with conventional electricity sources in an expanding list of geographic regions. Net metering and financial incentives, such as preferential feed-in tariffs for solar-generated electricity, have supported solar PV installations in many countries [62].

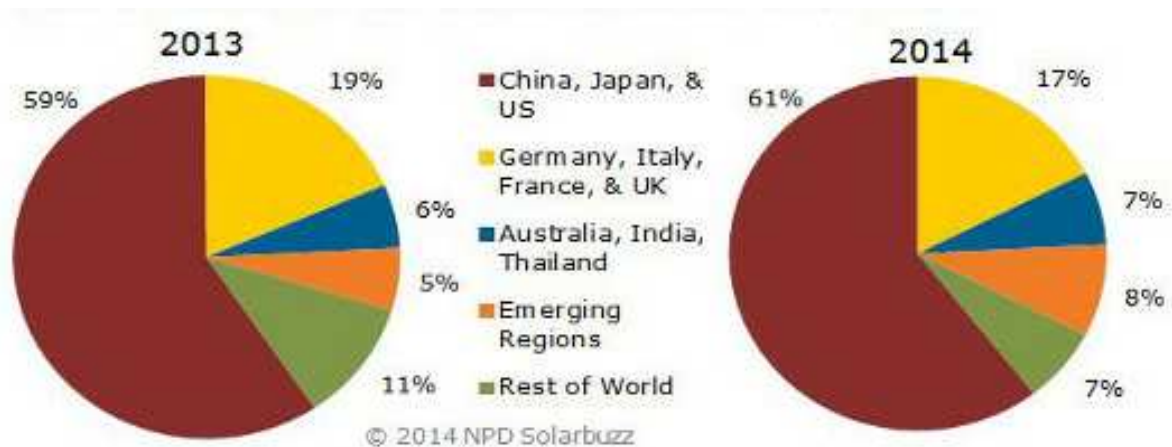


Figure 1. 9 Solar PV demand by key geographic segments for 2013 and 2014 (source: NPD Solarbuzz 2014 Marketbuzz)

1.4.1.3. BIOMASS

Biomass is a term for all organic material that stems from plants (including algae, trees and crops). Biomass is produced by green plants converting sunlight into plant material through photosynthesis and includes all land- and water-based vegetation, as well as all organic wastes. The biomass resource can be considered as organic matter, in which the energy of sunlight is stored in chemical bonds. When the bonds between adjacent carbon, hydrogen and oxygen molecules are broken by digestion, combustion, or decomposition, these substances release their stored and by chemical energy [62].

Of the total bioenergy produced today, wood biomass accounts for 87%, agricultural crops for 9% and municipal and industrial waste for 4% [63]. Biomass will increase from 1313 Mtoe in 2010 to 3271 Mtoe in 2040 [64]. Currently, the global yield for all biomass crops, including woody and herbaceous crops growing in temperate and subtropical regions, varies from 8 dry t/ha per years (for willow in Sweden) to 10 to 22 dry t/ha per years (for short-rotation woody crop in the USA). Some commercial plantations in Brazil have reported up to 20 dry t/ha per years. A conservative global biomass average would be 10 dry t/ha per years, although some small-scale field trials have reported four times this level of biomass production [65], [66]. This production of biomass, also achieved in some greenhouse crops in southern Spain, such as tomato, is 9.8 dry t/ha per years [67], [68].

1.4.1.4. HYDROPOWER

Hydropower or water power is power derived from the energy of falling water and running water, which may be harnessed for useful purposes. Since ancient times, hydropower has been used for irrigation and the operation of various mechanical devices, such as watermills, sawmills, textile mills, dock cranes, domestic lifts, power houses and paint making.

Hydroelectric power is currently the largest of the perpetual or so-called renewable energy resources (RESs). Hydropower contributes to electricity generation in 160 countries, but five of them (Brazil, Canada, China, Russia and the USA) account for more than half of the global hydropower production [69].

1.4.1.5. GEOTHERMAL

Geothermal energy is the energy contained as heat inside the earth. Geothermal energy for electricity generation has been produced commercially since 1913 [41]. Geothermal electricity and heat are limited to the characteristics of local resources and reservoirs. The substantial potential of geothermal energy is limited to certain parts of the world, where as the potential for small-scale applications (heat pumps) is broader. Technical exploitable potential will increase during the next several years due to innovation; whereas the limitations of the potential will lead to a steady reduction of growth rates [64]. Electricity is produced with an efficiency of 10–17%, and the geothermal kWh production is generally cost-competitive with conventional sources of energy. This source has also other uses, the thermal capacity in non-electrical uses are usually greenhouses, aquaculture, district heating or industrial processes [69].

1.4.2. NON-RENEWABLE ENERGY

Oil, coal, and natural gas are collectively known as fossil fuels. Today, eighty-five percent of all energy produced in the United States comes from burning these fuels. That energy powers almost two-thirds of our electricity and virtually all of our transportation.

1.4.2.1. NUCLEAR ENERGY

The world has 100 years or more of uranium reserves (especially if the world also uses breeder reactors to reprocess expended fuel). The United States, France, Japan, Germany, Russia and South Korea produce 74% of the world's nuclear energy, as electricity. Since Three Mile Island in the United States and Chernobyl in the Soviet Union, the world has been nervous about allowing each individual nation to regulate its own nuclear industry. There are also worries about nuclear weapon proliferation. Nuclear reactors produce nuclear waste with trace amounts of plutonium and fissionable uranium. If every country has nuclear reactors, then every country has the potential to reprocess the expended nuclear fuel into weapons-grade uranium or plutonium. It also opens the possibility for smaller groups to steal such expended fuel for reprocessing elsewhere. If countries use breeder reactors to reprocess expended fuel, then it is even easier to convert a portion into weapons-grade uranium or plutonium.

1.4.2.2. COAL

The fuel that powered the West's industrialization is still the most popular fossil fuel: around 6.2 billion tones are consumed annually, 75% of which is burned to produce electricity. A little under half of the world's power is made this way.

Global consumption increased by 4.5% in 2006, with most of that increased demand coming from the Asia-Pacific region, and principally China, which opens one new coal-fired power station roughly every 10 days.

The 1990's 'dash for gas' means that use of coal has fallen in the UK, although it has been rising again in recent years due to the increased gas prices. It now represents 17% of primary energy demand compared to 31% in 1990. However, new coal-fired power stations are planned, in part to help meet expectations of future electricity demand, so coal use may not decline much further. The challenge for engineers in this sector is to develop systems to capture and store the CO₂ to greatly reduce coal power's impact on the earth's climate.

1.4.2.3. OIL

In 1998 40% of the World's energy was derived from oil and 23% from coal. Most of the increased energy demand will be met by increased oil production in the OPEC Countries. Oil production in North America is expected to be flat or declining, and other areas do not have the potential for major increases in production.

The estimates of the total world oil supply that is economically recoverable vary, but the consensus is that we are approaching the peak in production within the next 10 years. These estimates also indicate that by around the year 2025, we will have used up 80% of the world's oil in roughly 60 years, a remarkable achievement. The various models also show that

new discoveries will not shift the production peak, but will merely flatten out the rate of decline.

1.4.2.4. GAS

Gas is a cleaner fuel than coal and it provides the UK with about 40% of its primary energy. We are the world's fourth largest producer, with more than 200 off-shore fields in production and reserves of 18 billion barrels of oil equivalent. However, rates of production are slowing and some estimate that this reserve will be gone in 2014 – forcing the UK to import all of its supplies.

The Middle East has the world's largest proven reserves, at 73.47 trillion cubic metres or 40.5% of world supply. As well as being the second largest consumer of gas, Russia is also the second biggest exporter, supplying many European countries. The income from gas underpins a resurgent Russian economy and political confidence.

1.5. SUSTAINABILITY ASSESSMENT

1.5.1. EFFICIENCY

The efficiency of conversion from the energy in the fuel source into electricity is an important parameter which needs to be considered when assessing electricity production technologies. Efficiencies strongly influence prices as well as sustainability, since the high levels of waste associated with an inefficient process are unsustainable. However, there are diminishing returns in efficiency improvements. Inefficient processes operating at 10% efficiency will significantly improve profits if a 1% improvement is made, whereas in an efficient process, already achieving 50% efficiency, a 5% improvement is necessary to achieve such gains. A summary of efficiencies for each power generation technology, as found in literature, is shown in Table 1 [70]-[79].

Table 1. 1 Electrical efficiencies of electricity generation

Technology	Efficiency range
Photovoltaic	4 - 22%
Wind	23 – 45 %
Hydro	>90%
Geothermal	10 – 20%
Biomass	16 – 43%
Gas	45 – 53%
Coal	32 – 45%
Nuclear	30 – 36%

Hydropower has the highest efficiency, from double to 5 times above the highest achieved in all other technologies. When located at a high quality wind resource, wind power is the second most efficient renewable energy technology, followed closely by high efficiency biomass. Natural gas shows the second highest overall efficiency and is the most efficient thermal technology. However, it must be considered that gas, coal and nuclear, have small ranges of efficiency, varying by up to 13%. This is unlike wind, which if not placed correctly can halve its potential and varies by up to 22%. Biomass has an even larger data range,

varying by up to 27%. At its highest efficiency, biomass is comparable with coal and higher than nuclear. At its lowest efficiency the electricity produced from biomass is one of the least efficient choices. Lowest quoted efficiencies are often for older technologies and methods. The large efficiency range for photovoltaic is due to differing cell types, with amorphous silica cells showing the lowest efficiencies and crystalline silica cells the highest. Geothermal efficiencies vary due to the temperature of the geothermal source; hotter geothermal sources give greater efficiencies.

1.5.2. GREENHOUSE GAS EMISSIONS

Most scientists agree that emissions of pollutants and greenhouse gases from fossil fuel-based electricity generation account for a significant portion of world greenhouse gas emissions; or 40% of the total CO₂ emissions for 2004. This is an increase of 53% since 1990.

In the United States, fossil fuel combustion for electric power generation is responsible for 65% of all emissions of sulfur dioxide, the main component of acid rain. Electricity generation is the fourth highest combined source of NO_x, carbon monoxide, and particulate matter in the US.

In July 2011, the UK parliament tabled a motion that levels of (carbon) emissions from nuclear power were approximately three times lower per kilowatt hour than those of solar, four times lower than clean coal and 36 times lower than conventional coal.

Table 1. 2 Lifecycle greenhouse gas emissions by electricity source [80]

Technology	Percentile (g CO ₂ /kWh _e)
Hydroelectric	4
Wind	12
Nuclear	16
Biomass	18
Solar thermal	22
Geothermal	45
Solar PV	46
Natural gas	469
Coal	1001

Though Solar PV generation is positioned as environmentally friendly, fabrication of PV cells utilizes substantial amounts of water in addition to toxic chemicals such as phosphorus and arsenic. These are often overlooked when promoting PV. Because of strict environmental regulations in the United States, for example, PV fabrication is often performed in countries with lower standards, such as China, which produces approximately half the world's PV panels.

1.5.3. WATER CONSUMPTION

Most large scale thermoelectric power stations consume considerable amounts of water for cooling purposes and boiler water make up - 1 L/kWh for once through (e.g. river

cooling), and 1.7 L/kWh for cooling tower cooling. Water abstraction for cooling water accounts for about 40% of European total water abstraction, although most of this water is returned to its source, albeit slightly warmer. Different cooling systems have different consumption vs. abstraction characteristics. Cooling towers withdraw a small amount of water from the environment and evaporate most of it. Once-through systems withdraw a large amount but return it to the environment immediately, at a higher temperature.

1.6. CONCLUSION

It has been shown that the renewable energies are capable of enhancing diversity in energy supply options for both developed and developing nations and at the same time contributing to long-term and cost effective sustainable energy supplies. In so doing they can make a major contribution to reducing both global and local atmospheric pollutants.

CHAPTER 2: Renewable Energies in Algeria

Economic, social and environmental concerns demand higher efficiency and more sustainable electrical power systems. Then, power systems need to evolve from its traditional conception to future power systems. New non-conventional generators are distributed in power systems, most of them based on renewable resources, which have been developed and connected to the grid. This chapter presents the progress and efforts for the usage of the existing, on-going and planned projects of the renewable energy in Algeria over these last decades. Through these projects could be very interesting under the clean development mechanism of Kyoto protocol because they reduce greenhouse gas emissions whereas contributing to sustainable development of desert communities if developed correctly.

2.1. INTRODUCTION

Climate change has become the major rallying cry behind several changes in the 21st century. Regardless of where we stand on this debate, everyone can agree on the following globally relevant facts:

- The cost of gasoline and other petroleum-related fuels is increases as the global demand for these fuels increases while availability of low cost reserves decrease making these fuels more expensive to produce.
- It is getting more difficult to get permits for new coal-fired generation.
- Auto-makers are increasingly moving towards electric vehicles leading to increase electrification of transport.
- The nuclear waste disposal issue has not yet been resolved.
- Electric load is continuing to grow both in quantity and complexity forcing utilities to think of new ways to deliver increased load without adding new generation.

Renewable electricity production is a matter for the future as almost all the country's electricity production is fossil fuel-sourced (99.6%). Renewable sources provide a top-up and are spread across hydroelectricity (0.4% of the total) and solar power (0.01% of the total).

Algeria's hydropower output dropped sharply in 2010, having peaked in 2009 and its production level in 2010 was lower than the mean production level observed over the period (267 GWh). The steady growth of fossil fuel-sourced electricity output over the period (increasing by a mean 5.6% per annum) has been indifferent to hydropower's tribulations. Figures on the solar power sector have been collected since 2008 but output remains low (4 GWh).

Algeria has stated its intention to use renewable sources to produce electricity. According to the Minister of Energy and Mines, Algeria needs to invest up to \$ 120 billion in renewable energies in 2030. The country has set its sights on becoming a green energy leader and intends to install 22 000 MW of renewably sourced capacity between 2011 and 2030.

As the major solar field in Algeria is located in hydrocarbon regions endowed with natural gas, our strategic aim is to create a mixed solar-gas synergy, taking advantage of our abundant natural gas and solar resources. Coupled with the renewable energies the natural gas is an energy resource of choice for the development of Algeria and offers the type itself of structuring vector for our integration to the world economy.

Independently of the units of solar energy intended to feed the remote centers, projects of the renewable energies connected to the national grid, are in course of development. Algeria strategy consists in carrying out a synergy between the solar one and the natural gas thanks to hybrid solar gas projects by profiting from the Algerian natural gas endowment and to the permanent sun shining of the south of the country.

A first gas-solar hybrid project, of large capacity, is under development. The project will enhance the solar energy share in the global energy balance, increased renewable

electricity connected to the national distribution grid. The NEAL company is in charge of this project [81].

The Hassi R'mel gas-solar hybrid power station will be built for 130 MW of gas and 25 MW of thermal solar energy with the parabola system of the giant mirrors on a surface of approximately 180000 m². The project will be established on a plate of ground of 130 ha. It will lay out of 250 solar collectors 150 meters length and 5 meters in diameter each one. The solar field is 90 ha. The production which will result from this power station will come from approximately 130 MW produced from gas turbines and 25 MW produced from the solar field [82].

The Algeria sees ideal opportunities of combining Algeria's richest fossil energy source (the natural gas) with Algeria's most abundant renewable energy source (the sun) by integrating concentrating solar power into the natural gas combined cycles.

The development of solar energy could save significant quantities of hydrocarbons and particularly of natural gas, which could be exported towards Europe and the United States. The positive implications are double: the reduction of burned fossil fuels will reduce the greenhouse gas emissions, while contributing to improve the energy supply of our partners.

2.2. ENERGY SITUATION

2.2.1. ENERGY SUPPLY

In 2008, Algeria has produced a total amount of 162,044 ktoe of energy, which is about 1,884,571 GWh. Its main energy source is crude oil (54.4%), followed by gas (45.5%). In comparison, the numbers concerning the renewable energies are much smaller and close to zero. Other energy sources, such as coal, nuclear power or heat are in fact zero, thus giving an impression that Algeria has quite a unilateral energy landscape. Published by the International Energy Agency (IEA), the numbers below offer more detail to Algeria's energy production:

Table 2. 1 Total energy production of Algeria (2008) [83]

Energy Source	in ktoe	in %
Coal and Peat	0	0
Crude Oil	88,187	54.4
Oil Products	0	0
Gas	73,783	45.5
Nuclear	0	0
Hydro	24	0.02
Geothermal, solar, etc.	0	0
Combustible renewables and waste	49	0.03
Electricity	0	0
Heat	0	0
Total	162,044	

Taking the table above (table 2.1) into consideration, the table below (table 2.2) offers quite a similar picture. It might yet seem surprising, that gas is now the main energy source with more than 60%, while oil only makes up 37% of the energy supply. This curiosity can be

explained by the massive amount of crude oil (-55,002 ktoe) and oil products (-19,334 ktoe) Algeria is exporting and thus decreasing the amount of available oil [84]. Plenty of gas is being exported, as well (-51,259 ktoe) [85].

Table 2. 2 Total primary energy supply of Algeria (2008) [84]

Energy Source	in ktoe	in %
Coal and Peat	755	2.0
Oil	13,721	37.0
Gas	22,524	60.8
Nuclear	0	0.0
Hydro	24	0.01
Geothermal, solar, etc.	0	0.0
Combustible renewables and waste	49	0.1
Electricity	-4	-0.1
Heat	0	0.0
Total (may not add up due to roundings)	37,069	

Gas in particular appears to be one of the main energy sources for a somewhat mid-term solution. According to the IEA projections, Algeria will have an average growth rate of about 2,7% in natural gas production until 2035. Having said that, most gas production is expected to be in the form of conventional gas, as Algeria (together with Nigeria) is expected to be the leading protagonist in gas production growth in Africa, thus increasing export rates once again, after they had dropped in 2009. In addition, the technology of liquefied natural gas (LNG) will be installed and exploited by 2013. According to the IEA, two major LNG liquefaction plants are planned for Algeria Skikda and and Gassi Touil. Both projects envision a starting point of construction in 2013[86].

2.2.2. ELECTRICITY

Between 2001 and 2011, electricity production rose from 26,250 GWh to 48,900 GWh. Between 2010 and 2011 there was an increase of 8.2%. The maximum power demand was 8606 MW, registered on 8 August 2011. This is an increase of 11.5% as compared to 2010. At the end of 2011, the installed capacity of electricity generation reached 11,524 MW, 10,926 MW of which was connected to the national transmission grid. Electricity sales increased by 8.7% to 38,900 GWh in 2011, as compared to 2010.

It appears that this development is mainly due to the economic growth that Algeria has experienced along the way. As Table 3.3 shows below, main source for the production of electricity is gas with a relative percentage to the total amount produced of over 97%. Although there are other minor sources of electricity, such as oil and hydro-power, a similar picture as seen in the tables above is being created, suggesting a rather one-sided production and supply (in this case) of electricity.

Table 2. 3 Electricity production and supply of Algeria (2008) [87]

Energy Source	in GWh	in %
Coal	0	0.0
Oil	792	2.0
Gas	39,161	97.3
Biomass	0	0.0
Waste	0	0.0
Nuclear	0	0.0
Hydro	283	0.7
Geothermal	0	0.0
Solar PV	0	0.0
Solar thermal	0	0.0
Wind	0	0.0
Tide	0	0.0
Other sources	0	0.0
Total Production	40,236	100.0
Imports	274	0.7
Exports	-323	-0.8
Domestic Supply	40,187	99.9

According to the CREG activity report of 2010 and the activity report of 2011, the percentile share of electricity production among the state-run and independent producers (IPP) looks as follows:

Table 2. 4 Production sorted by operator in 2010 and 2011 [88]

Operator	% (2010)	% (2011)
Sonelgaz Production d'Electricité (SPE)	54	56
Sharikat Kahraba Hadjrat-Ennous (SKH)	21	20
Sharikat Kahraba Skikda (SKS)	13	12
Sharikat Kahraba Berrouaghia (SKB)	6	6
Kahraba	6	5
Solar Power Plant One (SPP1)	-	1
Sharikat Kahraba Terga (SKT)	-	0,16
CEVITAL	-	0,001

2.3. RENEWABLE ENERGY RESOURCES AND WHY THEY ARE OF INCREASING IMPORTANCE

An energy resource qualified as a renewable resource if it is replenished by natural processes at a rate comparable or faster than its rate of consumption by humans. This leads to two major dimension of renewable energy resources.

2.3.1. SUSTAINABILITY

Sustainability from an energy perspective is meant to focus attention on using sources of energy at a rate comparable to that they can be replenished. As a result, they do not apply

to the traditional sources of energy like coal and oil since we know that we will run out of them at some point in the future.

2.3.2. REDUCED ENVIRONMENTAL FOOTPRINT

Renewable energy resources should ideally significantly reduce the emission of Green House Gases into the atmosphere, reduce the demand for limited resources such as water, and avoid the creation of other waste-products (i.e. fly ash) that cannot be easily recycled. Reduction of waste and its creation in a manner that can be disposed off in a harmless manner is a new area of focus.

While both traditional and renewable sources of energy have a financial aspect to them, the former creates a situation in which the commodity costs of the fuel used to produce energy will keep going up (as was evidenced by the cost of gasoline last year) and the potential to find the new sources of inexpensive fuel are decreased over time. A renewable resource on the other hand can continue to deliver power for much longer.

The latter imposes a different restriction on the generation of power. Fossil fuels (coal / natural gas / oil) based energy generation all deliver green-house gases which have now been proven to contribute significantly towards global warming and mechanisms are being developed to reduce their emissions.

Newer financial mechanisms are being thought of (i.e. carbon tax, cap and trade ...) to recognize the broader societal costs of these emissions which will also result in increased costs of generating electricity from the fossil fuels. Most of the newer renewable sources of energy are thought to be somewhat free from these taxes because they do not release any green-house gases.

2.4. POTENTIAL DEVELOPMENT OF RENEWABLE ENERGY

Beyond its hydrocarbon resources, Algeria has a high potential of renewable energy which it has the ambition to develop with the foreign partners. This development in particular huge reserves of solar energy would have several positive consequences for Algeria, its partners and the world community in general.

The promotion of the electricity produced starting from the renewable energy sources is in the forefront of the priorities of Algeria for the reasons of energy supply diversification, environmental protection and related to economic and social cohesion [89].

In the Algerian context, an electricity company, Sonelgaz, has used photovoltaic based solar energy to power the isolated cities and remote houses of south Algeria. These locations include Adrar, Timimoun (Tala Hamou-Moussa) and Tindouf (Gara Djebilet, Hassi Mounir, Draa el Khadra) as reported by Himri [90]. At present, Sonelgaz is leading the way towards the development and utilization the renewable energy sources in the country in general and wind energy in particular as can be seen from Haddouche et al. [91] and Sonelgaz [92]. According to Elimax [93], Algeria is among 15 African countries (South Africa, Eritrea, Mauritania, Cap verde, Algeria, Lesotho, Seychelles, Madagascar, Somalia, Djibouti, Morocco, Chad, Egypt, Mauritius, Tunisia) which have the good potential of wind energy.

2.4.1. WIND ENERGY

The kinetic energy of wind is a promising source of renewable energy with significant potential in Algeria. However, the energy that can be captured by wind turbines is highly dependent on the local average wind speed [88].

With regard to Algeria, the wind resource varies much from a place to another. This is mainly due to a much diversified topography and climate. A preliminary study of the seasonal and annual evolution mean velocity of the wind (figure 2.1), made possible to make a first identification of the windy areas of Algeria.

This representation of speed in the form of chart has two objectives: firstly is to identify the wide areas with good promises of exploitation of the wind power; secondly is to highlight the relative variation of the resources through Algeria.

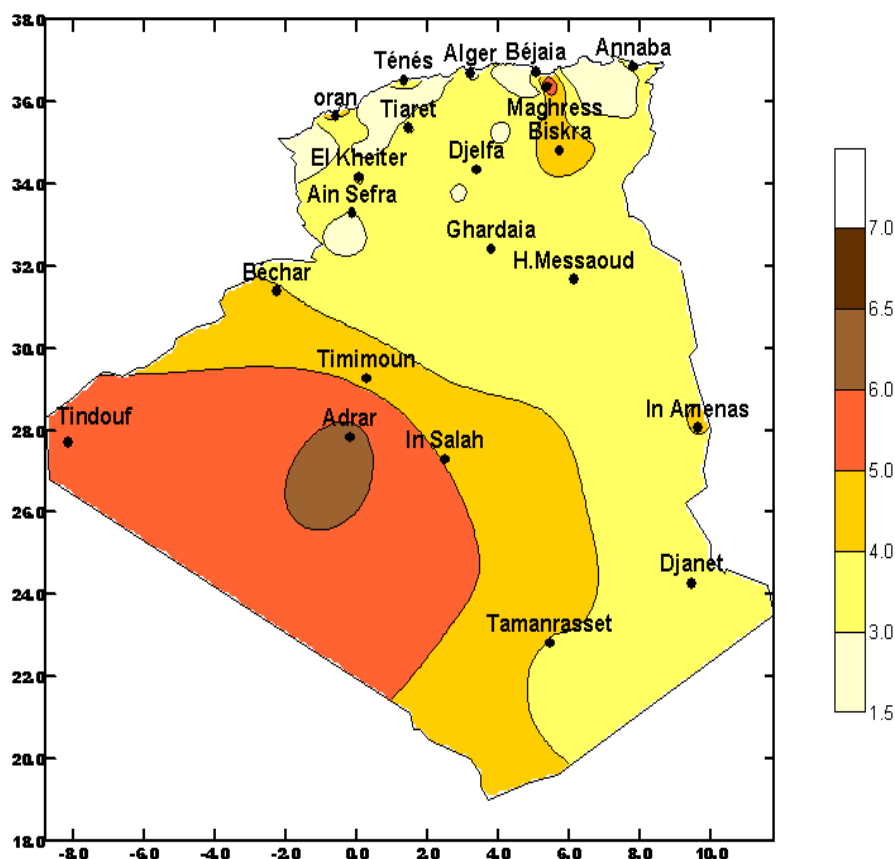


Figure 2. 1 Estimation of the wind resources [91]

Knowing the problems encountered for the electric power transport in the far areas as well as its high cost. It would be interesting to consider the application of conversion systems of the wind power for isolated areas having an appreciable wind potential. The South-west region shows all the characteristics of sites candidate to the exploitation of this energy.

The Algerian Renewable program plans at first, in the period 2011-2013, the installation of the first wind farm of a power of 10 MW in Adrar. Between 2014 and 2015, two wind farms with a capacity of 20 MW each are to be developed. Studies will be led to detect suitable sites to realize the other projects during the period 2016-2030 for a power of about 1 700 MW.

2.4.2. SOLAR ENERGY

Fortunately, its solar power capacity is one of the largest on earth. More than 2.000.000 Km² receives yearly a sunshine exposure equivalent to 2500 KWh/m².

The sunshine duration on the whole national territory exceeds the 3000 hours annually and even reaches 3900 hours on the high plateaus and the Sahara.

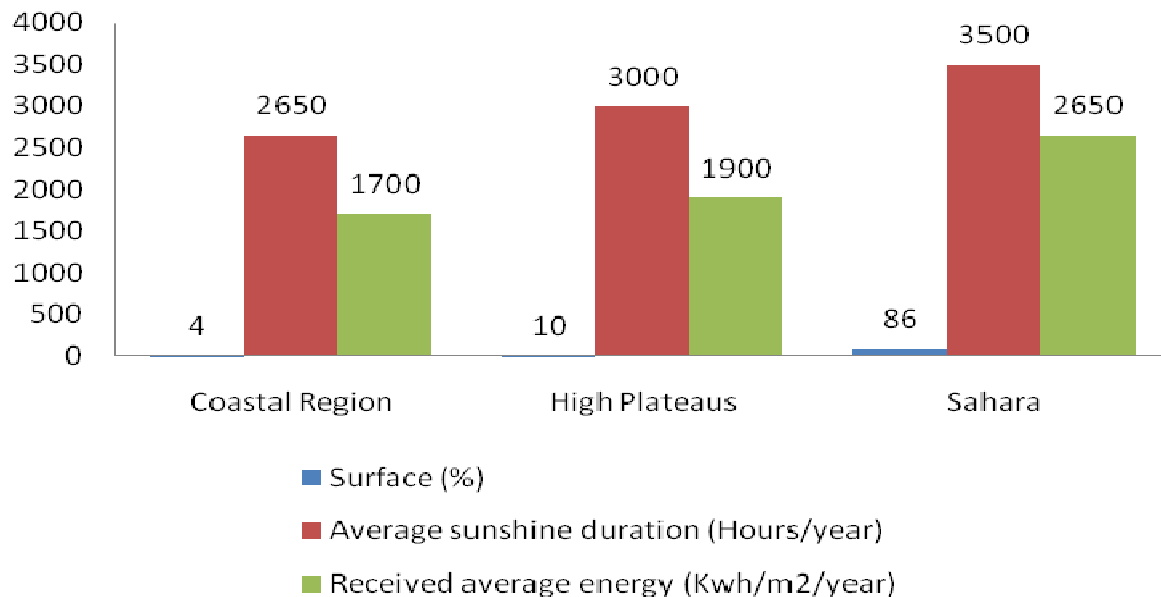


Figure 2. 2 Solar potential in Algeria [85]

Photovoltaic solar energy refers to the energy recovered from sunlight and transformed directly into electricity through photovoltaic panels. It results from direct photon-to-electron conversion in a semiconductor. In addition to the advantages related to the fact that photovoltaic systems do need low cost maintenance, this energy fully meets the needs of facilities in remote areas where connection to the grid is too expensive.

Photovoltaic solar energy is a non-polluting source of energy. The modularity of the photovoltaic solar system allows for innovative and aesthetic use of its components in architecture.

The energy strategy of Algeria is based on the acceleration of the development of solar energy. There are several ongoing electrification projects in rural areas using solar energy as a supplement to classical power grid. Photovoltaic systems are also successfully used for water pumping for the development of steppe areas. Another program for Saharanian areas electrification using photovoltaic systems is carried out for the benefit of remote the southern populations. These programs of solar energy supply give to the population of far villages a first access to information and communication since provided electricity makes possible to ensure various services.

The exploitation of this solar potential enables us to complete our program for rural electrification; today 95% of the country is covered by the domestic grid. Remote areas, far away from the power grid can only benefit from electricity supplied by an adequate use of renewable energy. The government plans launching several solar photovoltaic projects with a

total capacity of 800 MWp by 2020. Other projects with an annual capacity of 200 MWp are to be achieved over the 2021-2030 period.

2.4.3. SOLAR THERMAL ENERGY

Solar thermal energy is a technology that converts solar radiation into thermal energy. It can be used directly (for example to heat buildings) or indirectly (to produce steam to power turbo alternators that will in turn generate electric power). By using the heat produced by solar radiation rather than the radiation itself, the solar thermal energy system differs from other solar energy systems like the photovoltaic cells.

Direct solar radiation is concentrated by a collector on an absorber where it is transferred into a fluid that is either sprayed directly or drives the heat to a steam generator. All solar energy systems have a number of elements in common: a collector that concentrates the heat, a liquid or gas that transfers the heat to an extraction point, an evaporator, a turbine and a generator.

More commonly known as « Concentrating Solar Power » (CSP) system, the solar thermal energy technology can meet demand in electricity 24 hours a day if it is coupled with a thermal storage system or if production is combined with other energies like natural gas.

Algeria seeks to develop its solar potential, which is one of the most important in the world, by launching major projects in solar thermal. Pilot projects for the construction of two solar power plants with storage of a total capacity of about 150 MW each, will be launched during the 2011-2013 period. These will be in addition to the hybrid power plant project of Hassi R'Mel with a total power capacity of 150 MW, including 25 MW in solar.

The solar thermal power plants with a total capacity of about 1 200 MW are to be constructed over the period 2016-2020. The 2021-2030 programs provide for the installation of an annual capacity of 500 MW until 2023, then 600 MW per year until 2030.

2.4.4. GEOTHERMAL ENERGY

The geothermal exploration program in Algeria started in 1967 and was undertaken by the national oil company (SONATRACH). In 1982 the electrical company SONELGAZ in association with the Italian company (ENEL) undertook the geothermal recognition studies of the NE part of the country.

In the first stage, the geothermal studies concerned mainly the northern-east part of Algeria. From 1983 and onwards the geothermal work is being continued by the Renewable Energies Center and the program was extended to the whole north part of the country.

The geothermal development has remained stagnant during the last decade. Presently renewed effort is put into developing large projects with the establishment of the geothermal atlas of Algeria.

There are more than 240 thermal springs in Algeria. The geothermal energy in Algeria is generally of a low enthalpy type [94]. The total heat discharge from the main springs and existing wells is approximately 642 MWt. Three geothermal zones have been delineated according to some geological and thermal considerations:

- 1) The Tlemcenian dolomites in the northwestern part of Algeria
- 2) Carbonate formations in the northeastern part of Algeria
- 3) The sandstone Albian reservoir in the Sahara (south of Algeria).

The northeastern part of Algeria is geothermally very interesting. Application of gas geothermometry to northeastern Algerian gases suggests that the reservoir temperature is around 198 °C.

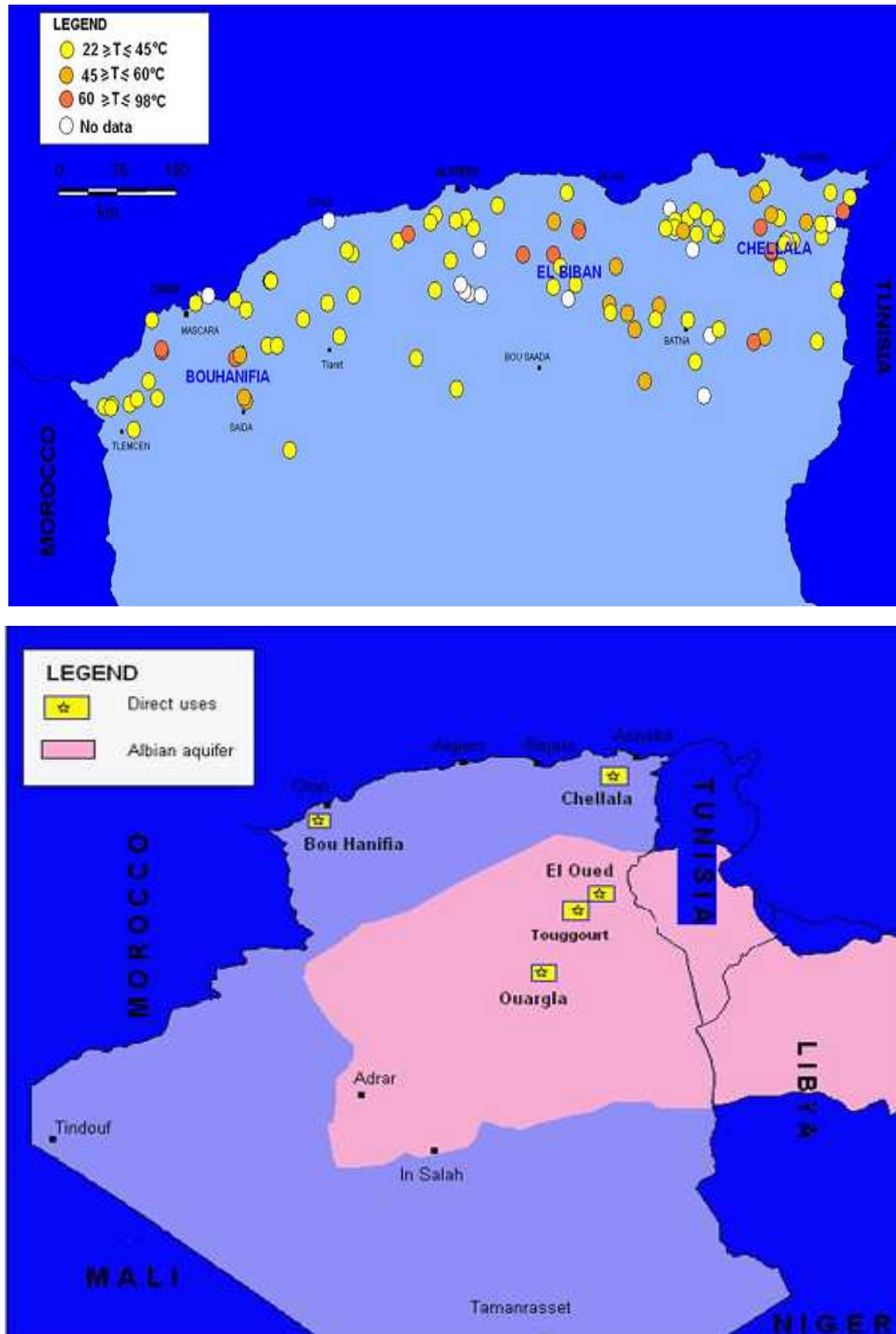


Figure 2. 3 Main geothermal areas [95]

2.4.5. BIOMASS ENERGY

The biomass potentially offers great promise, with 3.7 Mtoe per years coming from forests and 1.33 Mtoe per year coming from agricultural and urban wastes; however this potential is not enhanced and consumed yet. A preliminary survey showed the feasibility of production of electricity by modals of 2MW that can reach a peak of 6MW, from the discharge of Oued Smar in Algiers. The study integrates the drainage of the site.

2.4.6. HYDROPOWER

Restricted rainfall, high levels of evaporation and quick evacuation to the sea are barriers to the uptake of hydropower. However, 103 dam sites have been recorded, primarily in the North. More than 50 dams are currently operational and the combined capacity of the largest 13 dams is roughly 269 MW.

2.5. STRUCTURE OF THE NATIONAL POWER GENERATION IN MW

The renewable energy program is defined through different phases:

- ✓ Installation of a total power capacity of 110 MW by 2013 ;
- ✓ Installed power capacity to reach 650 MW by 2015 ;
- ✓ Installed power capacity to reach about 2600 MW by 2020 and a possibility of export of 2000 MW;
- ✓ An additional capacity of about 12000MW is expected to be installed by 2030 and a possibility of export up to 10 000 MW.

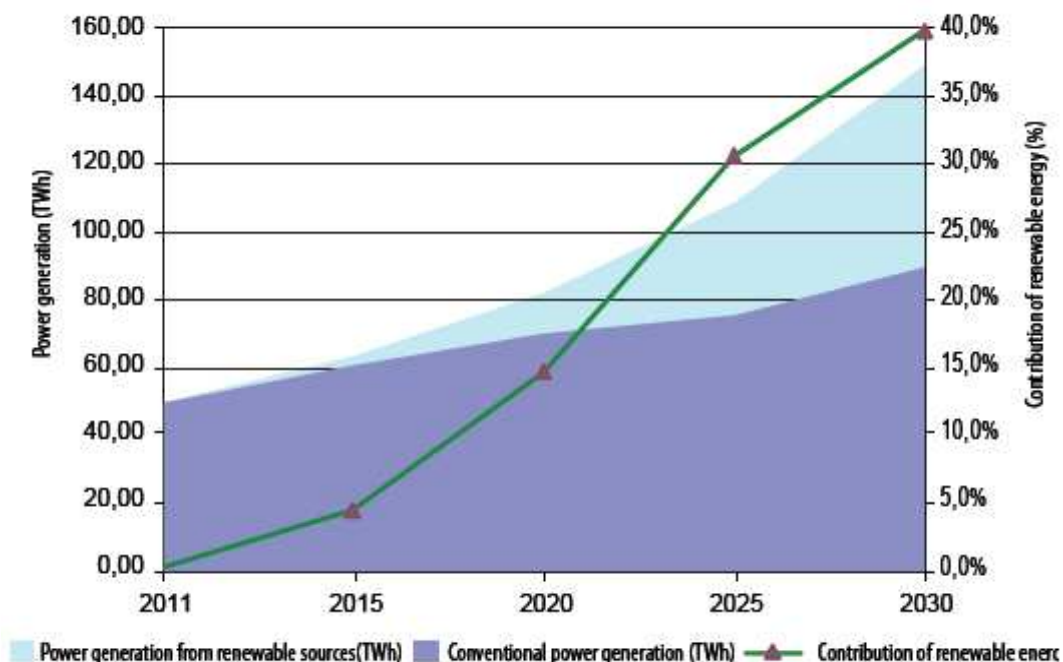


Figure 2. 4 Contribution of renewable energies for power generation in TWh [96]

2.6. ELECTRICITY PRODUCTION BY SOURCE IN ALGERIA

The SONELGAZ is the state-owned electricity and downstream gas utility. Over 90% of the electricity production is based on natural gas, with the balance from fuel oil/diesel and hydropower. To keep up with demand growth, 8-10 GW of new power generating capacity are expected to be built by 2015, about 70% by independent power producers. Electricity tariffs are low in Algeria: around 6 US cents/kWh for residential customers, and circa 3 US cents/kWh for industrial users. This is due to low internal prices for natural gas: it is estimated that industrial and power producers pay below 1 USD/Mbtu, while current export prices are over 8 USD/Mbtu. The government's objective is to adjust domestic energy prices to international levels, but this process is likely to be slow.

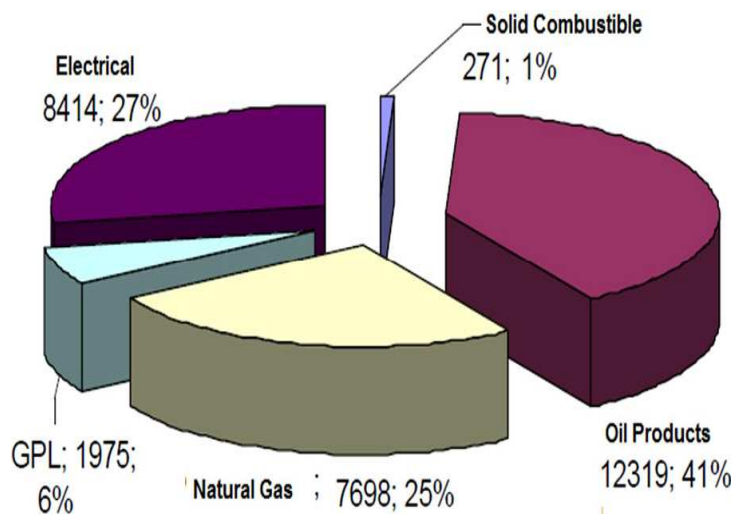


Figure 2. 5 Energy consumption by sources 2009 [96]

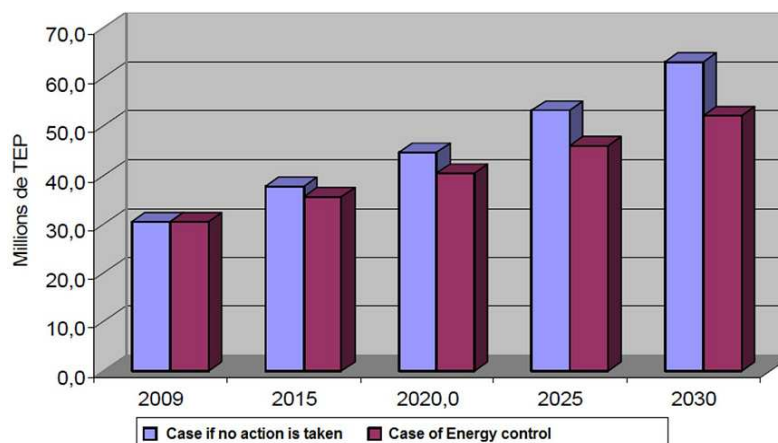


Figure 2. 6 Perspectives of the energy consumption [96]

2.7. LEGISLATIVE AND REGULATORY TEXTS

Three principal reasons plead in favor of renewable energies development in Algeria [97]:

- ✓ They constitute a solution economically viable to provide energy services to the rural isolated populations in particular in the Great South areas,

- ✓ They allow a sustainable development because of their inexhaustible character, and of their limited impact on the environment and contribute to the safeguarding of our fossil resources,
- ✓ The monetization of these energy resources can have only positive repercussions as regards of regional balance and jobs creation.

Algeria has decidedly chosen sustainable development as its energy strategy, the legal and regulatory framework adopted during the past years underscores our strong commitment. I can quote between others:

- 99-09 act of July 28th, 1999, related to energy efficiency;
- The law relative to the electricity and to the public distribution of gas, promulgated in February, 5th 2002, liberalized the sector of electricity by opening to competition the production and the marketing of electricity.

This law which takes in to account the protection of the environment, envisages the integration of renewable energies in the energy mix of the country. It opened in other side, the way to the promulgation of other inciting measures in favor of renewable energies. Advantageous premiums are granted to the producers of electricity produced from renewable sources. The purpose of the promulgation of this law is the implementation of a national policy of control of the energy based on the rational use of energy, the development of the renewable energies and the reduction of the negative effects of the energy system on the environment.

- ✓ A decree, on diversification of electricity production costs, was enacted the 25th of March 2004.

The incentive premiums of this decree shall attract private investors to implement integrated solar combined cycle plants in Algeria.

- ✓ Another law, the law on renewable energies within the framework of the sustainable development promulgated in August, 14th 2004, makes possible to institute economic incentives founded on the environmental benefit of the electricity produced from renewable sources.

This law will constitute a basis for lawful instruments aiming at the encouragement of the development of the renewable energies in their environmental and ecological dimensions.

The national power consumption will grow obviously, like that of all the countries in the process of development and certainly much more strongly than it is thought, taking into account of the most recent forecasts on our economic growth and especially industrial which are specified at the horizon.

2.8. EXISTING PROJECTS

2.8.1. RENEWABLE ENERGY DEVELOPMENT PROGRAM

The renewable energy development program of Algeria schedules a massive increase in the energy production from the renewable energy sources until 2030. According to the Ministry of Energy and Mines, this program will be arranged in four major phases:

- ✓ Installed power capacity of 110 MW in 2013
- ✓ Expansion of installed power capacity up to 650 MW by 2015
- ✓ At 2020 and yet another phase of capacity development, available capacity for domestic needs is expected to be about 2,6 MW, whereas another 2 MW are supposed to be ready for export
- ✓ In the year 2030 available capacities for domestic needs are envisioned to grow up to 12 MW. Export-ready capacities are scheduled to be about 10 MW.

2.8.2. PROJECTS IN THE PLANNING PHASE OR UNDER IMPLEMENTATION

- ✓ Hassi R'MEL CSP (concentrating solar power), operator: Abener & NEAL, total capacity: 150 MW, operating since June 2011
- ✓ AlSol, CSP solar Tower, total capacity: 3 MW, under construction
- ✓ Wind farm of Adrar, operator: Sonelgaz, total capacity: 10 MW
- ✓ Electrification of 16 villages with individual PV kits, operator: Sonelgaz and CEEG (engineering company for electricity and gas), total capacity: 5 MW
- ✓ Fabrication of PV modules, operator: Sonelgaz/ Rouiba Eclairage, total production capacity: 116 MWp/ year, January 2014

2.8.3. ENERGY EFFICIENCY PROGRAM

The energy efficiency program is a big step for Algeria towards an eco-friendly energy policy, showing that an ecologically sensitive use of already existing energy resources are just as important as developing new sources of exploitation. The announced goal is to provide the same service as usual, but with less energy being used in its process. Planned provisions to facilitate the desired energy efficiency include thermal insulation in domestic households, an extensive use of energy-saving lamps, efficient public lighting by using sodium vapor lamps, and the promotion of liquid petroleum gas (LPG) as fuel. Furthermore, public commercial vehicles are planned to run with natural gas in 2020. For the moment, a research pilot has been launched in Algeria to test the feasibility of this vision. At 2020, all major cities in Algeria are planned to follow this lead. Last but not least a rather ambitious plan is to develop air conditioning technology running with solar power although this idea is only at the outset and only exists in form of preliminary research, it can be considered to be one of the most changing reforms regarding the high usage of air conditions during summer months.

2.9. DEVELOPMENT OF MICRO-GRIDS IN REMOTE LOCATIONS

The economic and social development in Algeria in the last years has been in need of continues increasing in demand of electricity, especially in the isolated countryside [98]. The two major approaches to delivering electricity to remote areas such as a village are isolated solar home systems (SHS) and village microgrids (also known as minigrids). In deciding what energy system is optimal to power a rural village, the number of homes on the system will dictate which system is better. You may have to dust off your old Economics 101 text book on marginal cost, because the main tradeoff is between the marginal cost of distribution and the cost of installing a solar system in a house.



Figure 2. 7 Rural electrification by photovoltaic solar energy [98]

2.10. CONCLUSION

- ✓ Renewable Energy potential in Algeria is not completely estimated but it is considerable
- ✓ The program of renewable energy is still at the pilot phase
- ✓ Today the renewable energies represent only 0,02% of the electrical consumption
- ✓ Weaknesses: Infrastructure, Equipment, Know-How

Part 2: Energy Production System Modeling

CHAPTER 3: Modeling of Photovoltaic System

CHAPTER 4: Modeling of Wind Conversion System

***“Do not go where the path may lead. Go where there is no path and leave a trail”
Ralph Waldo Emerson (1803-1882)***

CHAPTER 3: Modeling and simulation of Wind Energy Conversion

The use of wind energy is increasing these last years. The power generated by the wind varies greatly throughout the day; it depends on the power available in the wind and has the same variation. This chapter deals with the modeling and the control of wind turbine generation systems by bond graph approach for integration in power systems studies. The modeling of the wind phenomenon, the turbine mechanical system and the electrical machine, along with the corresponding converter and electrical grid is described. This chapter presents an intelligent control method for the maximum power point tracking (MPPT).

3.1. INTRODUCTION

Renewable energy sources have a key role to play in the global energy mixture as a mean of reducing the impact of energy production on climate change. Wind has been used as a traditional energy source for centuries and is still commonly used in many developing countries. As a result of the modern technological developments, the wind turbines have improved considerably in the recent decades [99]. Wind has become an attractive energy source, especially in parts of the world where transmission infrastructure is not fully developed. Many countries are pursuing the option of the wind energy conversion systems; in an effort to minimize their dependence on fossil-based non-renewable fuels [100].

Wind energy is the most developed of all renewable energy technologies with more than 200GW of globally installed capacity in 2011. Analyses of wind farm maintenance costs show that up to 40% of the outlay is related to unexpected component failures that lead to costly unscheduled amendments. Wind farm operators are constantly looking for new technological developments in monitoring condition that can contribute to the minimization of wind turbine maintenance expenditure. Early fault detection through monitoring condition can help prevent major break downs as well as significantly decrease the associated costs. Moreover it enables the optimization of maintenance schedules, reduces down time, increases as set availability and enhances safety and operational reliability. Faults in the braking system are of particular concern since they can result in catastrophic failure of the wind turbine.

New wind turbine technology integrates power electronics and control systems, making it possible for wind power generation to participate in the control of active and reactive power. Nowadays most of the installed variable speed wind generators are based on the doubly-fed induction generator (DFIG) [101] but new types of wind generators based on permanent magnet synchronous generators (PMSG) [102] are expected to gain market popularity in the next years.

There are two common types of power interfaces between the PMSG and the grid. The first is a back-to-back converter connected to the grid. This configuration has a lot of switches, which cause more losses and voltage stress in addition to the presence of electromagnetic interference. The second is a diode-bridge rectifier, a boost converter and an inverter connected to the grid. This configuration is simple, less expensive, robust and rigid.

In this work, we focus on the conversion of wind into electrical energy on the use of bond graph method for modeling and simulation. It integrates modeling of multidisciplinary systems like electrical, mechanical and magnetic, being a well-established graphical method for modeling dynamical systems.

3.2. PRESENTATION OF THE GLOBAL SYSTEM

Figure (3.1) shows the global scheme of a renewable energy source connected to a load [102]. The selected wind generator employs a permanent magnet synchronous generator directly coupled to the wind turbine and connected to the electric grid through a power conditioning system (PCS) [103]. The stator windings of the PMSG are connected to the PCS, which is composed of a three-phase rectifier bridge, a DC-DC converter and a DC-AC

switching power inverter. The power electronics converter can be considered as an amplifier composed of three pairs of electronic switches (Mosfet, IGBT, etc.). Each pair composing a commutation cell.

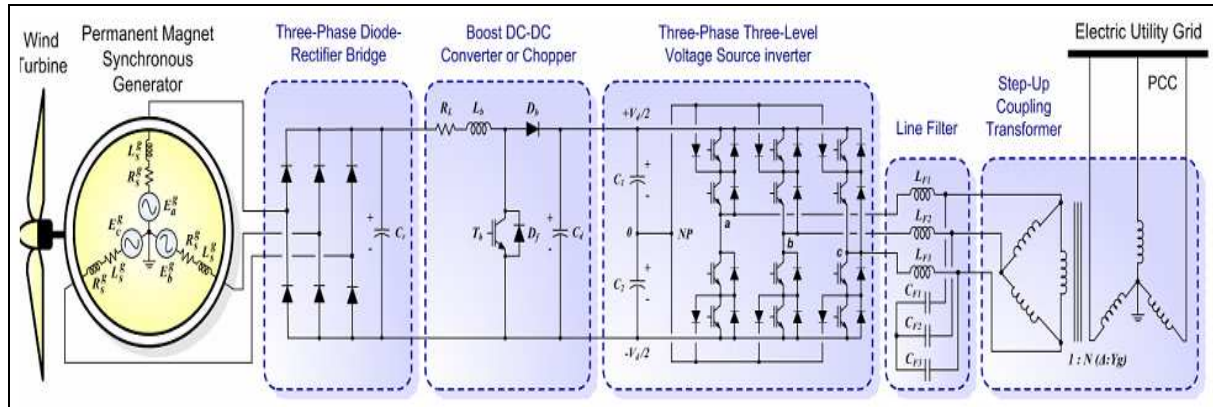


Figure 3. 1 Process description [103]

The filter may take several shapes and sizes, from a simple LR filter, which consists only of an inductance in series with a resistance, to a more complicated LC one, as represented in figure (3.1). Each filter configuration has its own characteristics and is used for specific requirements or analysis from the point of view of stability and harmonics analysis.

3.3. BOND GRAPH APPROACH

Bond graph is an explicit graphical tool for capturing the structures among the physical systems and representing the mass an energy network based on the exchange of power [100]. Some authors [105] - [106] have extended the bond graph concept to represent phenomena such as chemical kinetics and to extract causal models and control structures from the bond graph networks.

One of the advantages of bond graph method is that models of various systems belonging to different engineering domains can be expressed using a set of only nine elements: inertial elements (I), capacitive elements (C), resistive elements (R), effort sources (Se), flow sources (Sf), transformer elements (TF), gyrator elements (GY), 0-junctions (0-J) and 1- junctions (1-J). I, C, and R elements are passive elements that convert the supplied energy into stored or dissipated energy. Se and Sf elements are active elements supplying power to the system. TF, GY, 0-J and 1-J are junction elements that connect I, C, R, Se and Sf effectively creating the structure of the bond graph model [107] - [108].

Bond graph models are ideally suited for modeling a nonlinear system. A bond graph model does not assume any linearity constraints. The model hides the complexity of nonlinearity from the user of the model. Once the modeler defines the nonlinear relationship in the model, it is the job of the underlying bond graph software to solve the model. The whole process is transparent to the user of the model.

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1-port element is the most basic of the bond graph elements. This element has a single port for energy exchange with its environment. There will be a constitutive equation depicting the relationship between the co-variables of the element bond.

The only constraint on the constitutive equation is that the energy should be conserved as per the underlying physical law of bond graph modeling. Two different relationships between the co-variables (effort and flow) are depicted graphically in figure (3.2-a) and (3.2-b). The bond graph model for this relationship is depicted by 1-port elements in figure (3.2-c).

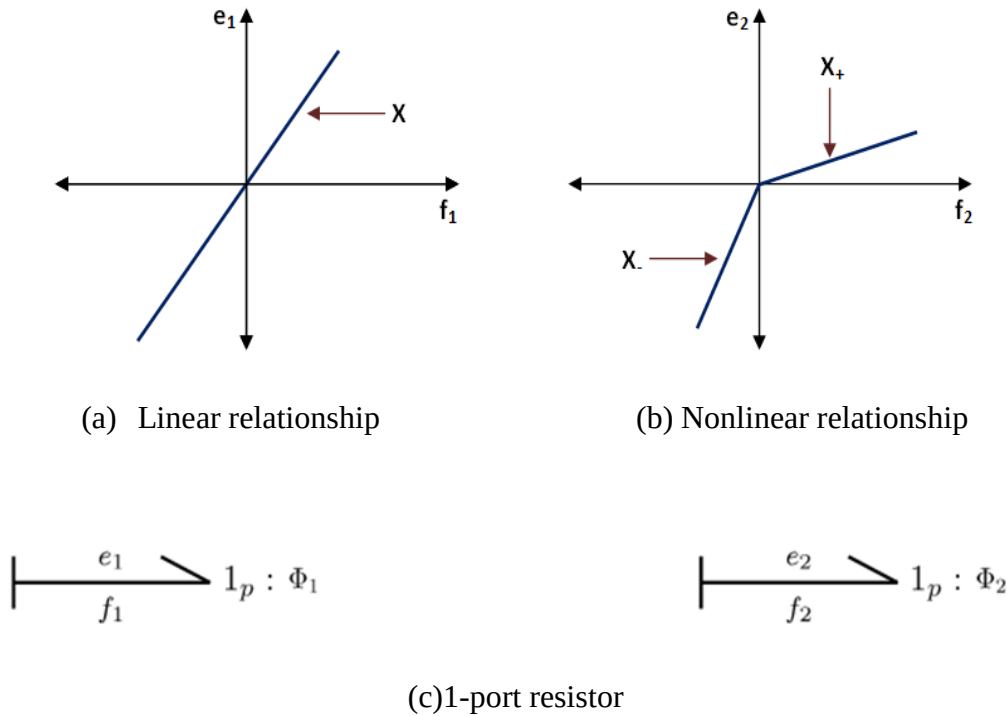


Figure 3. 2 Relationship between flow and effort for 1-port resistor elements [103]

The constitutive relationship for the 1-port resistor elements are given in equations (3.1) and (3.2). It can be seen that the model for both linear and nonlinear behavior look-alike, with the constitutive relationship hiding the difference. It is the job of the solver software to simulate the model differently.

$$e_1 = \phi_1 f_1 \quad (3.1)$$

$$e_2 = \phi_2(f_2) \quad (3.2)$$

$$\text{where, } \begin{cases} \phi_1 = X & \text{always} \\ \phi_2 = X_- & \text{if } f_2 < 0 \\ \phi_2 = X_+ & \text{if } f_2 > 0 \end{cases} \quad (3.3)$$

Bond graph provides a simple approach for modeling complex systems, which allows both a structural and a behavioral system analysis [109]. From the FDI point of view, the causal properties of bond graph models are used to determine the origin of a fault. In the bond graph diagnosis, it is important to have a bond graph model that includes all the parameters

that are related to the faults under analysis.

The word bond graph of our system is present in figure (3.3).

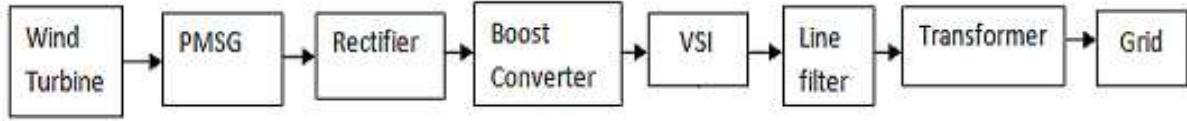


Figure 3. 3 Word bond graph of WECS [103]

3.4. BOND GRAPH MODELING

3.4.1. WIND BOND GRAPH MODELING

Wind speed estimation is highly important so as to determine the electric power to be supplied from wind power or wind [110]. It maintains a direct relation to the torque over the turbine axis and therefore it may also have some direct effect on the power output of the wind turbine generation system (WTGS) hence its evolution must be taken into account to properly simulate the WTGS dynamics.

Wind speed varies from one location to another and also fluctuates over time. The evolution of the wind speed according to time is modeled by a bond graph model starting from the data of measurement for a given site. In a context of theoretical modeling; the profile of wind must satisfy 2 criteria: the duration of the profile must be limited to reduce the time of simulation and the profile of wind must be representative of the characteristics layer (intensity, variability, statistical distribution...).

The wind speed can thus be modeled as a scalar function which evolves in time (figure 3.4)

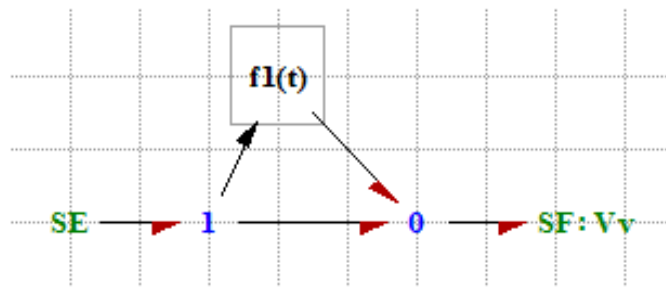


Figure 3. 4 Bond graph model of wind speed

$$V = f(t) \quad (3.4)$$

In this study, we represented the speed wind evolution of the deterministic way, by a sum of several harmonics as indicates the bond graph model following (figure 3.5):

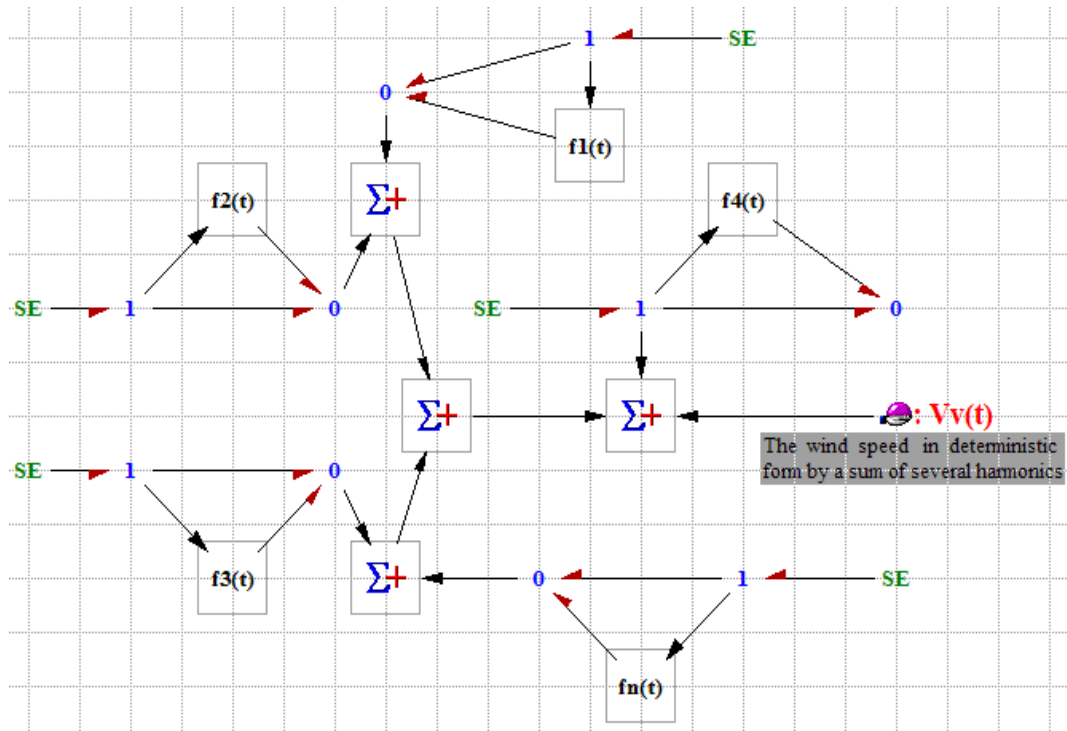


Figure 3. 5 Bond graph model of wind speed of the deterministic way by a sum of several harmonics

$$V_{wind}(t) = V_0 \left(1 + \sum A_k \sin(w_k t) \right) \quad (3.5)$$

V_0 is a value of wind velocity; A_k is amplitude of harmonic; w_k is frequency of harmonic.

Figure (3.6) presents a wind profile reflecting the stochasticity. It is a profile filtered and adapted to our studied wind system which has a slow dynamics [111].

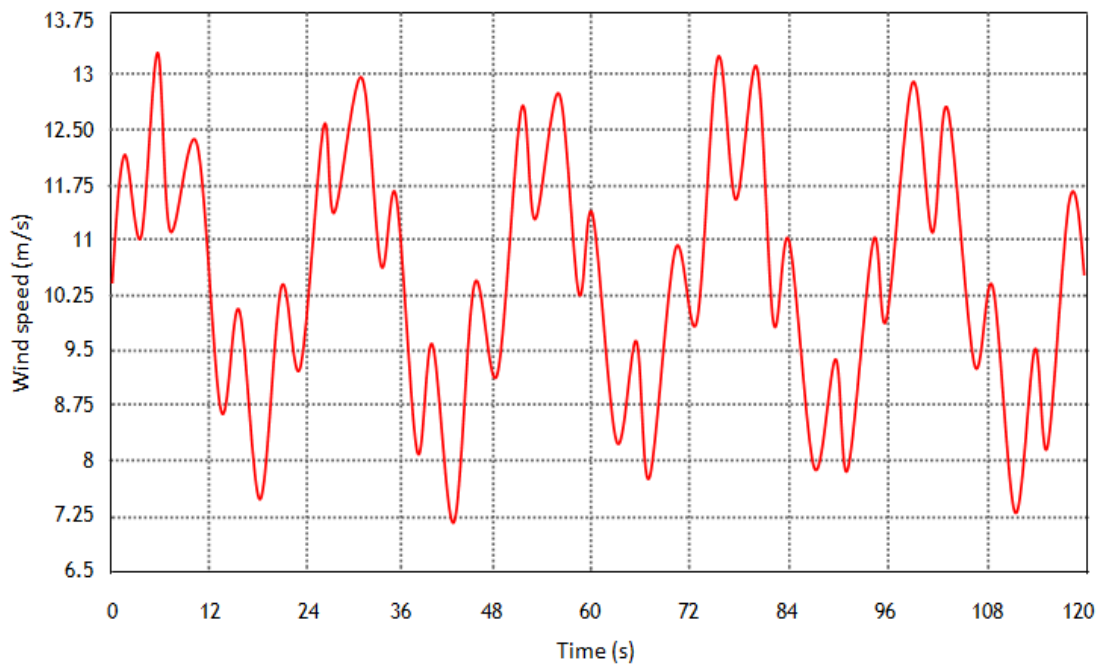


Figure 3. 6 Profile filtered wind

3.4.2. WIND TURBINE BOND GRAPH MODELING

The power of the wind turbine electrical generation systems can be expressed as the kinetic power available in the stream of air multiplied by a CP factor called power coefficient. It mainly depends on the relation between the average speed of the air across the area covered by the wind wheel and its angular speed and geometric characteristics of the turbine (including the instantaneous blade pitch angle configuration) (figure 3.7).

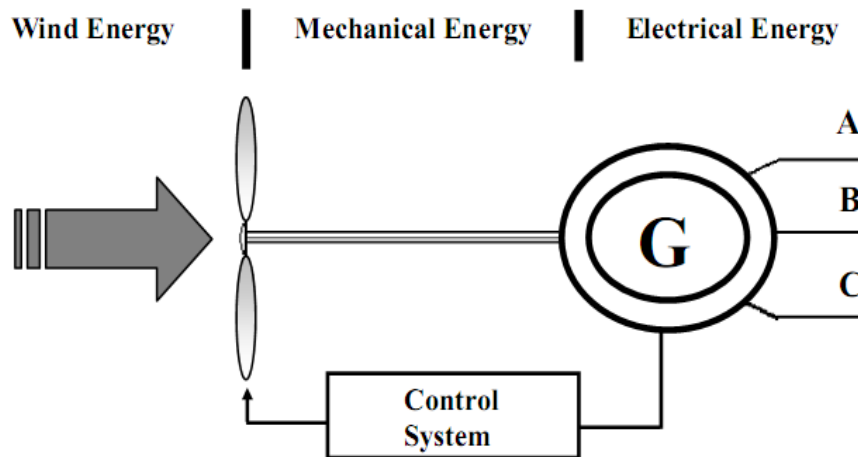


Figure 3. 7 Wind turbine

The objective of this section is to model the wind generator. The structure of selected wind mill has already been the subject of several studies [112] - [114] which resulted in developing the test bench in order to validate the control developed strategies. The modeled wind turbine has variable speed, a three blade horizontal axis and a rated power of 4.8 MW. Its parameters are summarized in Table 3.1.

Table 3. 1 List of turbine parameters

Description	Value
Rotor radius	57.5 m
Rotor viscous damping	7.11 kg/s
Generator damping	45.6 kg/s
Rotor inertia	$55 \times 10^6 \text{ kg m}^2$
Generator inertia	390 kg m^2
Drive train damping	775.49 kg/s
Drive train stiffness	$2.7 \times 10^9 \text{ kg/s}^2$
Drive train efficiency	0.97
Gearbox ratio	95

Figure (3.8) presents its bond graph model.

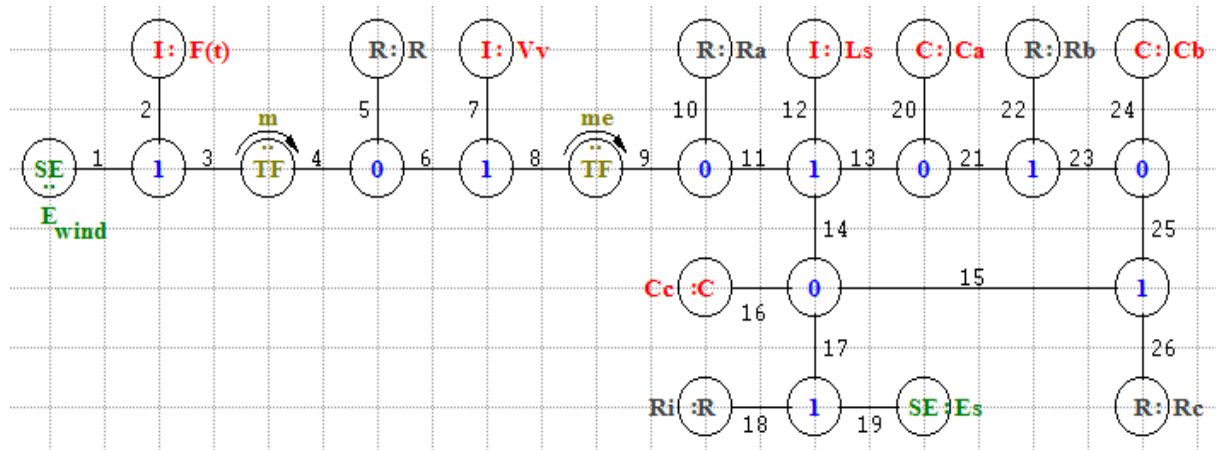


Figure 3. 8 Bond graph model of wind turbine

3.4.3. PERMANENT MAGNET SYNCHRONOUS GENERATOR

The PMSG has been considered as a system which makes possible to produce electricity from the mechanical energy obtained from the wind [115]. The selected WTGS employs a permanent magnet synchronous generator (PMSG) coupled directly to the wind turbine. To obtain the mathematical model of the PMSG, a few hypotheses have been made [116] - [117]: Permeability of the fully laminated cores is assumed to be infinite. Saturation, iron winding losses, as well as, slot effects are neglected. Only linear magnetic materials are considered. Under these assumptions [118]

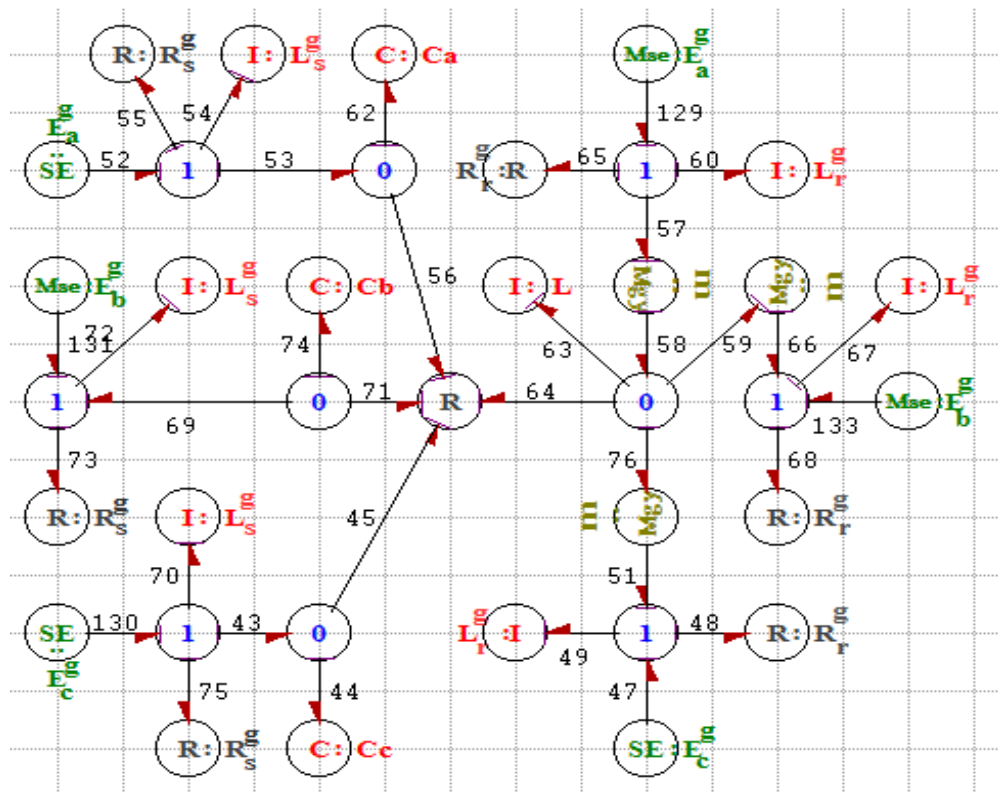


Figure 3. 9 Bond graph model of PMSG

The figure (3.9) represents the bond graph model of a permanent magnet synchronous

generator. Rotor speed and the moment of inertia are modeled by I , Stator and rotor resistances together with other frictions are modeled by R , The capacitors and mechanical structures are modeled by C , electromechanical transformation is modeled by GY and the electric source by SE . Figures (3.10) and (3.11) shows the power versus rotor speed of the turbine at various wind speeds and the torque versus rotor speed of the turbine at various wind speeds respectively [119].

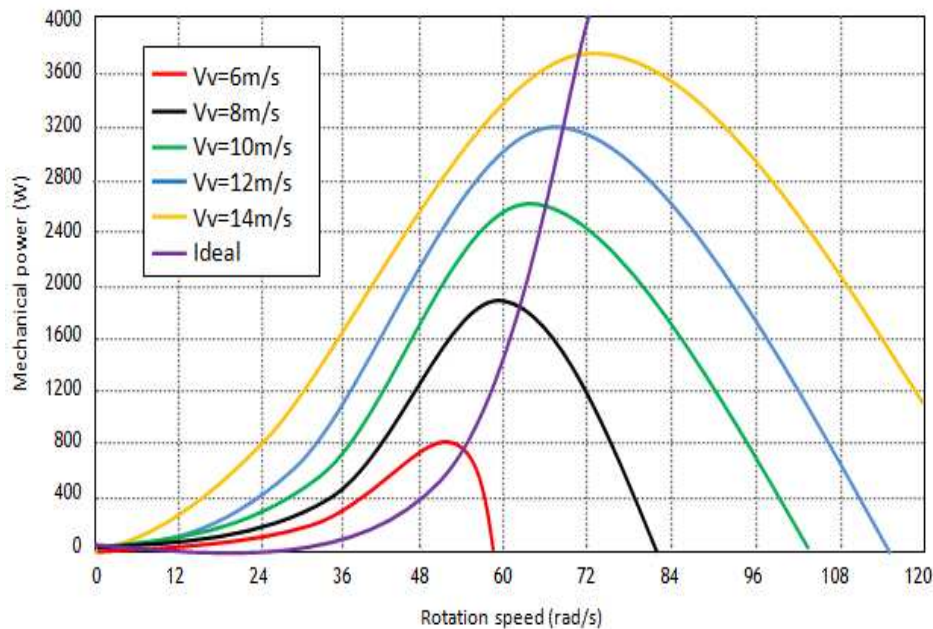


Figure 3. 10 Power versus rotor speed of the turbine at various wind speeds

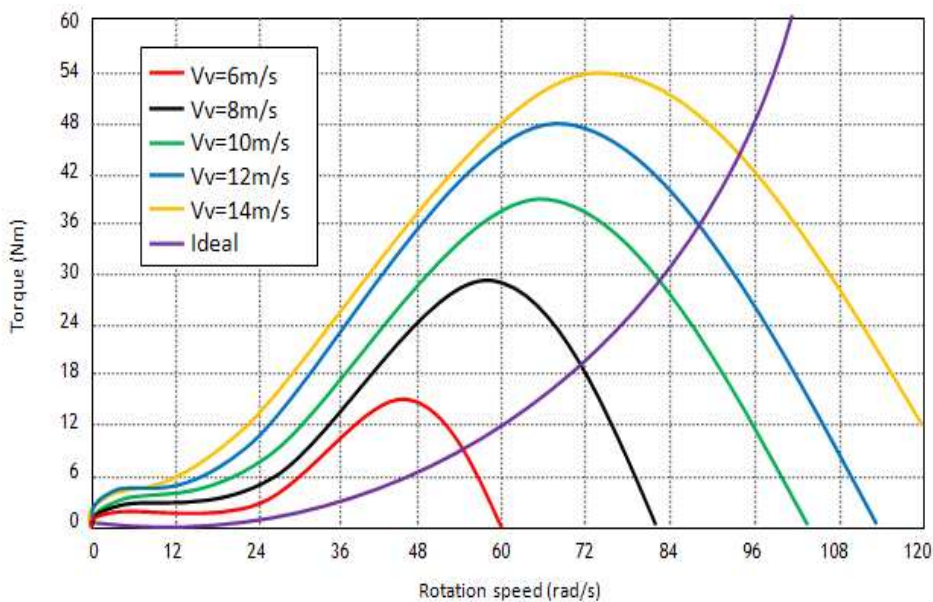


Figure 3. 11 Torque versus rotor speed of the turbine at various wind speeds

3.4.4. POWER CONDITIONING SYSTEM (PCS)

The power conditioning system (PCS) used for connecting renewable energy sources to the distribution utility grid must generate a high quality electric power, being at the same time

flexible, efficient and reliable. This device has the benefit of being simple, robust, cheap, and needing no control system. On the Three-phase three-level DC-AC voltage source inverter (VSI) using IGBTs is employed for connecting to the grid [120]. As the power rating of the inverter is intermediate to small, the output voltage control of the VSI can be achieved through pulse width modulation (PWM) techniques. This power inverter topology is proposed above others because it generates a more sinusoidal output voltage waveform than conventional structures without increasing the switching frequency. Its harmonic performance, efficiency and reliability are better than conventional two-level inverter topologies. The connection to the utility grid is made through a step-up transformer and a low pass filter, which reduces the high-frequency disturbance on the distribution grid.

Since the VSI needs a fixed DC-link in order to allow a decoupled control of both active and reactive powers exchange with the electric grid, an additional interface between the PMSG and the DC side of the VSI is required. For this purpose, a DC-DC boost converter is used to connect the output of the full-wave rectifier bridge to the DC bus of the power inverter. This two-stage AC-DC energy conversion system offers an additional degree of freedom in the operation of the system when compared with conventional one-stage configurations, permitting a pursuit of various control objectives simultaneously with the WECS system operation.

3.4.5. DC-DC CONVERTER

A large number of dc-dc converter circuits are known that can increase or decrease the magnitude of the dc voltage and/or invert its polarity.

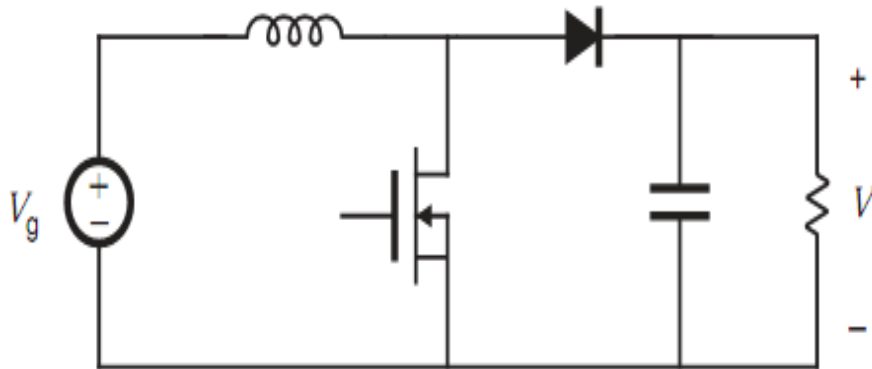


Figure 3. 12 Circuit of boost-up chopper

The standard unidirectional topology of the DC-DC boost converter or chopper in figure (3.12) consist of a switching-mode power device containing two semiconductor switches (a rectifier diode and a power transistor with its corresponding anti-parallel diode) and two energy storage devices (an inductor and a smoothing capacitor) for producing an output DC voltage at a level greater than its input DC voltage.

This converter acts as an interface between the full-wave rectifier bridge and the Voltage Source Inverter by employing pulse-width modulation (PWM) control techniques. The bond graph model of the chopper is in figure (3.13).

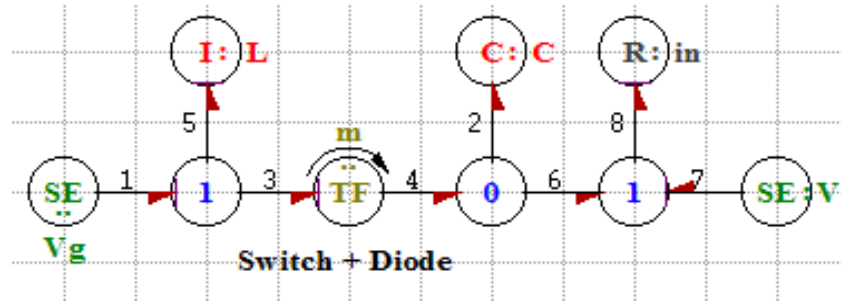


Figure 3.13 Bond graph model of boost-up chopper

3.4.6. VOLTAGE SOURCE INVERTER

The three-phase three-level voltage source inverter proposed corresponds to a DC-AC switching power inverter using IGBTs operated through sinusoidal PWM [121]. As the high-frequency harmonics produced by the inverter as result of the PWM control techniques employed are mostly filtered by the sinusoidal line filter, the VSI can be seen as an ideal sinusoidal voltage source, which is depicted in figure (3.14).

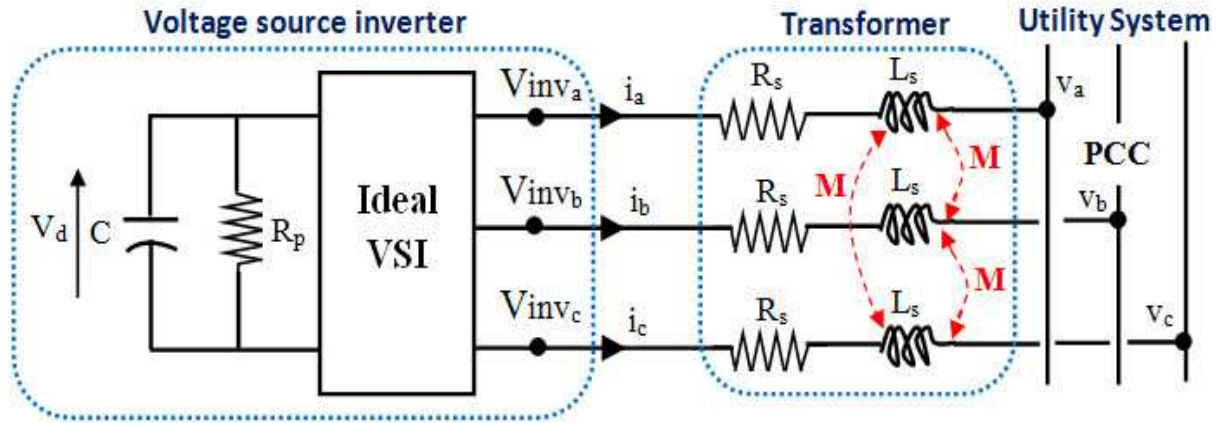


Figure 3.14 Equivalent circuit diagram of the grid-connected VSI

This inverter is considered ideal and shunt-connected to the network through an inductance L_s , accounting for the equivalent leakage of the step-up coupling transformer and a series resistance R_s , representing the transformers winding resistance and VSI semiconductors conduction losses. The magnetizing inductance of the step-up transformer can also be taken into consideration through a mutual equivalent inductance M .

The bond graph model of a three phase inverter has been addressed in several research papers [122]-[125]. Each presented model has different characteristics and is used for different applications.

They share the particularity of using an electronics witch (MTF) for modeling the three commutation cells of the converter, taking into account phase-neutral voltages. Here, the three phase three-level voltage source inverter is modeled with three electronic switches (k_1 , k_2 , k_3), using the phase-phase voltages.

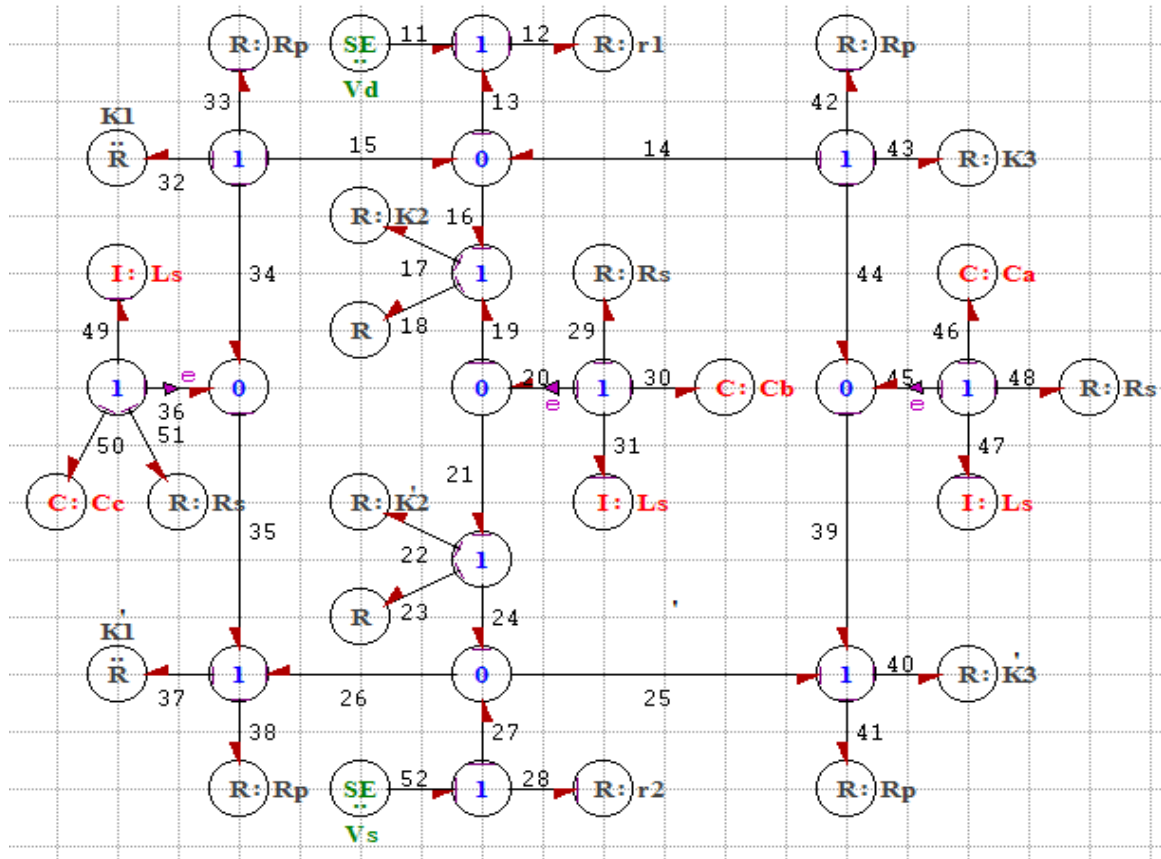


Figure 3.15 Bond graph model of the grid-connected VSI

The proposed model is more general since it is valid for both unbalanced and balanced modes. The bond graph model of the three-phase three-level voltage source inverter proposed is given in figure (3.15).)

3.5. BOND GRAPH CONTROL STRATEGY

The bond graph control scheme for the three-phase grid-connected wind energy conversion system is depicted in figure (3.16). The proposed algorithm was validated by means of simulations performed with the Symbols code in two different situations, the former assuming the presence of the proposed control system and the latter its absence. In both cases the output power was evaluated in order to perform a subsequent comparison.

$$\Omega_{opt} = \frac{\lambda_{opt} \cdot V_v}{R} \quad (3.6)$$

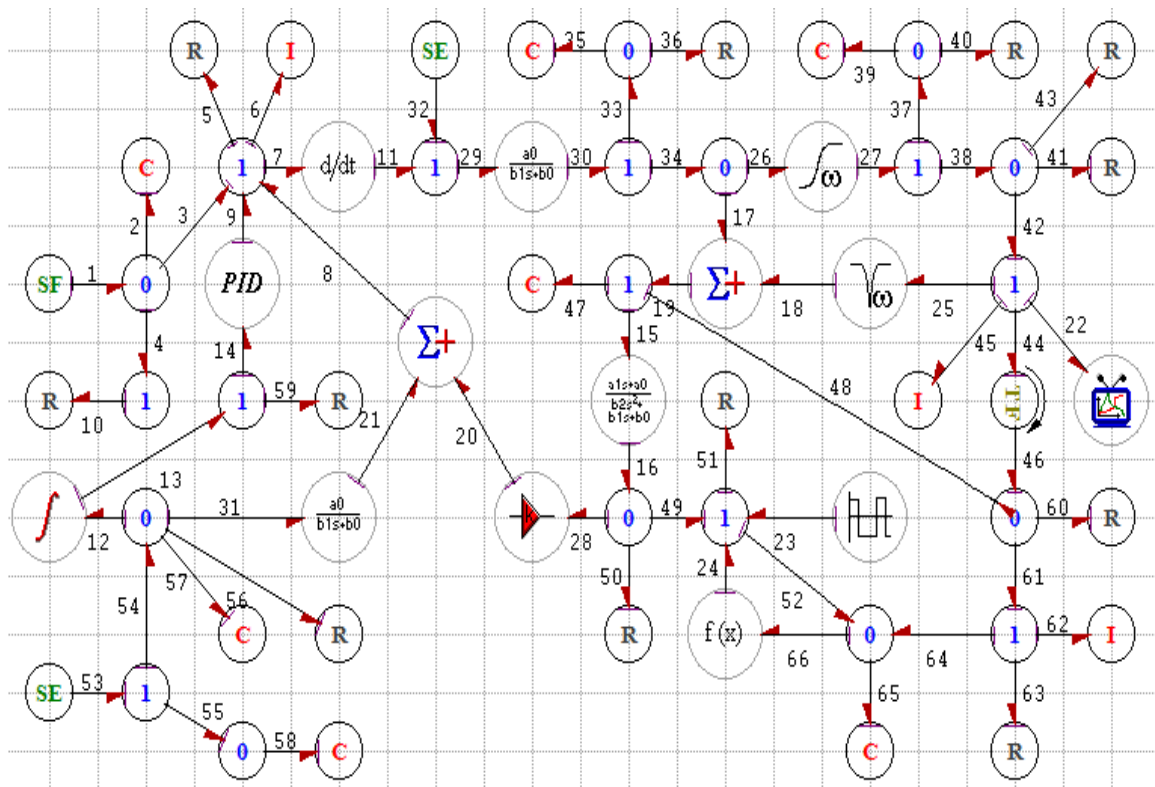


Figure 3. 16 Bond graph model of system with MPPT

3.6. SIMULATION RESULTS

The figures (3.17) and (3.18) show results of simulation with and without speed control. The power of the former is obviously better.

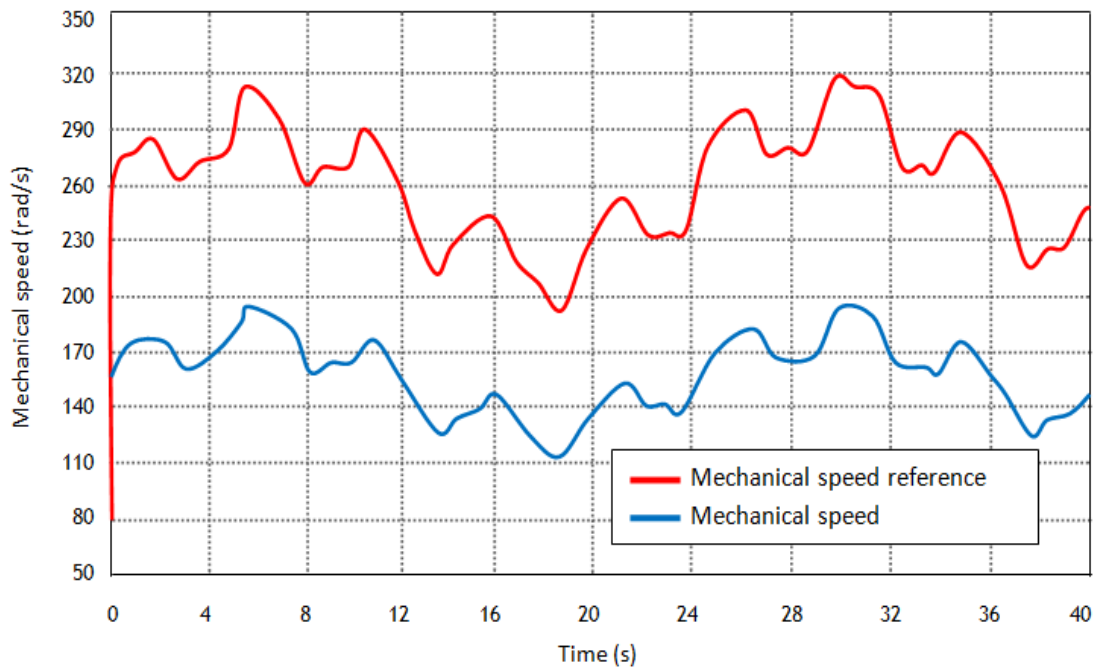


Figure 3. 17 Mechanical speed with speed control

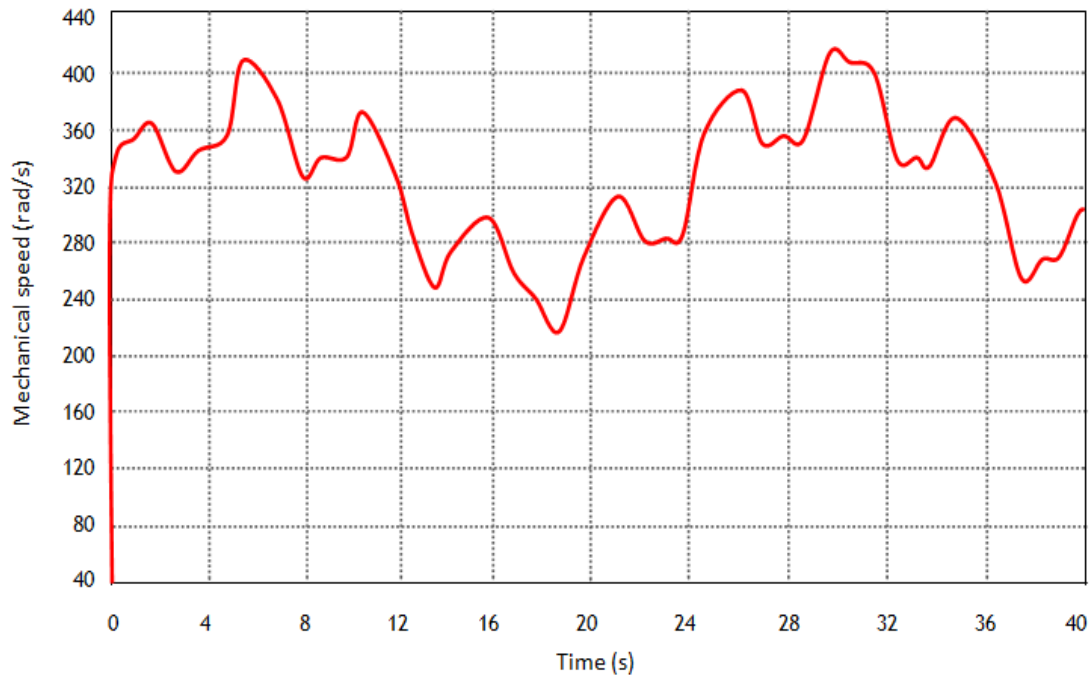


Figure 3.18 Mechanical speed without speed control

Figure (3.19), Shows the active power injected into the net. This one is following the imposed reference power (set as maximum). In figure (3.20), the reactive power also follows its reference (set as zero in our model). That means the unity power factor is successfully obtained.

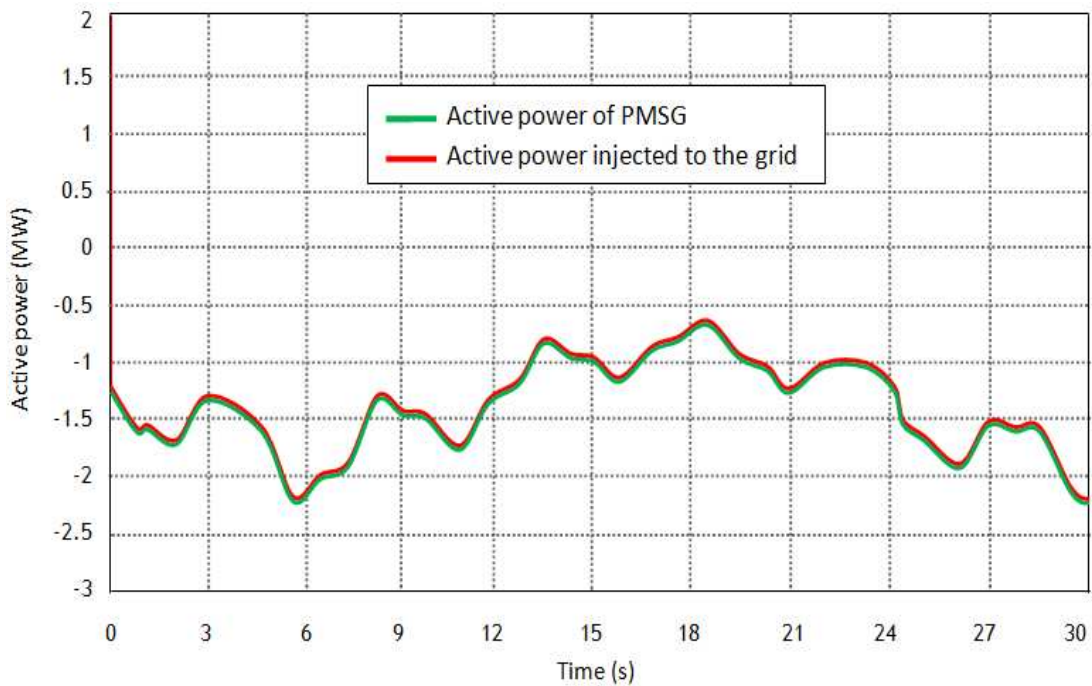


Figure 3.19 Active power

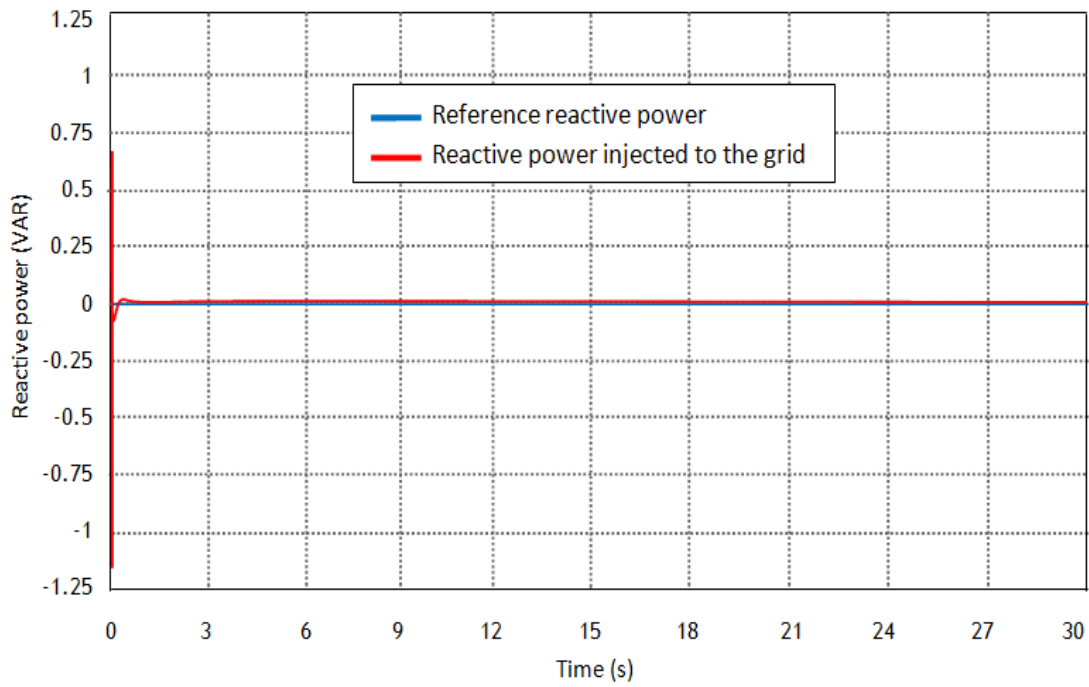
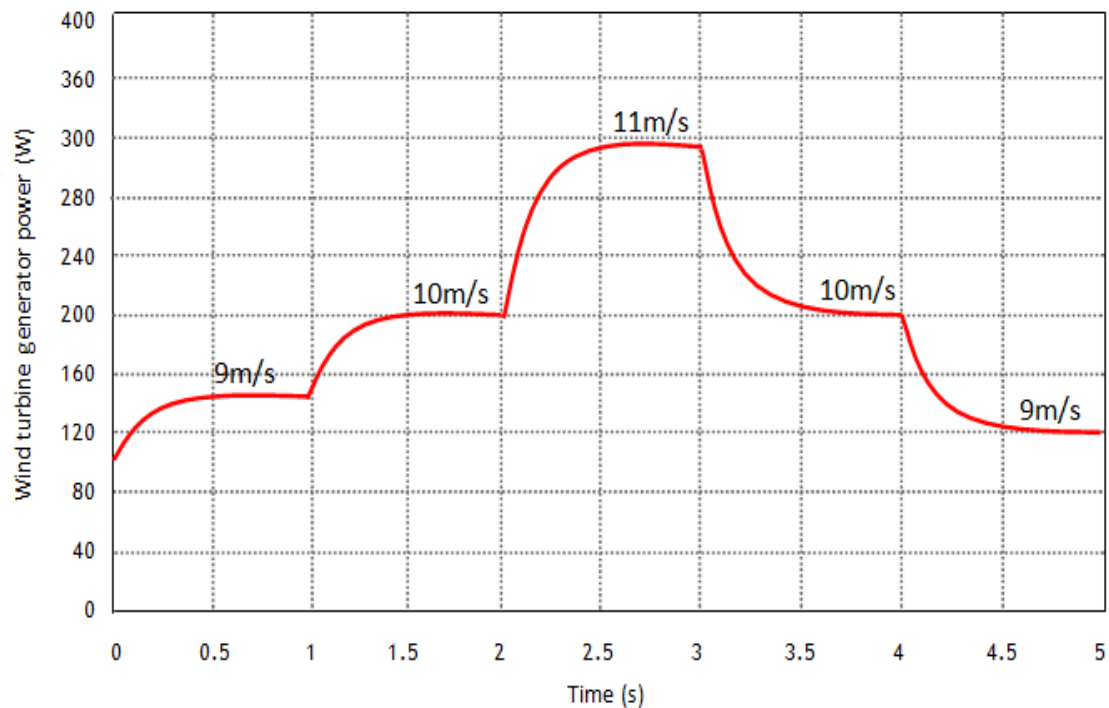
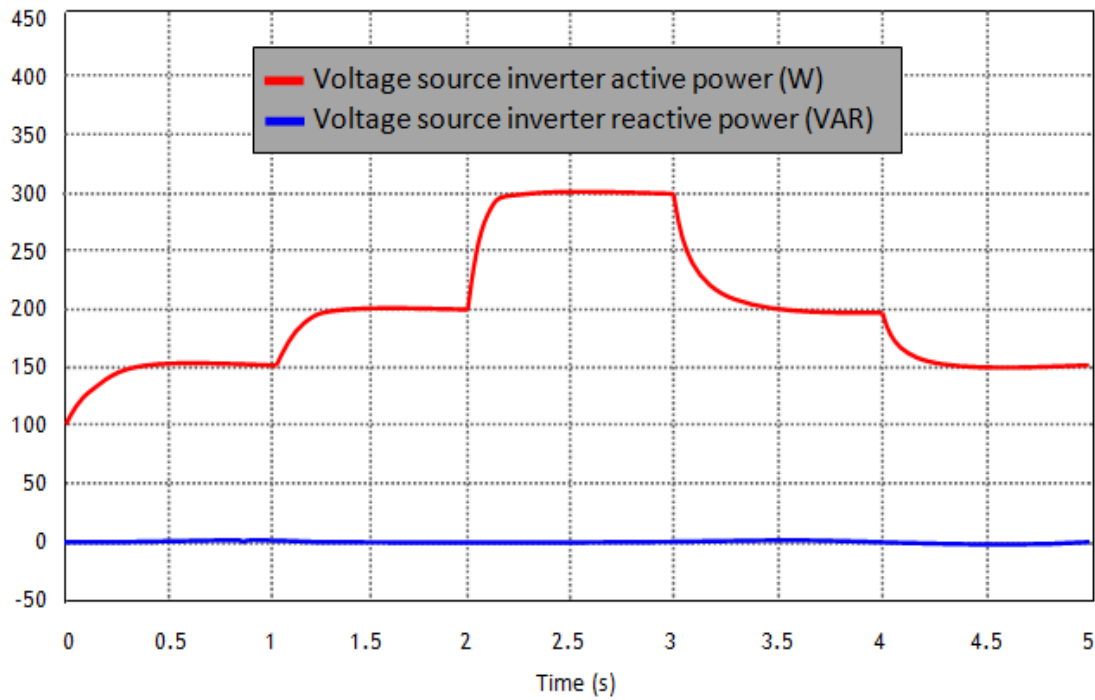


Figure 3. 20 Reactive power

In order to investigate the effectiveness of the proposed models and control algorithms of the three-phase grid-connected, time-discrete dynamic simulations were implemented using Symbols environment.



(a) Wind turbine generator output power with active power control mode

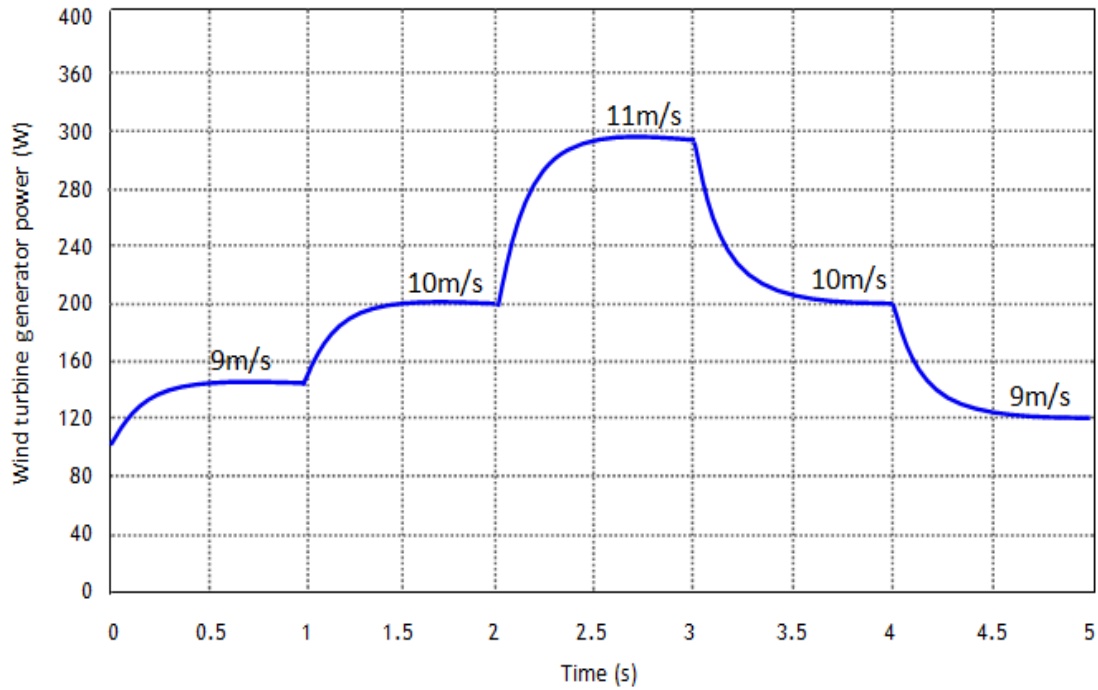


(b) Voltage source inverter output active and reactive power

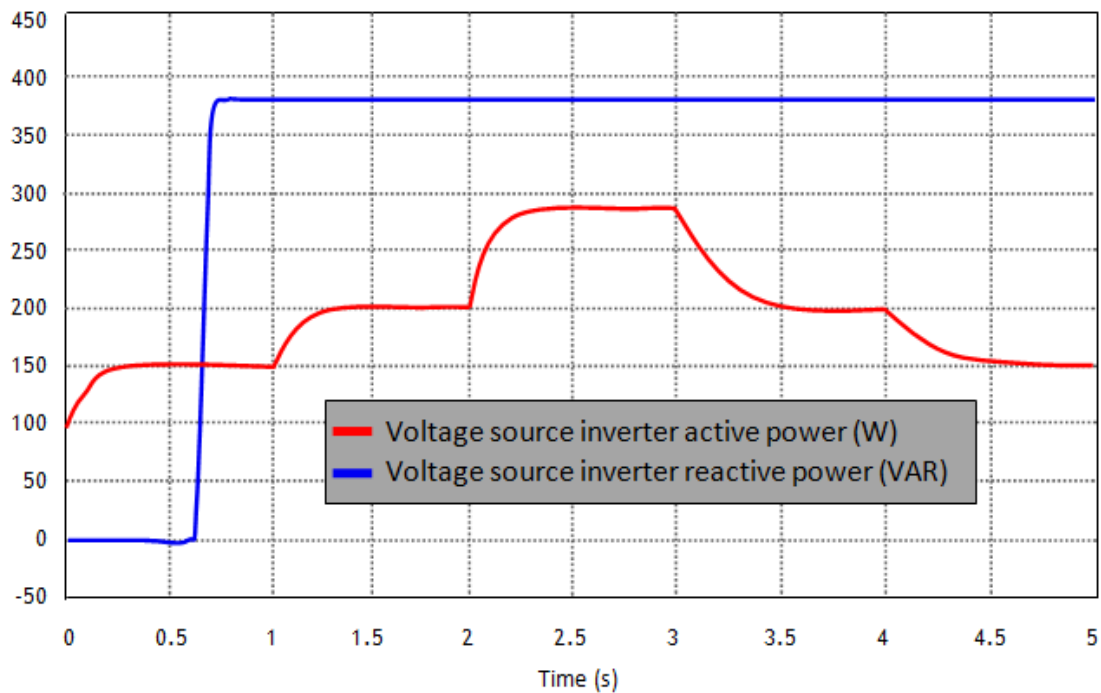
Figure 3. 21 Simulation results for active power control mode

Simulations depicted in figure (3.21) show the case with only active power exchange with the utility grid, for a typical 400W three-bladed horizontal-axis wind turbine generator connected to a 380 V electric system. The wind speed varies in steps every 1 s as described in the figure, producing proportional changes in the maximum power drawn from the wind energy conversion systems with a settling time of almost 0.6 s. As can be observed, the bond graph method proves to be accurate in following the MPP of the wind energy conversion systems, for an optimum duty cycle perturbation step in accordance with the chopper dynamics.

Simulations of figure (3.22) show the case with active and reactive power exchange with the utility grid, i.e. the active power control mode is activated all the time while the voltage control mode is activated at $t=0.6$ s. As can be observed, all the active power generated by the wind turbine generator is injected into the electric grid, except losses. These losses are increased with the injection of reactive power, causing a slightly lower exchange of active power than the previous simulation case. The injection of reactive power allows continuously controlling the magnitude of the instantaneous voltage at the power conditioning system at the set reference voltage.



(a) Wind turbine generator output power with bond graph control method



(b) Voltage source inverter output active and reactive power

Figure 3. 22 Simulation results for active power control mode and voltage control mode

In the case with no BG-MPPT algorithm, the DC-DC converters are operated at fixed duty cycles and the power output is shown in red dashed line. As can be easily derived from figure (3.23), during the wind speed changes, the generator output tracks the corresponding maximum power very successfully with just small delays in the dynamic response. In the case

of operating the WECS with no MPP control, i.e. at a near fixed voltage and consequently fixed rotor speed, the output power drawn from the wind turbine generator is almost 20 % lower.

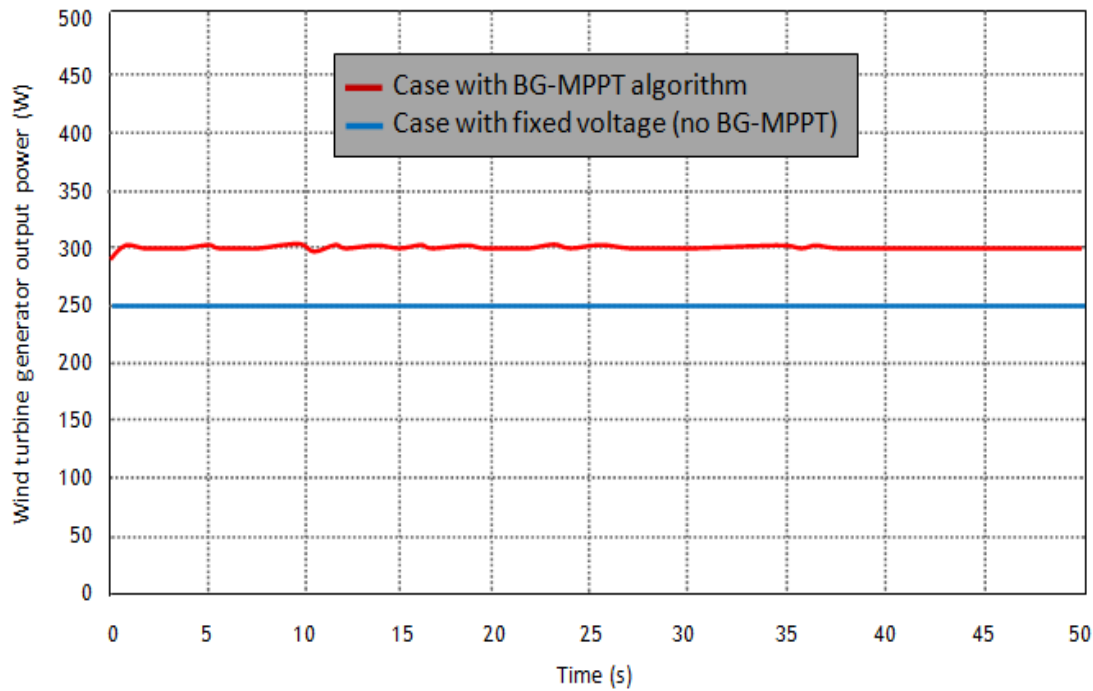


Figure 3. 23 Simulation results of the proposed BG-MPPT algorithm

3.7. CONCLUSION

The objective of this chapter is to show that the bond graph rest on solid mathematical bases which make it possible to consider applications on a large scale, in particular in modeling. If the resolution of complicated problems always requires and will still require very a long time, much of work and a wide range of knowledge in statistics, treatment of the signal, automatic,... it is not doubtful that the bond graph can reduce considerably the task of the engineers by allowing an effective and generic approach nonlinear problems

In this chapter, we developed a model of the wind system starting from the modeling of each principal component of the system: wind, the turbine, voltage source inverter and the synchronous generator with permanent magnet. A realization is elaborate under Symbols software. The obtained simulation results demonstrate the robustness of the control device whose objective is to maximize energy captured from the wind turbine for each wind speed and the control of the active power and reactive one injected into the grid via converters.

CHAPTER 4: Modeling and simulation of photovoltaic system

This chapter explores its potential by undertaking the analysis, modeling and design of a photovoltaic system, application in water pumping. Another point developed in this work presents the optimization of a photovoltaic (PV) water pumping system using maximum power point tracking technique (MPPT). The presented MPPT technique is used in photovoltaic water pumping system in order to increasing its efficiency. A buck-boost chopper allows an adaptation interface between the panel and the battery checked by a tracking mechanism known as the MPPT (Maximum Power Point Tracking). A new algorithm is presented to control a maximum power point tracker MPPT through a bond graph. From the chemical reactions in the batteries to the control laws of the power electronics structures, a bond graph model is proposed for every single part of the system. The model is used in simulations and the results compared to actual measurements. The model is used in simulations and the results compared to actual measurements, showing an accuracy of nearly 99%.

4.1. INTRODUCTION

Considering the preoccupation with an exhaustion of the known world reserves (oil, coal, gas, etc), the economic crises (blaze of the prices of oil), the accidents of the nuclear power stations such as those of Three Mile Island (the USA, 1979) of Chernobyl (the USSR, 1986) or of Fukushima (the Japon, 11 March 2011), the preoccupation with a pollution, the need unceasingly growing in energy, all these prospects reinforced the interest of general public towards renewable energies, in particular the photovoltaic energy, which is essential like one of the sources of the renewable energies most promising [125].

Photovoltaic PV systems provides a viable means of power generation for applications like powering residential appliances, telecommunications, refrigeration, water pumping (particularly in agricultural irrigation). Photovoltaic-power generation is reliable, involves no moving parts, and operation and maintenance costs are very low. These systems operate silently and create no atmospheric pollution. Their only major handicap is that they have a high capital cost [126]. However with the continuous decrease of the cost of solar cells, there is an increasing interest in photovoltaic (PV) system applications.

Today, the use of photovoltaic energy for the water pumping is an incipient technology characterized by costs gradually in fall. Since the first installations at the end of the Seventies, the systems of solar pumping had a great part in the projects of solar energy application and they belong nowadays to the most significant applications of photovoltaic energy. This can be mainly allotted to the fact that it is not economically feasible to connect such distant sites to the electrical supply network [127].

A pumping solar system constitutes following principal elements: photovoltaic panels with their accessories, the electric engine of drive, the pump, and the system of distribution including the drain and storage.

An overall explanation about how the photovoltaic water pumping system works was reviewed. A sit was mentioned before the system has two general models: AC and DC. Since the PV system has been invented most of the researches had focused on the DC motors or direct-couple photovoltaic and their functions [128].

It is in this context that we proposed in our previous works to apply the bond graph approach [129], [130] in the field of renewable energy, where it induces a universal spirit, founded on the analogy and the duality, which makes it possible to establish the object model, not only starting from the physical observation, but also starting from a purely functional definition. The model is a tool of knowledge representation, but also a tool for synthesis of control laws.

4.2. PROPOSED SYSTEM

Figure (4.1) show a stand-alone photovoltaic centralized system utilized to provide energy for residences sited at remote locations, far from grid distribution lines. These systems are composed of a single array of photovoltaic panels, implemented in series and/or parallel connection depending on the power of the system. While using buck-boost DC/DC converters with bond graph MPPT for PV array to extract the maximum available power from them. The

battery which is of lead-acid type is used to store the energy, to regulate the DC-Bus voltage through a reversible current DC/DC converter and to supply the load in the stand-alone case when low solar radiation conditions.

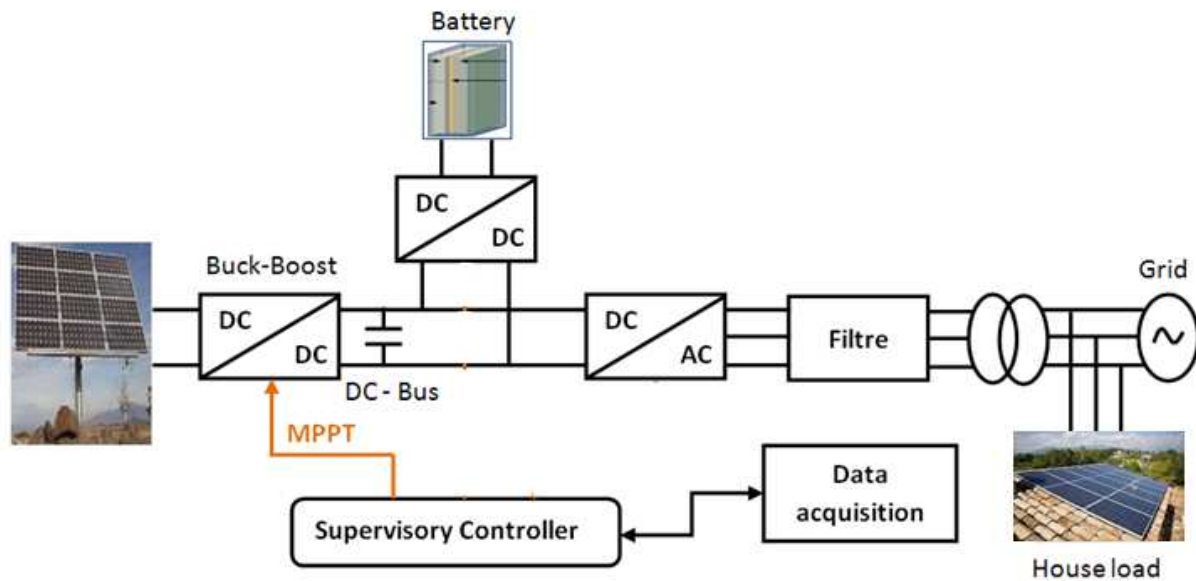


Figure 4. 1 Proposed configuration

The energy produced for PV source is transferred from the DC-Bus to the house load through a DC/AC inverter controlled and filtered by an LC filter, while the excess power feeds the utility grid. Based on the data acquisition (Temperature, Irradiance, DC-Bus voltage...etc) the Supervisory Controller send the commands to the different converters in order to optimize and control the energy.

4.3. PHOTOVOLTAIC SYSTEM MODELING

The modeling and simulation of photovoltaic system have made a great transition and form an important part of power generation in this present age. PV systems' modeling however is quite complex. In literature, several computational methods are proposed by several researchers [121] - [133] for modeling the different components of stand-alone PV systems. Although some of these methods are impractical, complicated and require high computational effort, and some of these modeling was limited to simulation of photovoltaic module characteristics. Other methods are based on software simulation using readymade programs like PSpice, Matlab-Simulink and Labview [134] - [136].

Automatic data acquisition systems are currently used for both monitoring the system performance and control of its operation. The obtained information can be used to evaluate the plant efficiency during long periods and to optimize future systems in terms of performance and reliability. These systems are based on the use of micro-controller and microprocessor for PV applications [137]. Artificial intelligence techniques are becoming useful as alternate approaches to conventional techniques or as components of integrated systems. These methods used to model PV arrays, to estimate the maximum power point tracker and to predict the produced energy from the system [138]. Recently, interest was given to the modeling and simulation of the whole PV system based on bond graph [139], [141].

4.3.1. PHOTOVOLTAIC GENERATOR MODELING

Several models of solar cell exist to calculate their electric characteristics [142] - [145]. To improve the accuracy, model parameters such as irradiance correction factor and Temperature coefficient of a series resistance are discussed in [146]. All these models have the disadvantage that required parameters are not published in standard data sheets. A Photovoltaic system directly converts sunlight into electricity. The basic device of a PV system is the photovoltaic cell; they may be grouped to form panels or arrays [147], [148]. This model is the most classical one found in the literature [149] and involves: a current generator for modeling the incident luminous flux, two diodes for the cell polarization phenomena, and two resistors for the losses (figure 4.2). For the bond graph representation, the PV generator is then modeled by a flow source $Sf = I_{ph}$ in parallel with two resistors R_{sh1} and R_{sh2} , the whole followed by a serial resistance R_s [150] - [152]. The PV diode bond graph representation is a non-linear resistor R_{diode} (figure 4.3).

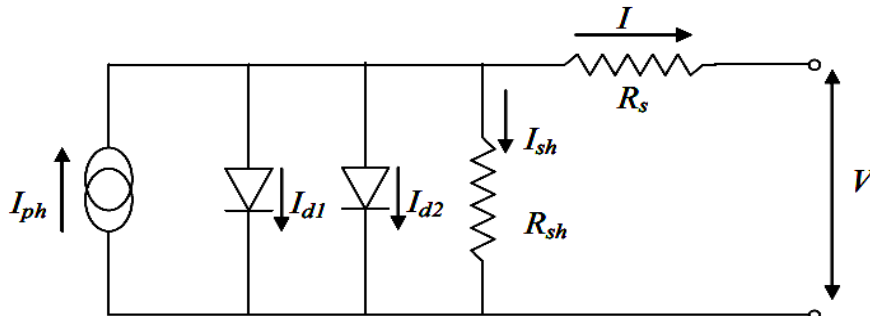


Figure 4. 2 Equivalent electrical circuit of a cell

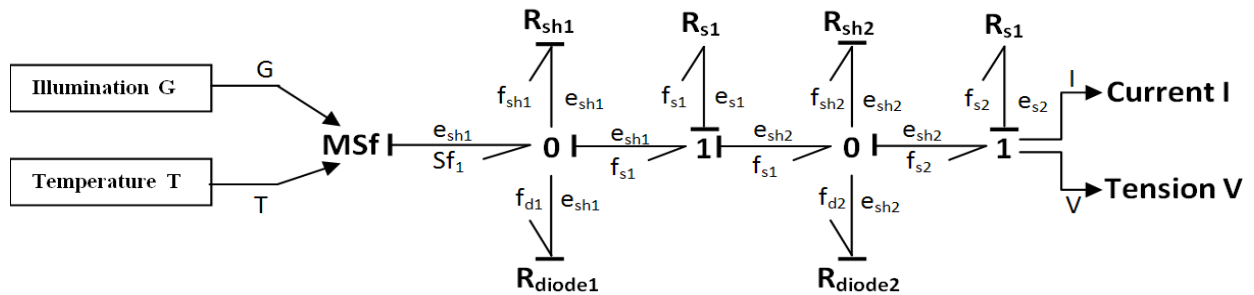


Figure 4. 3 PV Bond graph model with two diodes

Table 4. 1 Parameters of the PV module BP Solar SX 150S

Electrical Characteristics	Value
Maximum Power (P_{max})	150W
Voltage at P_{max} (V_{mp})	34.5V
Current at P_{max} (I_{mp})	4.35A
Open-circuit voltage (V_{oc})	43.5V
Short-circuit current (I_{sc})	4.75A
Temperature coefficient of I_{sc}	$0.065 \pm 0.015\% / ^\circ C$
Temperature coefficient of V_{oc}	$-160 \pm 20 \text{ mV} / ^\circ C$
Power temperature coefficient	$-0.5 \pm 0.05 \% / ^\circ C$
NOCT	$47 \pm 2 ^\circ C$

BP Solar SX 150S PV module is chosen for our application. The module is made of 72 multi-crystalline silicon solar cells in series and provides 150W of nominal maximum power. Table 1 shows its electrical specification.

In order to characterize the solar cell, we used the model presented to provide the values of the tension V , of the current I and of the generated power produces P .

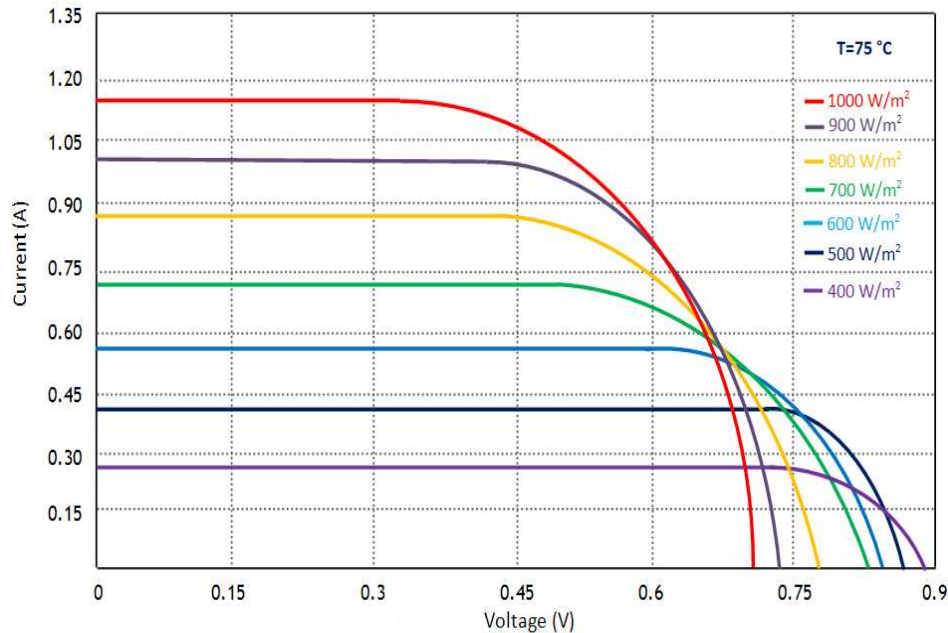


Figure 4. 4 (I-V) characteristic for various illuminations

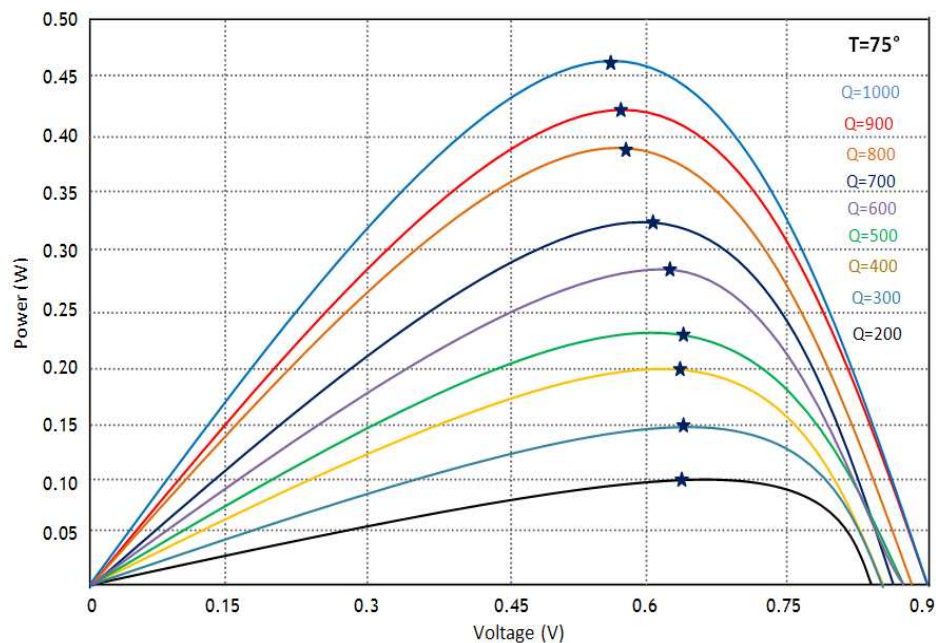


Figure 4. 5 (P-V) characteristic for various illuminations

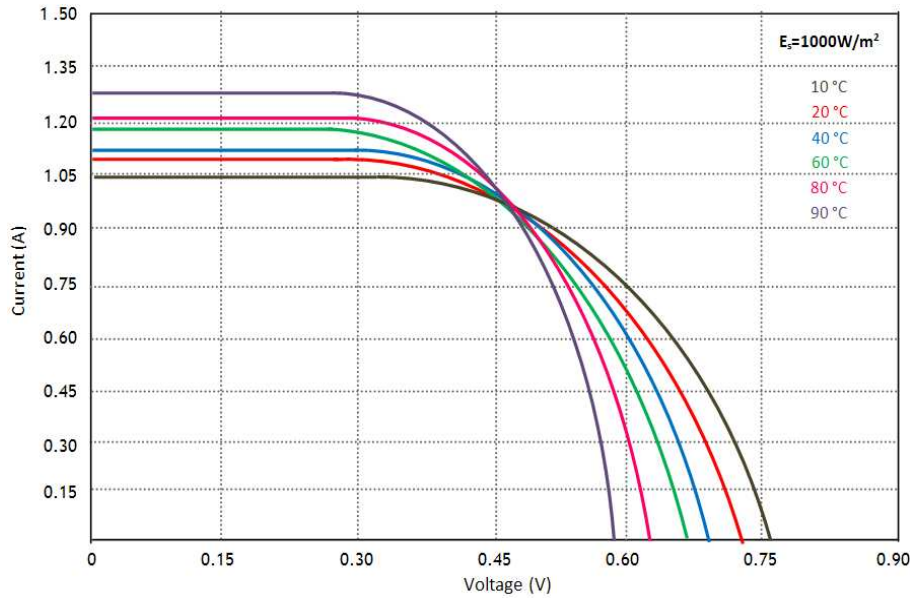


Figure 4. 6 (I-V) characteristic for the various temperatures

If the temperature of the cell increases, the photo current I_{ph} also increases, this is due mainly to the reduction in the forbidden band dispatcher of material. This increase is about 0.1% by $^{\circ}\text{C}$ the forward current of the junction increases also, but much more quickly and involving a reduction in the open circuit tension of about 2mV by cell. The reduction in the provided power is estimated at approximately 0.5% by $^{\circ}\text{C}$ for a module.

4.3.2. ELECTRICAL ENERGY CONVERTER MODELING

A buck-boost converter provides an output voltage which can be controlled above and below the input voltage level. The output voltage polarity is opposite to that of the input voltage.

Figure (4.7) shows the circuit diagram of a buck-boost converter. This converter either steps up or steps down the input DC voltage fed from the diode rectifier. The converter consists of a DC input voltage source V_i , inductor L , controlled switch K , filter capacitor C and diode D .

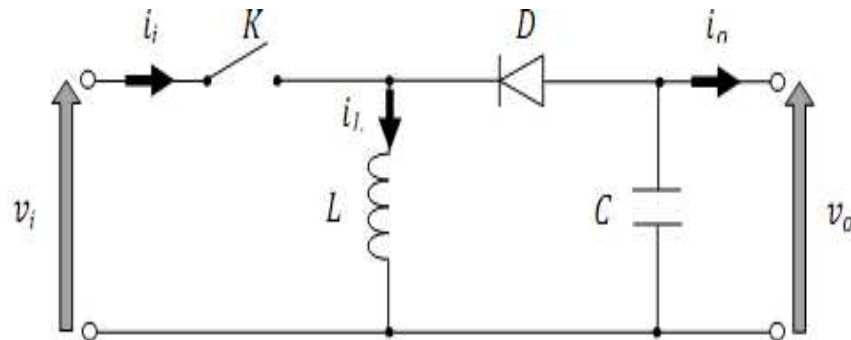


Figure 4. 7 Equivalent circuit of a buck-boost converter

According to the above circuit, we obtain the dynamic equation of the buck-boost converter as follow:

$$\begin{cases} C \frac{\partial v_o}{\partial t} = -di_o(1-d)(i_L - i_o) \\ L \frac{\partial i_L}{\partial t} = -dv_i + (1-d)v_o \\ i_i = di_L \end{cases} \quad (4.1)$$

Where d is the duty ratio of the power switch k ; v_i and v_p are the input and output voltage; i_i , i_o and i_L are the input, output and inductance current, respectively. The bond graph model of the buck-boost is thus given by the figure (4.8).

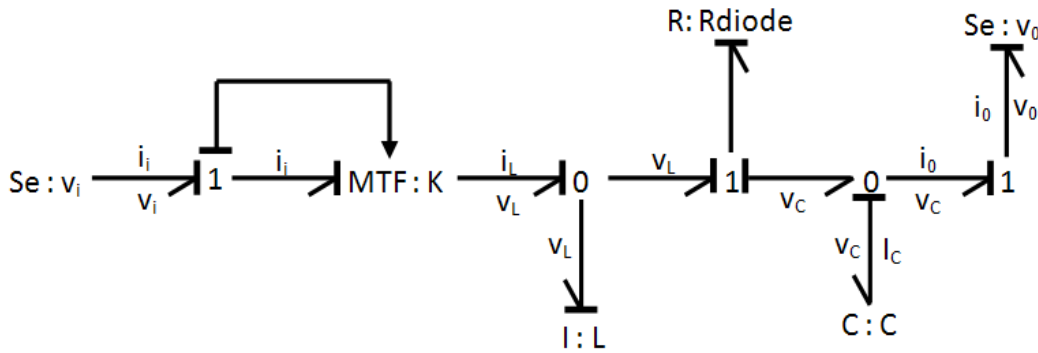


Figure 4. 8 Bond graph model equivalent circuit of buck-boost converter

Reversible current DC/DC converter: to ensure the charge and the discharge of the storage battery, the current must be reversible so that the energy transfer would be in the two directions, from the DC-Bus to the battery and vice versa. For that a Reversible current DC/DC converter is necessary, it's realized by associating a boost chopper and a buck we as shown in figure (4.9).

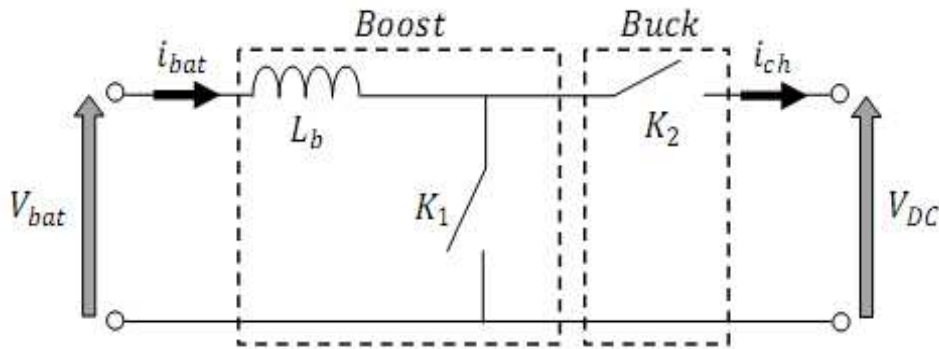


Figure 4. 9 Equivalent circuit of a the reversible current DC/DC converter

The control of the switches k_1 and k_2 is simultaneous with a complementary duty cycles db and $1 - db$, the reversible current DC/DC converter shown in figure (4.9) is described the equation (4.2), as:

$$\frac{\partial i_{bat}}{\partial t} = \frac{1}{L} (d_b V_{DC} - V_{bat}) \quad (4.2)$$

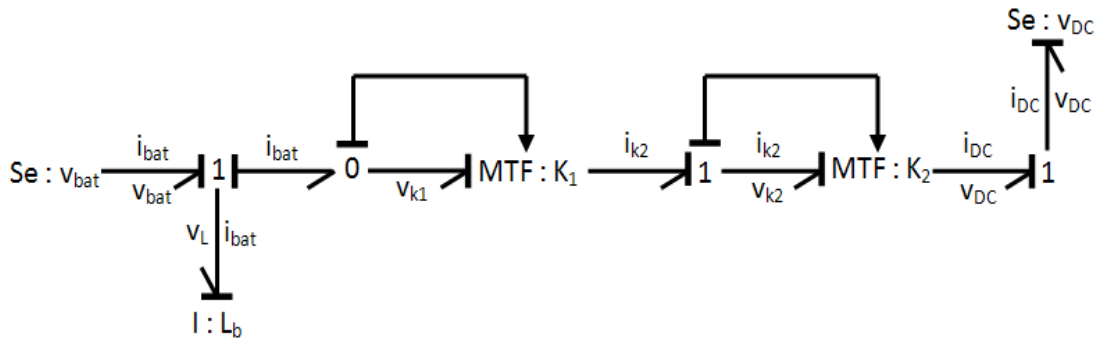


Figure 4. 10 Bond graph model of equivalent circuit of a the reversible current DC/DC converter

4.3.3. BATTERY MODELING

It is characterized by a representation with not dissociated electrodes. The mechanism of operation of this accumulator is particular: It rests on an exchange of ions lithium inserted in the porous electrodes without formation of new products, which implies a weak modification structural of the accumulator [153] - [154]. Each electrode can thus be regarded as a lithium tank modeled by a capacity C. The free energy $DG=DH-T.DS$ of this reaction of exchange transformed into electric power determines the tension between electrodes, but number X of moles of electrons exchanged per mole of lithium is not known a priori and can be fractional.

The equations of the reaction are as follows:



We call $x.Li_{total}$ the total quantity of lithium at the beginning in the negative electrode. At the moment t, xli is the quantity of lithium in the positive electrode (cathode), whereas the quantity of lithium in the other electrode (anode) is $x.Li_{total} - x.Li$. We can then use only one capacity which simply will take care and discharge according to the quantity from lithium transferred from one electrode to the other and thus will elaborate the global model with not dissociated electrodes, i.e. with only one virtual equivalent electrode [155].

The global model is represented by the figure (4.11), we finds in the heart of the model, the ideal electrochemical conversion represented by an element TF and the various phenomena of the double layer of activation and transport of matter which are also described in a similar way, which gives an effective generic character on this model. We notes the representation of the diffusion, also called relieving, by a R-C ensemble implying a slow return to balance under the effect of the internal gradients of lithium concentration in the electrolyte and the electrodes. We also note the bonds towards the thermal part of the model which is not presented here [156].

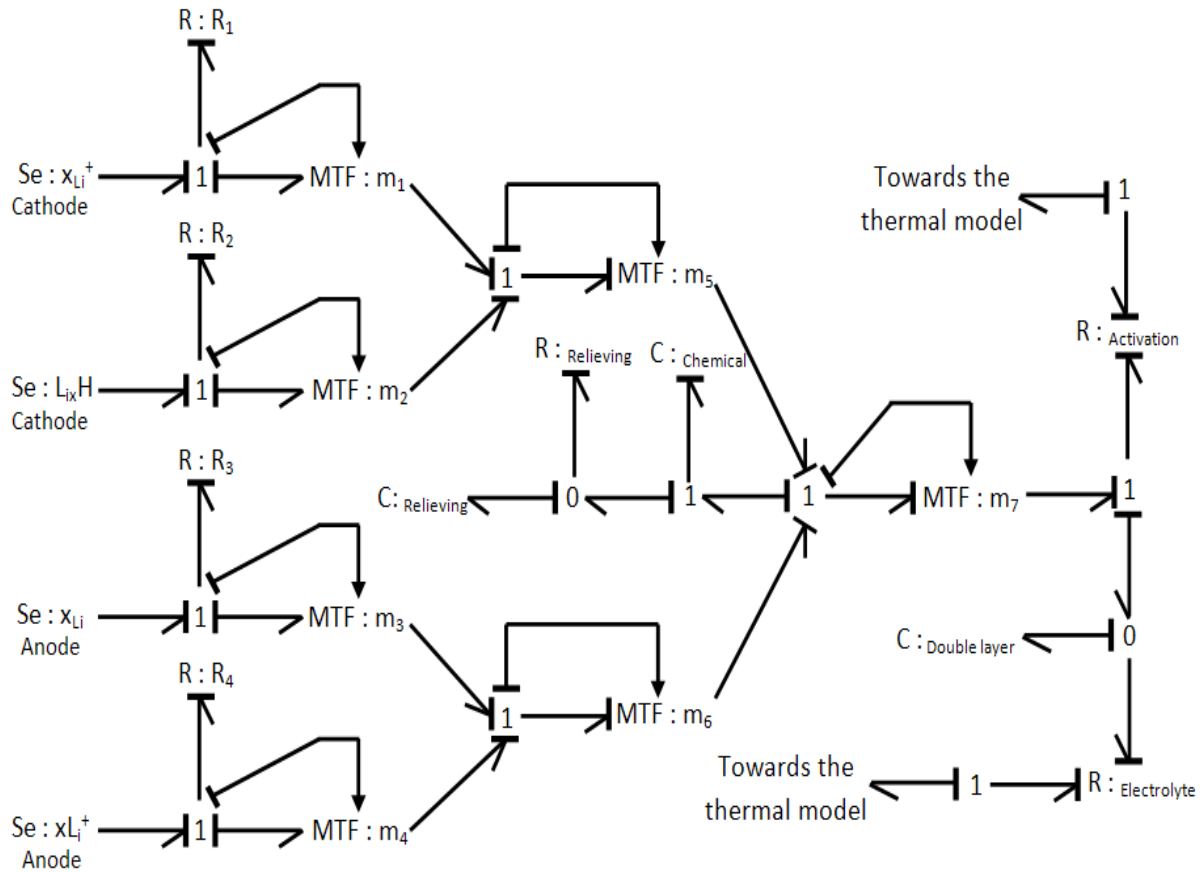


Figure 4. 11 Bond graph model of a lithium battery

4.3.3.1. INFLUENCE TEMPERATURE ON THE STORAGE CAPACITY

The battery temperature enormously influences the behavior of the characteristic basic operation of the storage system and in particular on its storage capacity.

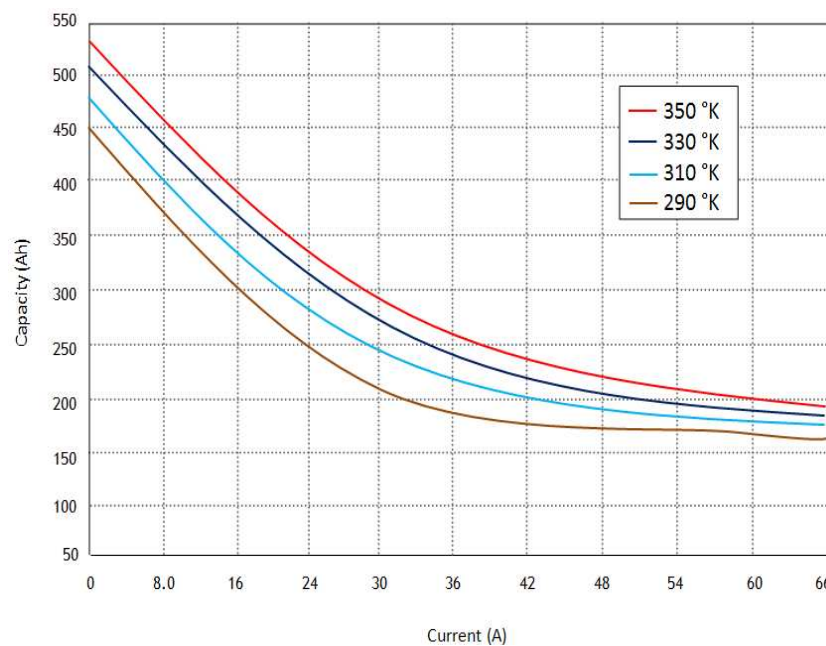


Figure 4. 12 Influence temperature on the storage capacity

Figure (4.12) shows that the increase in the temperature is accompanied by an increase moderated with that of the batteries storage capacity.

If this temperature drops up to the value $T=40\text{ }^{\circ}\text{C}$, then the capacity is close to 440 Ah for a minimum. It can reach values maximum of 45 C for a value which approaches the 500 Ah. We consider that the manufacturers of these battery elements took account of the various climates where this equipment would be installed in order to have best performances, under operation.

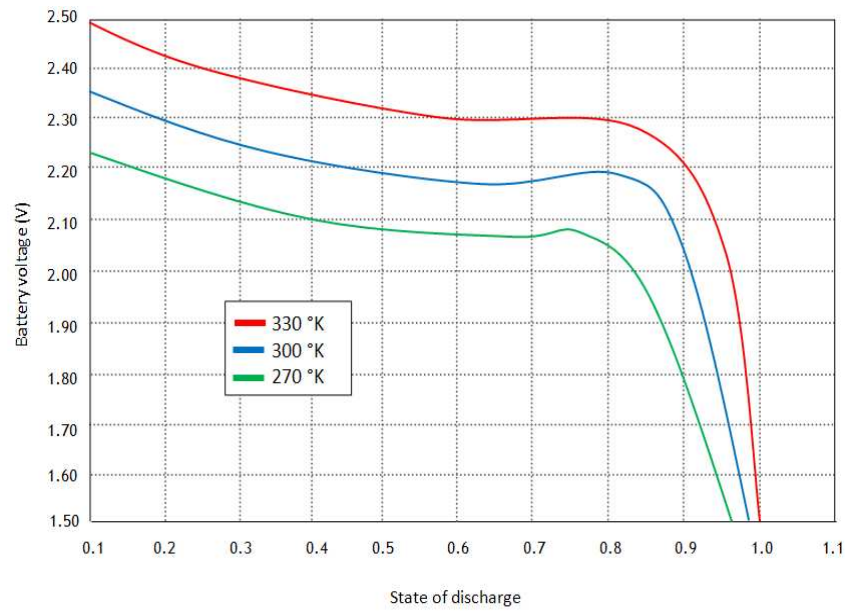


Figure 4. 13 Impact of temperature

4.3.3.2. INFLUENCE TEMPERATURE ON THE STATE OF THE BATTERIES

The mode of load (or discharge) is used to express the relationship between the rated capacity of a battery and the charging current (or discharge).

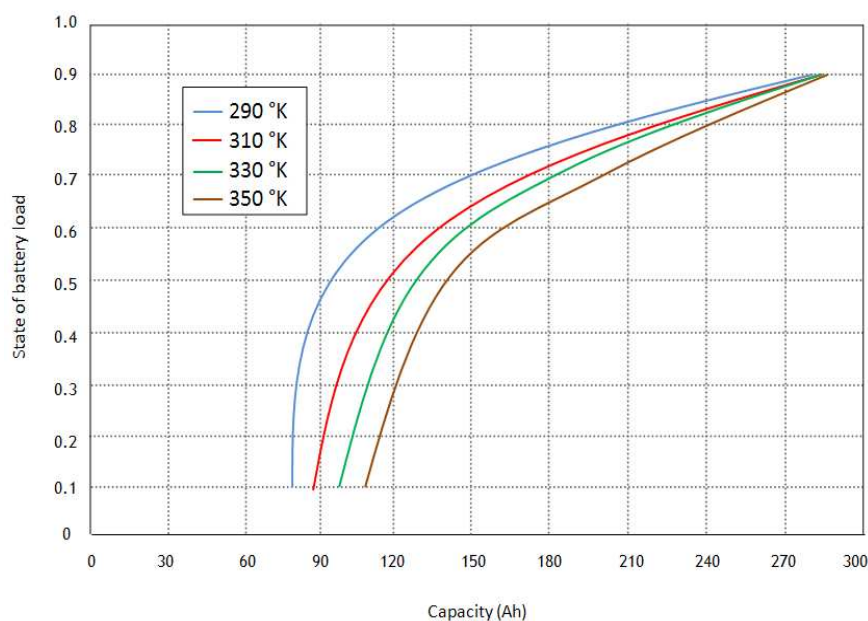


Figure 4. 14 Influence temperature on the batteries load

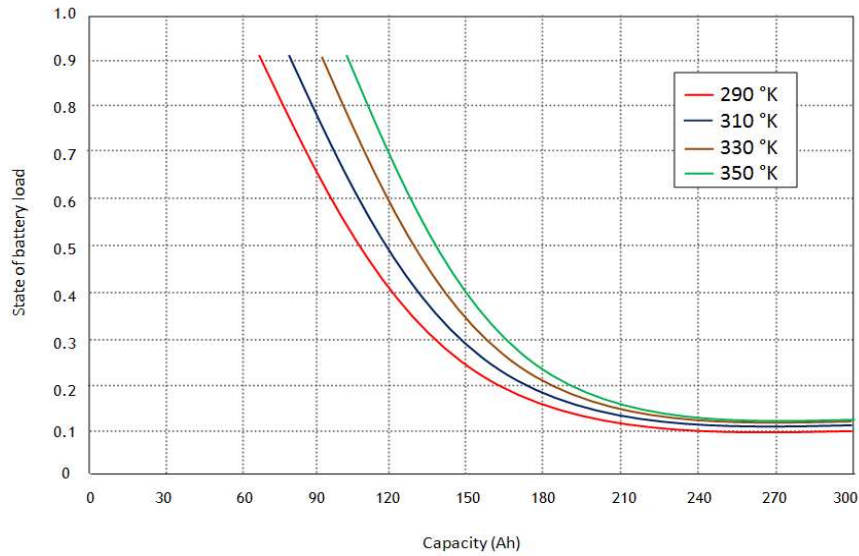


Figure 4. 15 Influence temperature on the batteries discharge

Figures (4.14) and (4.15) represent the state of load according to the capacity, either in load and or in discharge. In the loading case, the temperature and the state of discharge follow the same evolution. On the other hand in the case of the discharge, the temperature while decreasing is accompanied by a discharge state which increases. These states can lead within the framework of the batteries maintenance, with best followed by their state for the studied site and a better optimization.

4.3.3.3. INFLUENCE TIME

To study the influence of time, one seeks to approach with a close management in real time, state of the battery load, which in its turn is determining for the effective exploitation of the storage system.

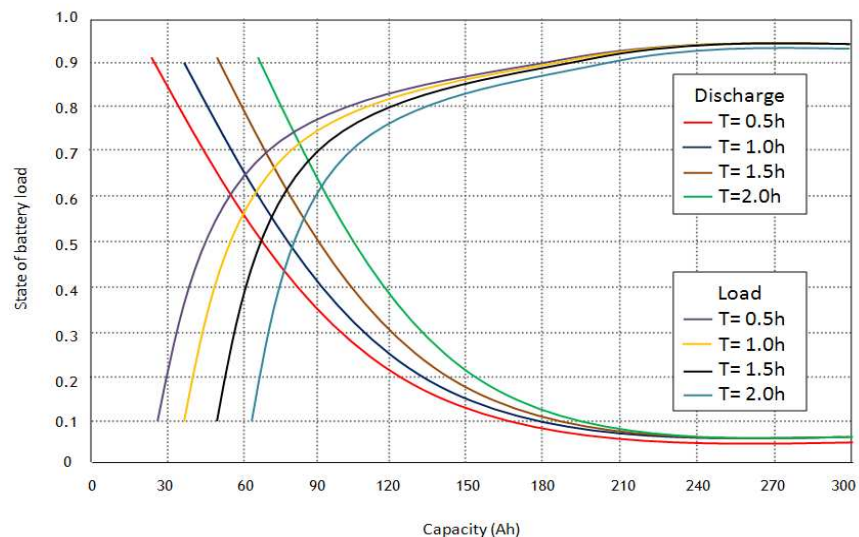


Figure 4. 16 Influence time on the state of the battery

In the loading case, plus the duration of time increases, the batteries load state is below 1. In the case of the discharge, plus the time duration is significant. It is noted that the state of discharge reaches its maximum value for a long duration discharge.

4.3.3.4. THE INTERNAL RESISTANCE

Figure (4.17) represents the evolution of internal resistance for our accumulator

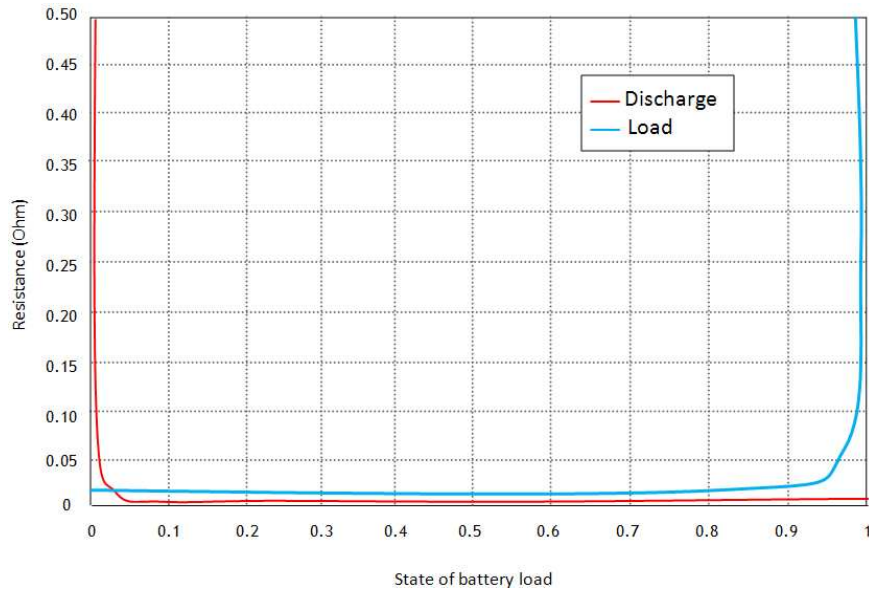


Figure 4. 17 Resistance of the battery (load, discharge)

The internal resistance of the battery thus depends on the load state. Its value becomes all the more significant when the full load is reached. In reasoning with constant current, there will all the more be losses that the full load is reached and that the output in load of the accumulator would be thus weaker in this zone (figure 4.17, load).

4.4. BOND GRAPH MPPT

In the literatures, many MPPT techniques have been proposed to achieve the goal for solar and wind energy conversion systems, including the voltage feedback method (VFM), power feedback method (PFM), perturb and observe method (POM), and incremental conductance method (ICM) [157] - [162]. They are based on load line adjustment under varying atmospheric and load conditions.

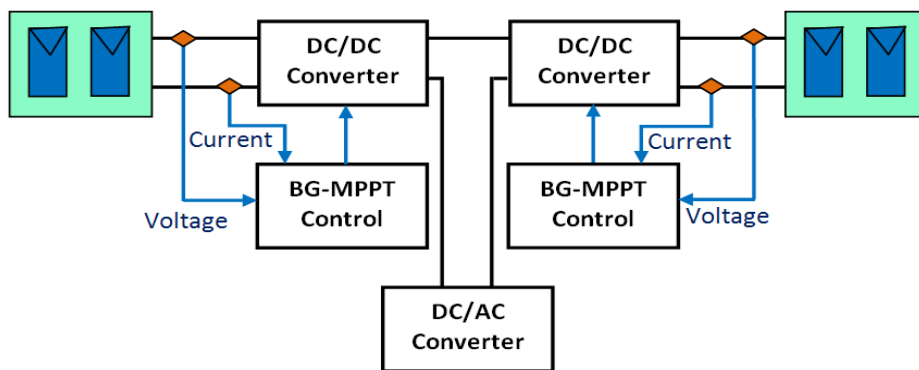


Figure 4. 18 Connection of PV modules in a distributed BG-MPPT photovoltaic

This work proposes maximum photovoltaic power tracking (MPPT) for the photovoltaic (PV) array using the bond graph approach (BG-MPPT). Since the PV array has low conversion efficiency, and the output power of PV array depends on the operation

environments, such as various solar radiation, environment temperature, and weather conditions. Maximum charging power can be increased to a battery using a MPPT algorithm.

The energy conversion of the absorbed solar light and cell temperature is directly transferred to the semiconductor, but electricity conduction has anomalous diffusion phenomena in inhomogeneous material. BG-MPPT can provide a dynamic graphical model to describe non-linear characteristics. For a small-scale PV conversion system, the proposed method is validated by simulation with different operation environments

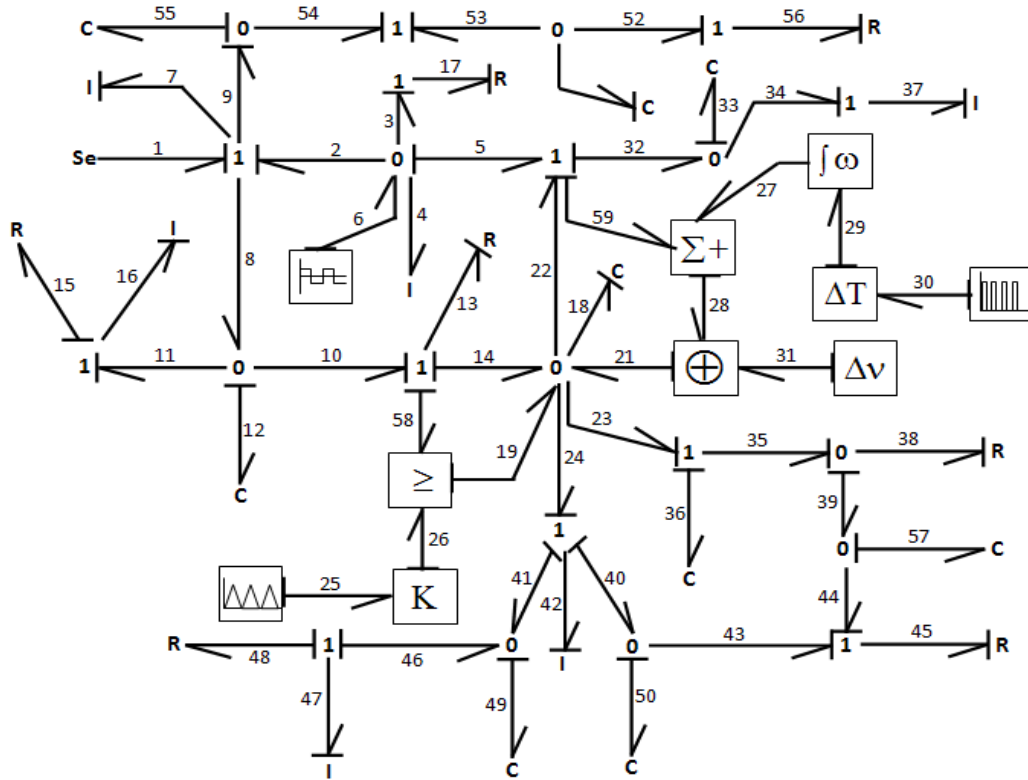


Figure 4. 19 Bond graph controller

The bond graph control requires that variable used in describing the control rules has to be expressed in elements of bond graph (elements R, I and C) with bond graph junction (0, 1 and TF) [140]. In this work, the bond graph control MPPT method has two input variables, namely $\Delta P(k)$ and $\Delta U(k)$, at a sampling instant k . The output variable is $\Delta U(k+1)$, which is voltage's increase of PV array at next sampling instant $k+1$. The variable $\Delta P(k)$ and $\Delta U(k)$ are expressed as follows:

$$\Delta P(k) = P(k) - P(k-1) \quad (4.6)$$

$$\Delta U(k) = U(k) - U(k-1) \quad (4.7)$$

Where $P(k)$ and $U(k)$ are the power and voltage of PV array, respectively. So, $\Delta P(k)$ and $\Delta U(k)$ are zero at the maximum power point of a PV array.

In figure (4.19), e25, SE1 and e6 are respectively the converter switching duty ratio, the demanded cell voltage and the actual cell voltage in the j^{th} MPPT cycle, where $j = k, k+1$.

The MPPT controller calculates the new cell voltage set point based on the converter switching duty ratios and the measured cell voltages in the past and at present. The lead compensator (e27) forces the cell voltage to follow the demanded cell voltage signal. In the practical design of the control software, the threshold ε , which is a small positive number close to zero, is used to determine whether the MPP has been reached and e26 is used as a positive increment in the demanded cell voltage. The variable δj can be defined as:

$$\delta 1 = e_2 + e_4 + e_5 - e_3 \quad (4.8)$$

$$\delta 2 = e_{31} - e_{28} \quad (4.9)$$

$$\delta 3 = e_{31} + (e_2 + e_4 + e_5 - e_3) \frac{\delta 2}{\delta 1} \quad (4.10)$$

When $|\delta 1| > \varepsilon$, the MPPT controller can be simplified as:

$$SE_1(k+1) = SE_1(k) + e20, \delta 3 > \varepsilon 3 \quad (4.11)$$

$$SE_1(k+1) = SE_1(k), |\delta 3| > \varepsilon 3 \quad (4.12)$$

$$SE_1(k+1) = SE_1(k) - e20, \delta 3 < -\varepsilon 3 \quad (4.13)$$

When $|\delta 1| < \varepsilon 1$, the MPPT controller can be simplified as:

$$SE_1(k+1) = SE_1(k) + e20, \delta 2 > \varepsilon 2 \quad (4.14)$$

$$SE_1(k+1) = SE_1(k), |\delta 2| < \varepsilon 2 \quad (4.15)$$

$$SE_1(k+1) = SE_1(k) - e20, \delta 2 < -\varepsilon 2 \quad (4.16)$$

The flowchart of our proposed MPPT controller is present in the following figure

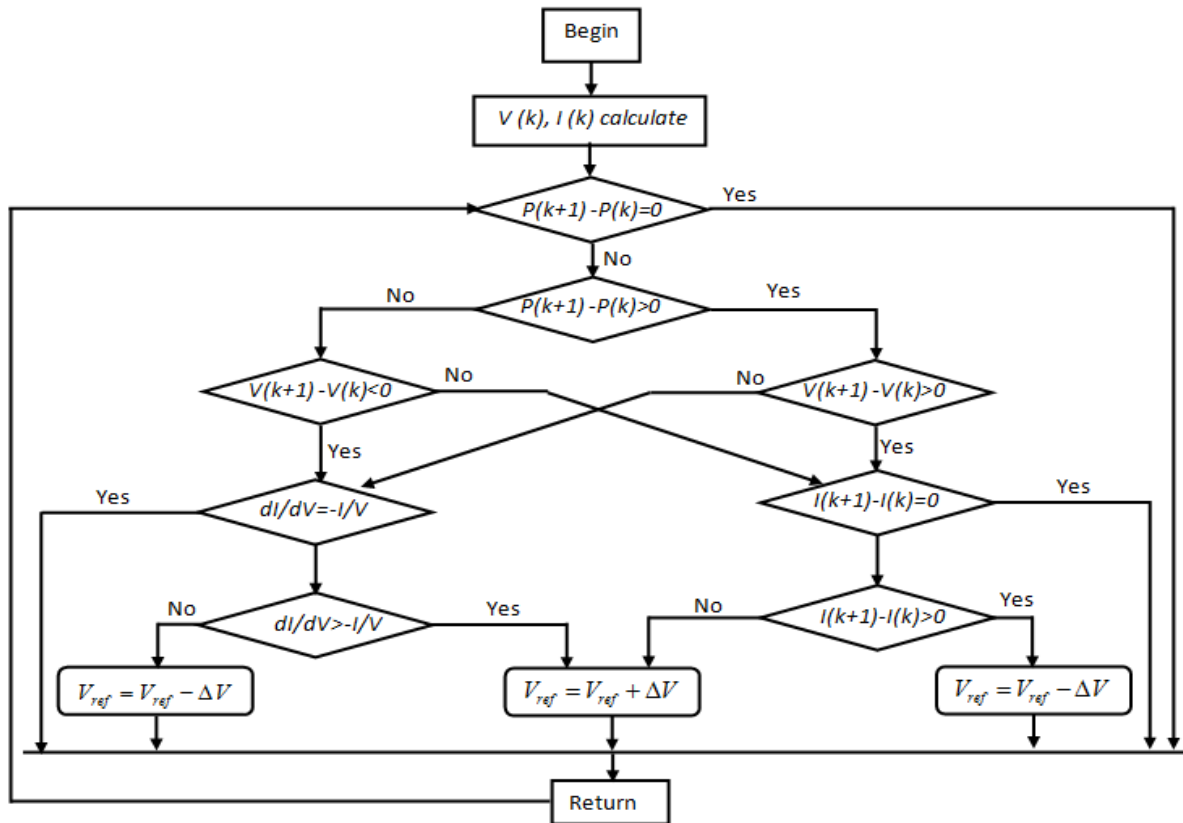


Figure 4. 20 Flowchart of BG-MPPT controller

Modeling is to build the bond graph model into the software. In our case we have chosen the SYMBOLS (SYstem Modeling by BOND graph Language and Simulation) that is powerful for research. SYMBOLS is object oriented hierarchical hybrid modeling, simulation and control analysis software. It allows users to create models using bond graph, block-diagram and equation models. Differential causalities and algebraic loops are solved out using its powerful symbolic solution engine.

The proposed algorithm was validated by means of simulations performed with the Symbols code in two different situations, the former assuming the presence of the proposed control system and the latter its absence. In both cases the module output power was evaluated in order to perform a subsequent comparison. During the tests, the PV module was submitted to constant temperature and solar radiation conditions.

In the former test the DC/DC converter was connected between the module and the load without controller; in this case the PV module was connected to generic impedance. Under these conditions, the output power is always less than 135 W. In the latter test the same conditions were maintained, but the MPPT control was properly inserted. In this case the output power is always greater than 135 W, as can be seen in figure (4.21).

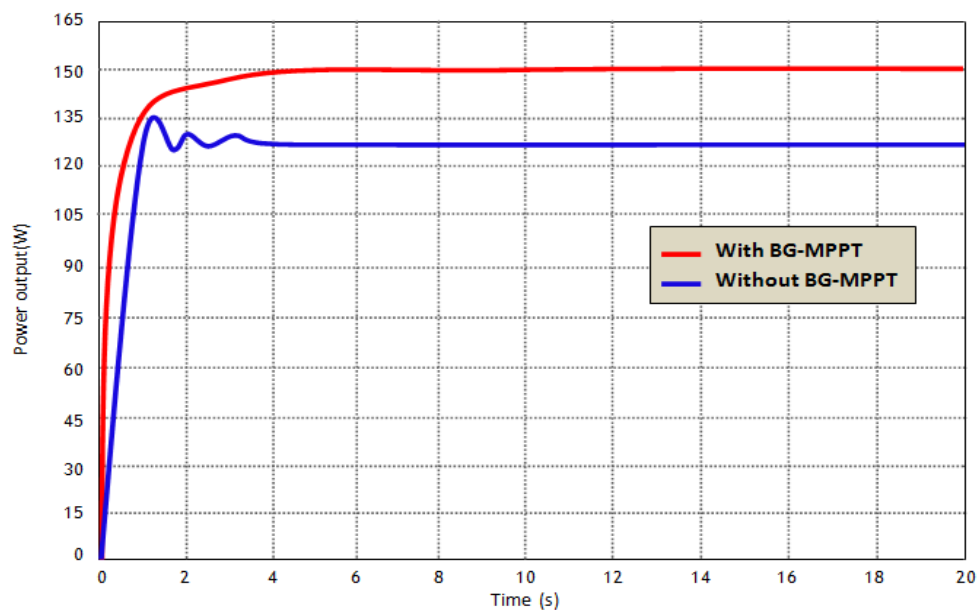


Figure 4. 21 Output power with/without MPPT

According to the results, the voltage across the PV generator when operating with MPPT is stable. This is contrary to the case of a functioning without MPPT; the PV generator is operating at its maximum power, and MPPT could estimate the optimal tension quickly. Also, we find a huge error at the outset because the solar generator was initially in open circuit while the initial release of MPPT was nil.

In the programming method, program is a set of commands that every line of its commands is called statement. Any command line in program includes combination of logical and mathematical operation. Some of the symbols are shown in next figure

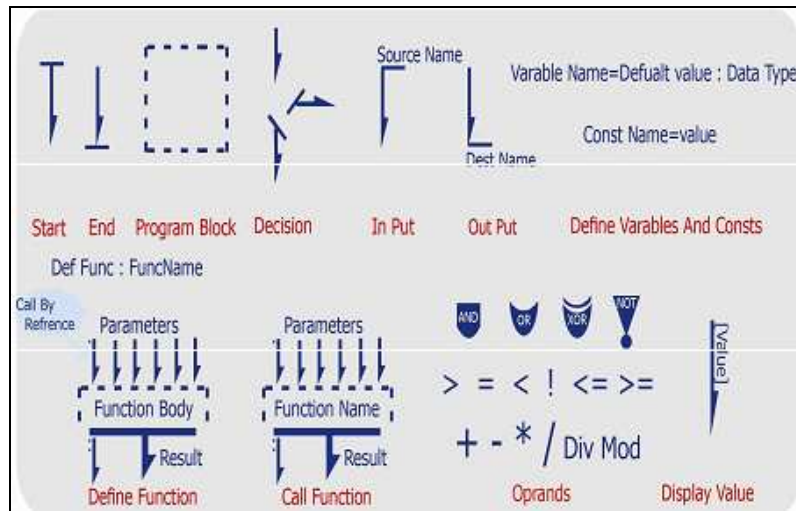


Figure 4.22 The symbols of bond graph programming

A prototype MPPT system (figure 4.23) has been developed using the described method and tested in the laboratory.

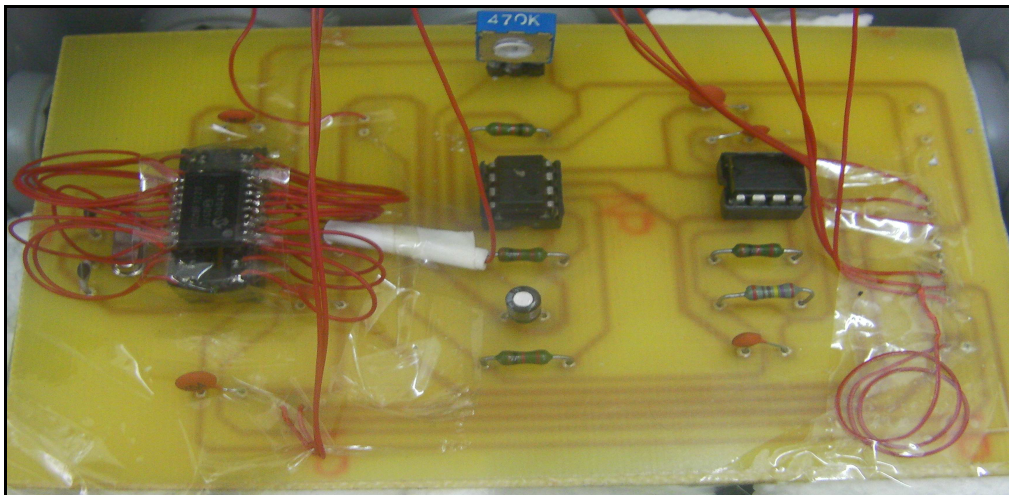


Figure 4.23 Prototype bond graph MPPT system

4.5. BOND GRAPH MODELING OF PHOTOVOLTAIC PUMPING SYSTEM

Algeria has one of the fastest growing economies in Africa. However, its remotely isolated rural areas pose problems to rural energy management and development. Development of renewable energy sources, therefore, has a vast potential in Algeria. Thus, for rural applications, various established models [163], sizing techniques [164], and optimization methods [165] of photovoltaic water pumping system (PWPS) have been reported in the literature. Solar energy, with excellent sun shine of over 2000 h per year, is paramount for these applications. Photovoltaic water pumping systems are particularly suitable for water supply in remote areas where no electricity supply is available. The pumped water can be used in many applications such as domestic use, water for irrigation and village water supplies.

For stand-alone solar water pumping systems, there has been a significant amount of research performed. A model was developed for simulating solar-PV water pumping systems [166], and this reference also includes an excellent literature review of past research on solar water pumping systems.

Other researches published in photovoltaic water pumping were interested essentially either in water pump modeling and control [167] – [169] or in overall system modeling and simulation [170] so as to bring a contribution to the study of the behaviors of the photovoltaic generators and converters used to feed an asynchronous machine actuating a centrifugal pump [171].

The mathematical models of the inverter and the motor pump set are described in a great number of research papers. Thus, we can quote [172] – [173]. These models describe the characteristic of each component of the pumping subsystem as the inverter, the motor or the pump. But these models do not give a direct relationship between the operating electrical power of the pumping subsystem and the water flow rate of the pump. In this chapter, we use a graphical (bond graph) model which directly links the output water flow rate versus the input operating electric power and total head.

The main objective of the present work is to develop a general method for the evaluation of the long term performance of a photovoltaic powered water pumping system with maximum power point tracker. In the present work, the variations in system performance resulting from solar source variations have been taken into consideration to establish a model for the complete system. Also, a bond graph model is developed for each component to simulate the performance of the different components of the PV pumping system.

In this context, emphasis is given in the present study in order first to simulate the operational modes of a typical PVPS and secondly to provide an analysis based on experimental measurements, concerning the flow water, the rotation speed of motor, the voltage and the current of the PV generator.

4.5.1. SYSTEM DESCRIPTION

The use of solar energy for the water pumping is particularly well adapted to the rural zones where water is cruelly lacking. The increasing demand for water in these zones makes that a paramount interest is related to the use of the solar modules like energy source to the power packs. A pumping system can be distinguished according to its electric motor type and water storage equipment. Most systems are either equipped with a DC current motor or a synchronous one.

The structure studied in this work is given by figure (4.24). It is composed of an array of photovoltaic panels, implemented in series and/or parallel connection depending on the power of the system. The Buck-Boost DC/DC converters use bond graph MPPT for PV array to extract the maximum available power from them. The battery which is of Lead-Acid type is used to store the energy, to regulate the DC-Bus voltage through a reversible current DC/DC converter and to supply the motor-pump when low solar radiation conditions.

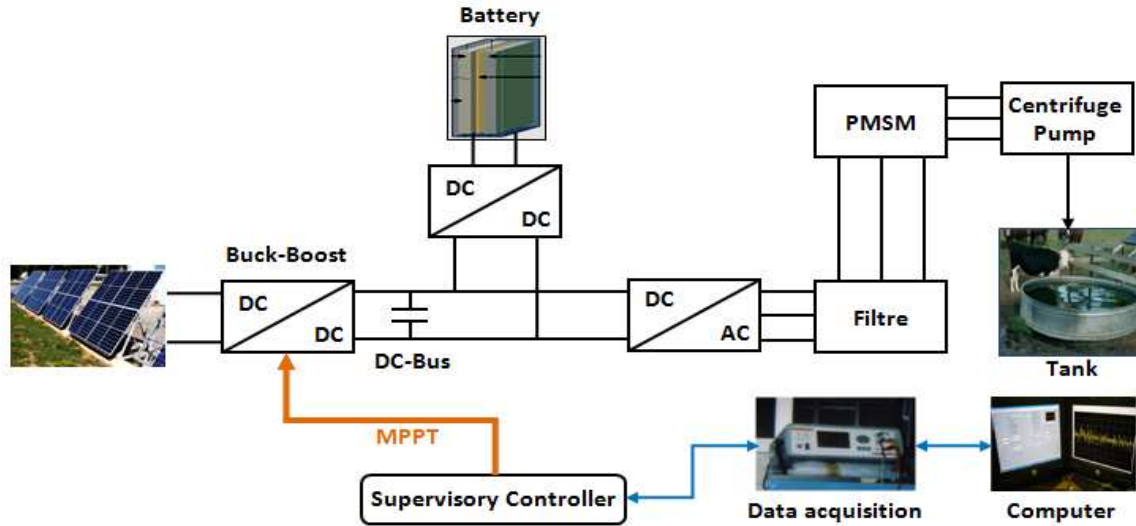


Figure 4. 24 Pumping photovoltaic system

4.5.2. EXPERIMENTAL STUDY

To study the climate of an area, several data are necessary like humidity, the sun, snow and others. The knowledge of these factors is required because it affects the human activities and their consumption of production and energy of practices in particular. Setif is located at north East of Algeria, more precision, to 5.30 East (longitude) and 35.92 of north (latitude). The altitude of this city changes between 895m to 1265m; average altitude is approximately 1080 m, it is approximately 110 kilometers from the sea. It is located in a zone characterized by cold winter with the average temperatures around 8°C and of relative humidity testing 63% and hot summer with the average temperatures approximately of 40°C and can reach 46°C and more, with a relative humidity around 38%. The model of Capderou [174], used for the atlas of Algeria, models the distribution of the direct, diffuse and total radiation throughout the year with small errors [175].

The PVP sizing model is done through the following steps: determination of total head, determination of hydraulic energy, determination of electrical energy, determination of available solar energy and finally, determination of electric peak power. The hydraulic energy

per day (Wh/day) is calculated with the formula: $E_H = \frac{\rho \cdot g \cdot Q \cdot H_T}{3600} = C_H \cdot Q \cdot H_T$ Where: H_T is the total head (m), ρ is the water density (1000 kg/m³), g is the acceleration due to gravity (9.81m/s²) and Q , the amount of water pumped per day (m³/day) [176]. By considering:

$$C_H = \frac{\rho \cdot g}{3600} = \frac{1000 \text{ kg} \cdot \text{m}^{-3} (9.81 \text{ m} \cdot \text{s}^{-2})}{3600 \text{ s} \cdot \text{h}^{-1}} = 2.725 \text{ kg} \cdot \text{s} \cdot \text{h} \cdot \text{m}^{-2} \quad (4.17)$$

The hydraulic energy becomes: $E_H = C_H \cdot Q \cdot H_T$, in our study, the required daily flow will be 11m³ per day. $Q = 11 \text{ m}^3 / \text{day}$

The total head H_T is $H_T = H_s + H + H_D + H_d$, H_s : static head, difference between the surface of the water and the deepest point to which the water must be pumped; H represents the drawdown, the difference between the static and the dynamic level of water; H_D dynamic

head represents the losses through the pipeline; H_d : singular losses (in a specific component)

In our study $H_T=103\text{m}$ so $E_H = C_H \cdot Q \cdot H_T = (2.725) \cdot (11) \cdot (103) = 3087.425 \text{ Wh}$. Thus, the average daily load is 3087.425 watt-hours. At 103 volts (nominal operating voltage of the motor), this is equivalent to 29.4 ampere-hours a day. The maximum radiation is lower in the month of December 4.36 hours or 4,36 kWh/m²) and water requirements are a maximum 11m³/day. Assuming losses of 20% due to the temperature and dust, the theoretical sizing of our system will be:

$$W_p = \frac{E_H}{\tau(1-\text{losses})} = \frac{3087.425}{4.36(0.8)} = 885.15 \text{ W}_p \quad (4.18)$$

τ : The pumping time required to meet the daily water needs.

As it has been determined that the operating point of the field would be around 103 volts due to the characteristics of the inverter, the field will consist of 3 panels in series. The generator power is 885.15 W_p, the current will be about 8.7 A. The choice of panel type will determine the number of parallel panels. So, it will take two modules in parallel because the maximum intensity of the module is 4.35 A.

Table 4. 2 Sizing of pumping system

Hydraulic energy (Wh)	Irradiance (Hours)	Losses %	Power (W)	Voltage (V)	Current (A)	Configuration S*P
3087.425	4.5	20	885.15	103	8.7	2*3

The field will have a power of 900 W_p and will consist of 06 panels of 150W_p.

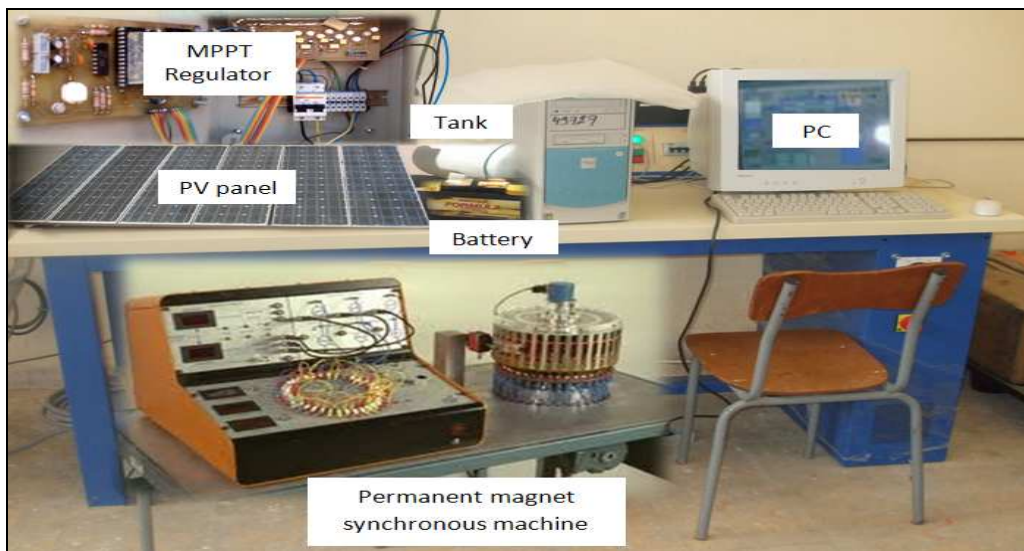


Figure 4. 25 Experimental setup

Figure (4.26) to (4.28) show the important characteristics of the experimental PV pumping system. The maximum pump flow (2.549 l/s), global efficiency (35 %) and PV current (8.593A) are obtained in the midday (figure 4.27.2). For a constant ambient temperature (25°C), the optimal flow rate is obtained for irradiance equal to 1000 W/m², corresponding to a global efficiency equal to 35 %, the terminal voltage of PV generator with

MPPT (1200V) (figure 4.28). These results will be used, in the next section, to validate the simulations made using the proposed bond graph model.

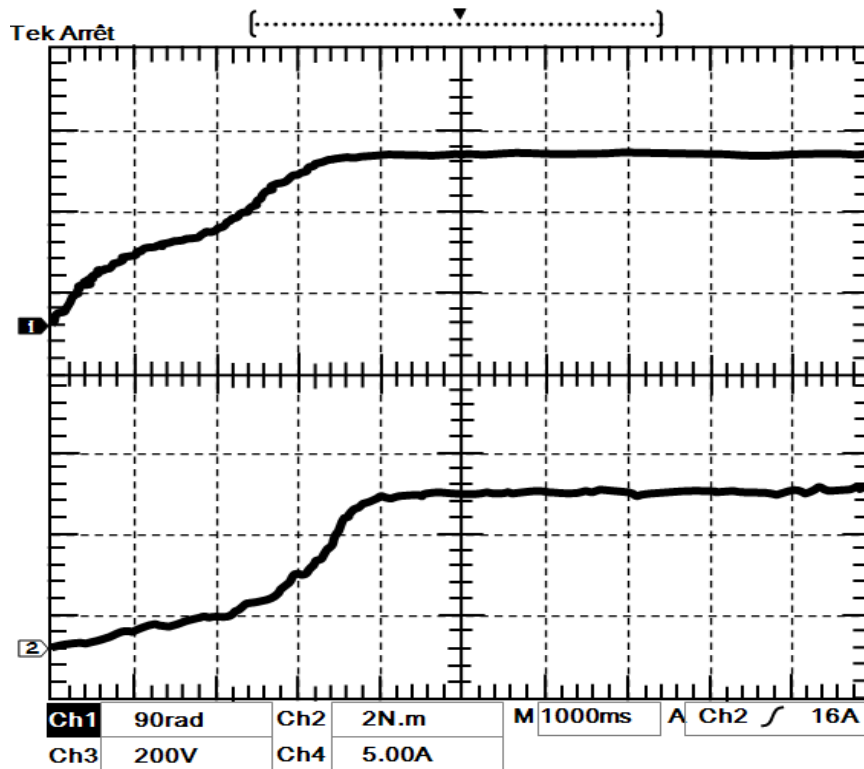


Figure 4. 26 Rotation speed (curve 1; $90\text{rad.s}^{-1}/\text{Div}$ - $1000\text{ms}/\text{Div}$), resistance torque (curve 2; $2\text{ N.m}/\text{Div}$ - $1000\text{ms}/\text{Div}$)

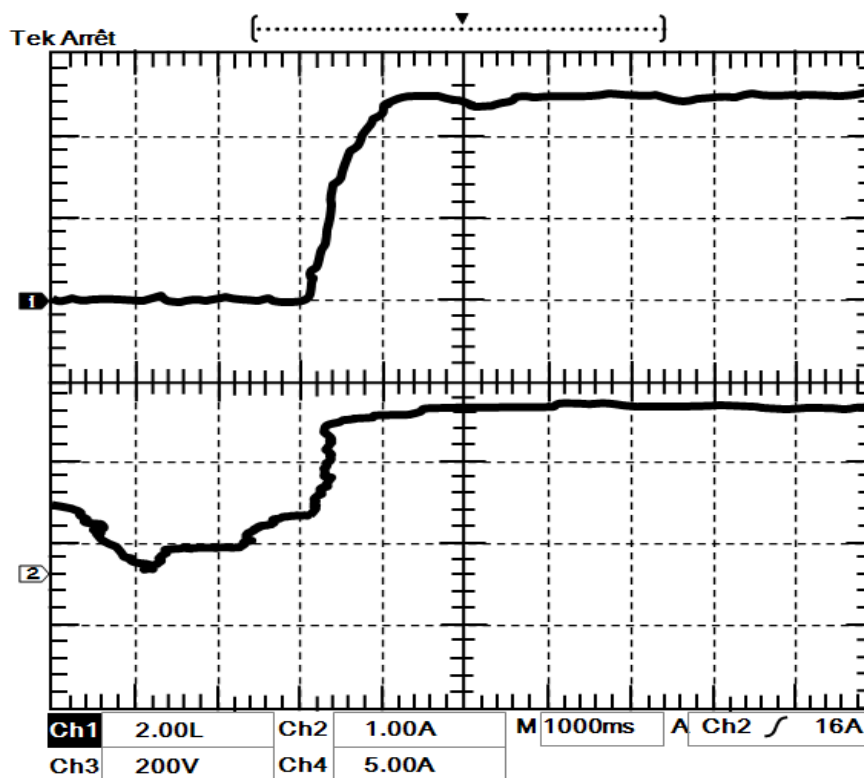


Figure 4. 27 Water flow (curve 1; $2\text{L}/\text{Div}$ - $1000\text{ms}/\text{Div}$), PV generator output current (curve 2; $3.35\text{A}/\text{Div}$ - $1000\text{ms}/\text{Div}$)

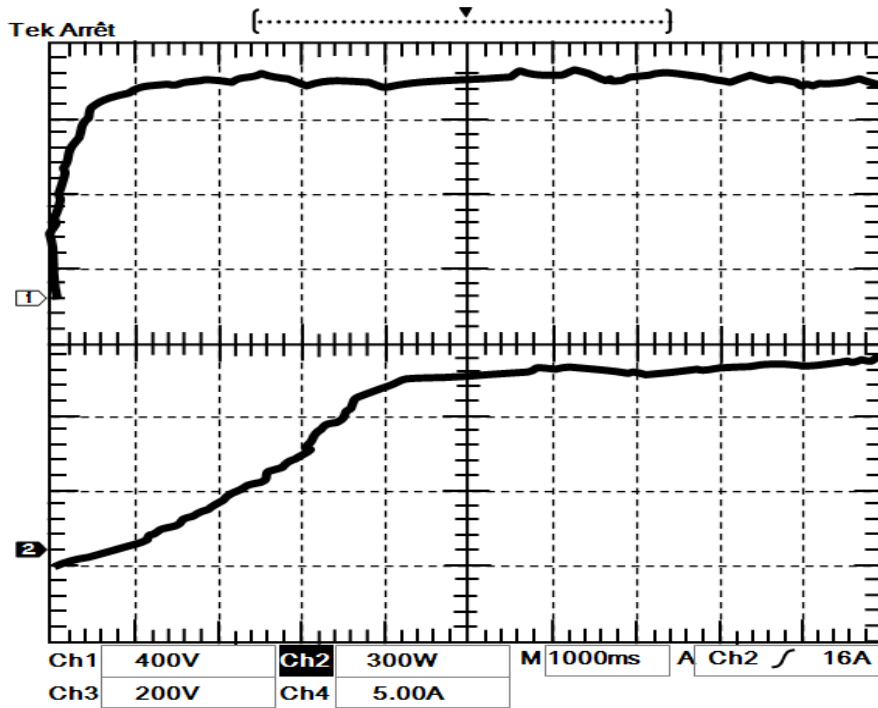


Figure 4.28 Terminal voltage of PV generator (curve 1; 400V/Div-1000ms/Div), PV generator output power (curve 2; 300W/Div -1000ms/Div)

4.5.3. SIMULATION RESULTS

4.5.3.1. ALGORITHM OF THE COUPLING WITH BG-MPPT

The algorithm used in the MPPT simulations is described by the code below.

Begin

1: Write (MS, PMSM, PC, I)

% To introduce the parameters characteristic of the system: module solar, permanent magnet synchronous motor, pump centrifuge, inverter)

2: Read (X_0 , p_0 , α_0 , $\Delta\alpha$)

$P_0 \leftarrow IV$

$\alpha_0 \leftarrow 0$

$\Delta\alpha \leftarrow h$

$x_0 \leftarrow [I; V; \omega]$

% Read the initial conditions of the vector $X_0 = [I \ V \ \omega]^T$, $p_0 = IV$, $\alpha_0 = 0$, $\Delta\alpha = h$

3: Read (E , T)

% Read the illumination E and the temperature T

4: $\alpha_1 \leftarrow \alpha_0 + \Delta\alpha$

5: $V_m \leftarrow \frac{V_p}{(1-\alpha)}$, $I_m \leftarrow (1-\alpha)IP$

$P_1 \leftarrow IV$

$x_1 \leftarrow [I; V; \omega]$

% To solve the preceding equation by bond graph method

6: $\Delta\alpha \leftarrow \alpha_1 + \alpha_0$

$\Delta p \leftarrow p_1 + p_0$

```

7: while ( $|\Delta\alpha| \leq \varepsilon$ ) do
8:   If ( $E > 1000$ ) then
      $\alpha_m \leftarrow \alpha_1$ 
      $p_m \leftarrow p_1$ 
      $Q \leftarrow 0$ 
      $H \leftarrow C_1 \cdot \omega^2 - C_2 \cdot \omega Q - C_3 \cdot Q^2$ 
     % To determine the height of splashing of the pump
9:     If ( $H_1 > H_g$ ) then
       % Determination of the flow of the pump Q
        $H \leftarrow H_g + \Delta H$ 
        $H \leftarrow C_1 \cdot \omega^2 - C_2 \cdot \omega Q - C_3 \cdot Q^2$ 
10:    % To determine the quantity of pumped water
        $q_t \leftarrow 2 \cdot \int_{t_1}^{t_n} Q \cdot dt$ 
       Else
11:     $Q \leftarrow 0$ 
12:    Return step 10
       End if
     Else
13:    To associate the initial condition
14:    Return step 3
       End if
     Else
15:    If ( $\Delta p < 0$ ) then
16:     $\Delta\alpha \leftarrow \frac{\Delta\alpha}{2}$ 
17:     $\alpha_0 \leftarrow \alpha_1$ 
      $p_0 \leftarrow p_1$ 
      $\alpha_1 \leftarrow \alpha_0 - \Delta\alpha$ 
18:    If ( $\Delta\alpha < 0$ ) then
      $\alpha_0 \leftarrow \alpha_1$ 
      $p_0 \leftarrow p_1$ 
      $\alpha_1 \leftarrow \alpha_0 + \Delta\alpha$ 
19:    Return step 5
       End if
     Else
20:    If ( $\Delta\alpha < 0$ ) then
21:     $\alpha_0 \leftarrow \alpha_1$ 
      $p_0 \leftarrow p_1$ 
      $\alpha_1 \leftarrow \alpha_0 - \Delta\alpha$ 
       End if
22:    Return step 7
       End if
     End while
End.

```

The flow chart is illustrated by figure 4.29.

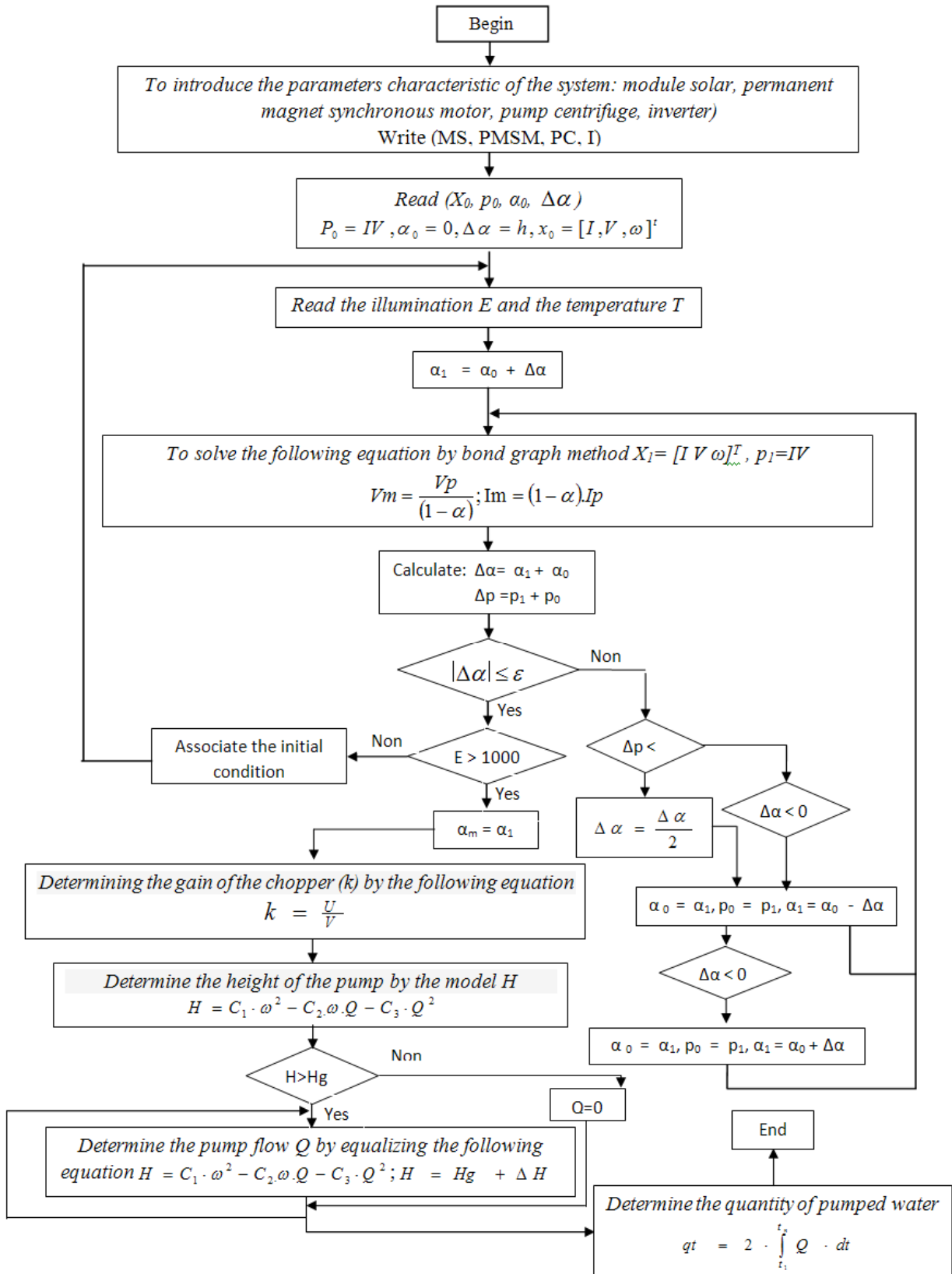


Figure 4. 29 Flow chart of the coupling with BG-MPPT algorithm

4.5.3.2. MPPT COUPLING SIMULATIONS

A prototype MPPT system has been developed using the bond graph method and tested in the laboratory. This method is based in its research of the point of maximum power by permanently adapting the photovoltaic generator to the load of course by the intermediary of a Buck-Boost DC-DC converter whose cyclic ratio is taken as being a parameter of control since it is necessary to follow in a continuous way the optimum of power [177]. The use of a converter DC-DC offered the advantage of increase in tension in front of the reduction in its current (to maintain the conservation of power at its output).

The idea suggested is used to act on the duty cycle of the chopper to ensure the adaptation. To elaborate an algorithm of research of the maximum power by taking account of these variations, the gradient of the entry power $g = \partial p / \partial \alpha$ is regarded as signal of variation ε . In optimal operation the variation ε must tend to be cancelled so that the extreme can be reached. The research of the MPP is made by the intermediary of the $\Delta\alpha$ steps carried on the duty cycle α .

Research starts with a step of rather large $\Delta\alpha$ variation until the first exceed of maximum power point (change of sign $\partial p / \partial \alpha$). The continuous process then by reversing the direction of variation of $\Delta\alpha$ with amplitude $\Delta\alpha_2 = \Delta\alpha_1 / 2$ until changes sign of ε . The sign of $\Delta\alpha$ is reversed and the step of variation becomes $\Delta\alpha_3 = \Delta\alpha_2 / 2$. Research continues until $\Delta\alpha_n \approx 0$. The last value corresponding to the maximum power then is used for controlled of the chopper. The process of research is then stopped and restarts only in case or a variation of irradiance is detected. The optimization of the system is determined by the resolution of a nonlinear system of equation (4.19) by taking the duty cycle as a parameter.

$$\begin{cases} I_p = I_{cc} - I_0 \left[\exp\left(\frac{V_p - R \cdot I_p}{V_{th}}\right) - 1 \right] \\ V_m = R \cdot I_m + K_1 \cdot \omega \\ K_1 \cdot I_m = A \omega^2 \end{cases} \quad (4.19)$$

With:

$$V_m = V_p / (1 - \alpha) \quad (4.20)$$

$$I_m = (1 - \alpha) \cdot I_p \quad (4.21)$$

From where, electric power is:

$$p = V_m \cdot I_m \quad (4.22)$$

With an aim of testing the continuation of the maximum power ensured by the MPPT during the change of the climatic conditions, a change in irradiance is applied to the system varying from 500 W/m² with 800 W/m² for a period of 4 s, as shown in figure (4.30).

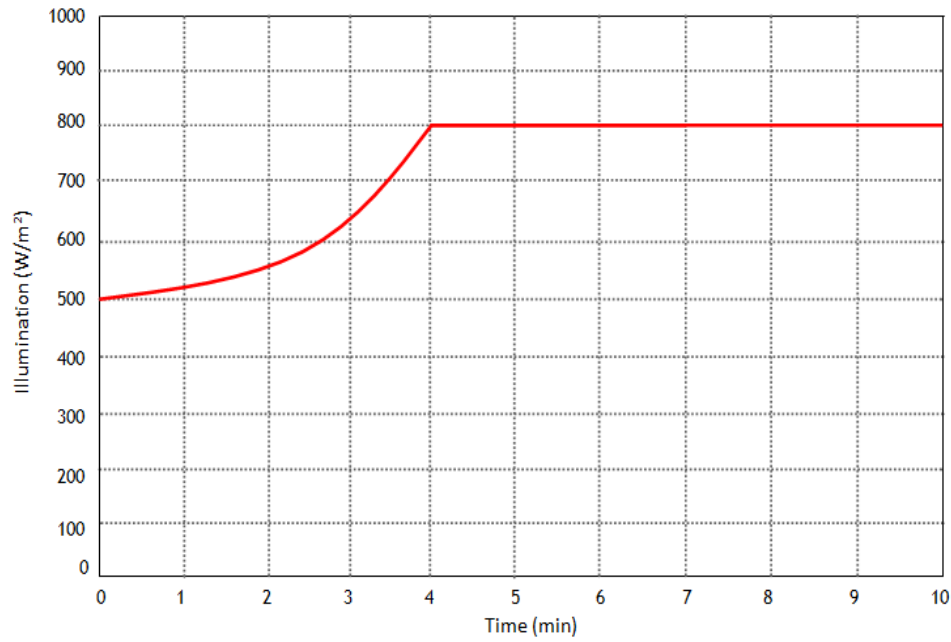
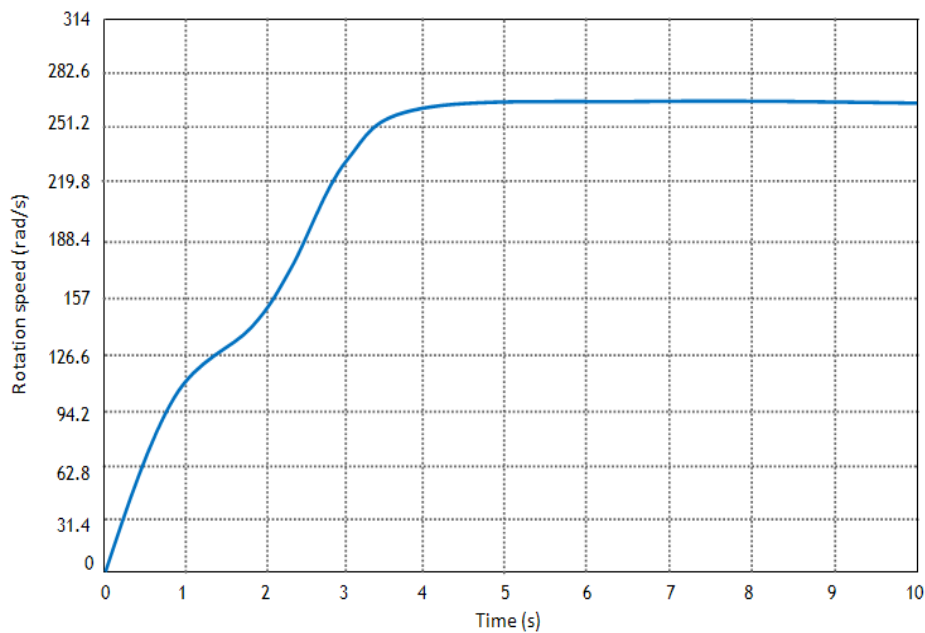


Figure 4.30 Curve of irradiance

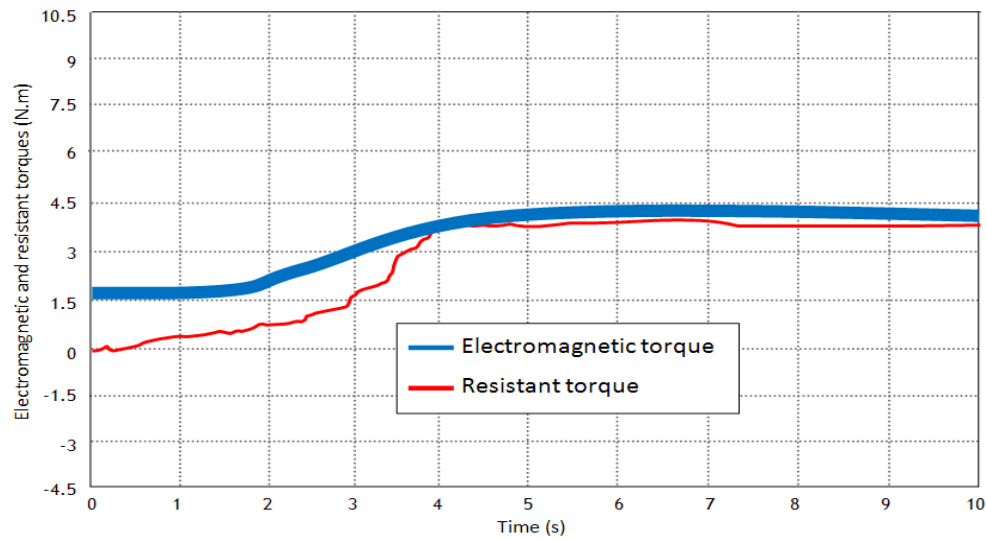
The choice of a parabolic change in irradiance is considered to better represent the reality of the phenomenon. In practice, the variations of irradiance are done rather in a gradual way.

The simulation results of the pumping solar system with MPPT are shown on the figure 4.31.

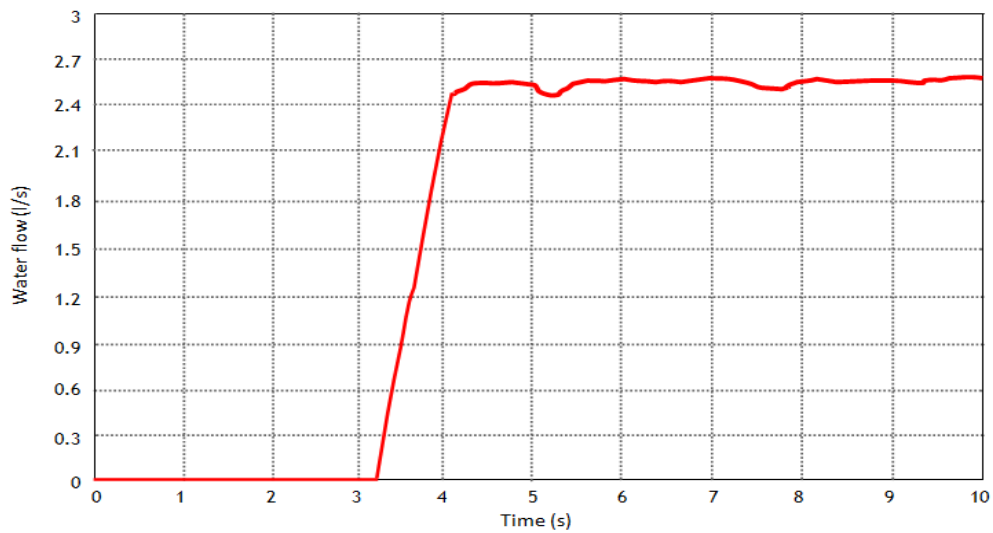
We represent the evolutions according to the time of rotation speed, of the couples electromagnetic and resistant, the water flow, and total manometric height.



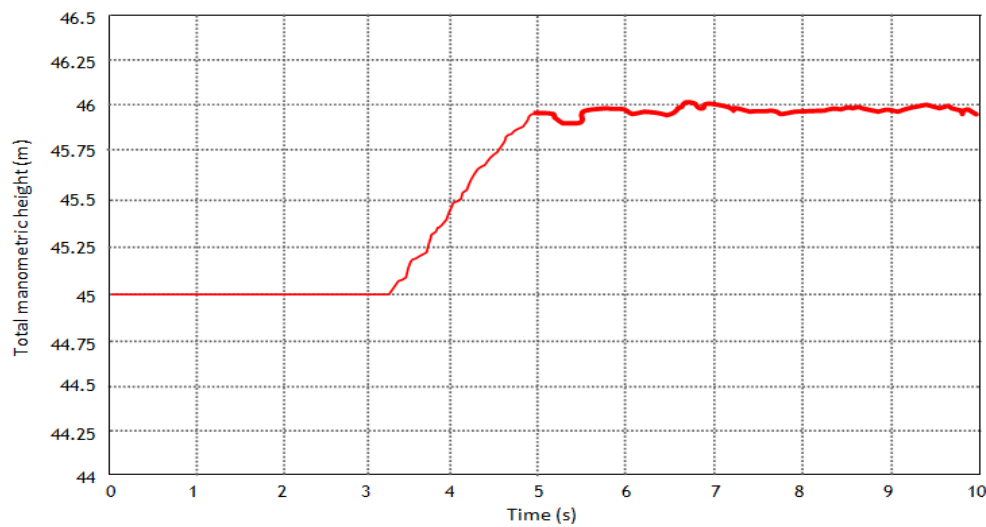
(a) Rotation speed



(b) Electromagnetic and resistance torque



(c) Water flow



(d) Total manometric height

Figure 4. 31 Simulation of the pumping system with MPPT

According to these results, we notice that the pump output water after having reached a certain range speed, this flow is at least low compared to that obtained during the food by network. This is due mainly to the power limit of the solar generator and to the order voltage/frequency law which requires more care to regulate this report. Moreover, this report considered for weak tensions is not the same as that used for strong tensions.

Thus, the choice of a simple profit between the tension and the frequency are only one control motor simplification.

According to the figure (4.31.b), the electromagnetic torque is fluctuating; this is caused by commutations on the tension inverter level and by the order law which imposes the switching times. With regard to the maximum power point tracking, we noted that this last functions correctly; the results deferred here after show this operation.

The following table shows the simulation values and experimental measurements of the parameters studied for different illumination.

Table 4. 3 Comparative study between simulation and experimental measurements

Illumination (W/m ²)	Pump flow (l/s)		Rotation speed (N.m)		Power (W)	
	Simulation	Experimental	Simulation	Experimental	Simulation	Experimental
400	2.125	2.111	157.25	165.7	540	535
500	2.405	2.399	188.42	186.5	610	605
600	2.538	2.512	219.85	218.2	680	678
700	2.543	2.517	251.22	248.5	750	748
800	2.548	2.555	271.03	275	800	810
900	2.548	2.555	275.39	275	805	810
1000	2.556	2.555	277.15	275	810	810

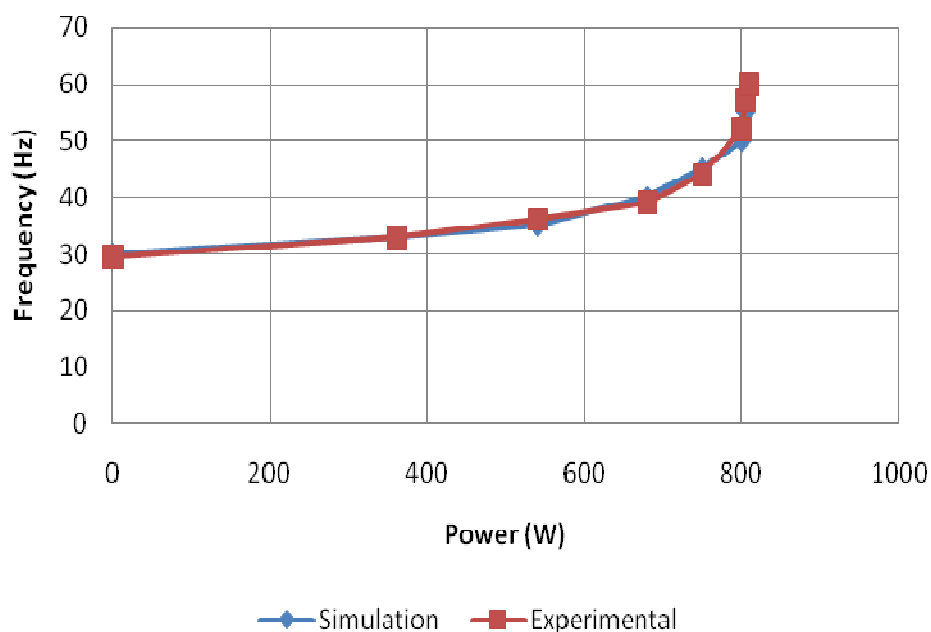


Figure 4. 32 Simulated and measured laboratory for system frequency as a function of power

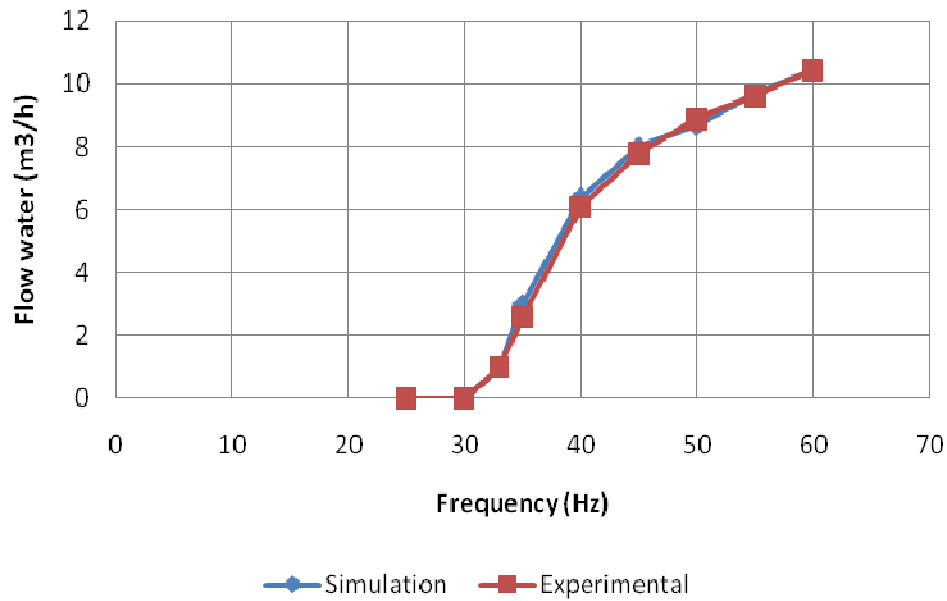


Figure 4. 33 Simulated and measured laboratory flow water as a function of pump frequency

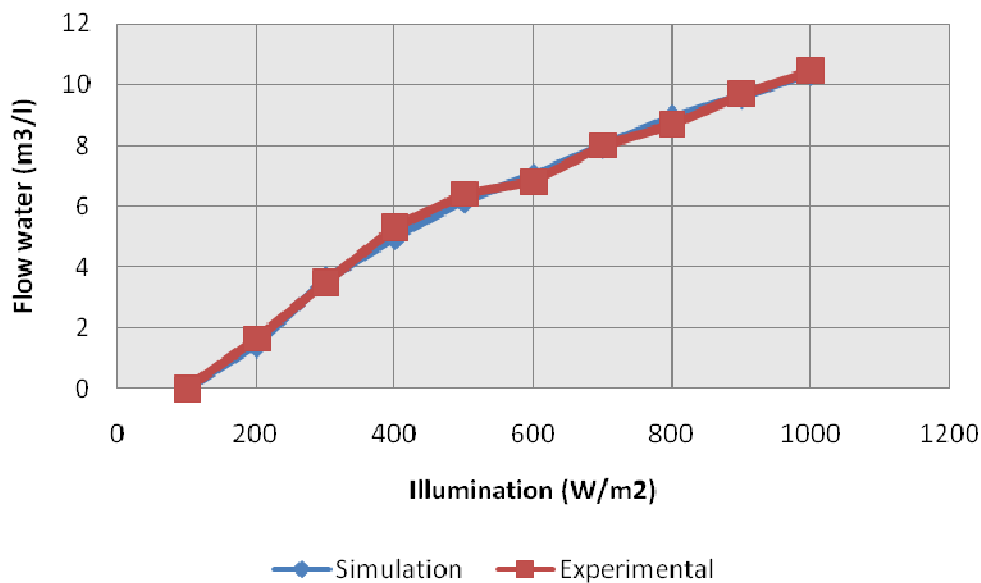


Figure 4. 34 Simulated and measured laboratory of flow water as a function of illumination

Figure (4.32) presents simulated data and laboratory measurements for system frequency as a function of PV power. As can be seen in this figure, the model predicts the system frequency accurately over the most frequent operating range (one-quarter to full load). At low input PV power of less than one-quarter the load, the model over estimates the system frequency by a maximum deviation of 1.5 percent.

Simulated and measured flow water as a function of system frequency are shown in Figure 4.33. Good agreement is observed over the complete range of operations between measured and simulated flow water. However, at zero flow water, the pump may rotate but the input power is not sufficient to overcome the total pumping head; the water column may

rise up to a certain height but not to the surface. Measured and simulated frequencies at which water starts reaching the surface were found to be 33 and 33.7 Hz, respectively, with a 2 percent deviation. Figure (4.33) also shows the system operating point if connected to the public grid where frequency is fixed at 60 Hz approximately. As can be seen in this figure, the model accurately predicts system performance at 60 Hz.

Figure (4.34) shows simulated data and laboratory measurements of flow water as a function of illumination (W/m^2). Maximizing power forces the pump to provide water from 175 (W/m^2). The amount earned during a half-day is 8.29 (m^3/h).

As a result of the comparison between the experimental and the simulation and in order to confirm the established bond graph model and the obtained simulations, we belonged to experimental measurements of the output power, rotation speed and water flow. The curves obtained are identical to simulations. We can conclude that there is a similarity and concordance.

4.5.3.2.1. TEST OF ACCURACY

With an aim of knowing the limits of operation of the pumping system, a new irradiance profile shown in figure (4.35) is considered.

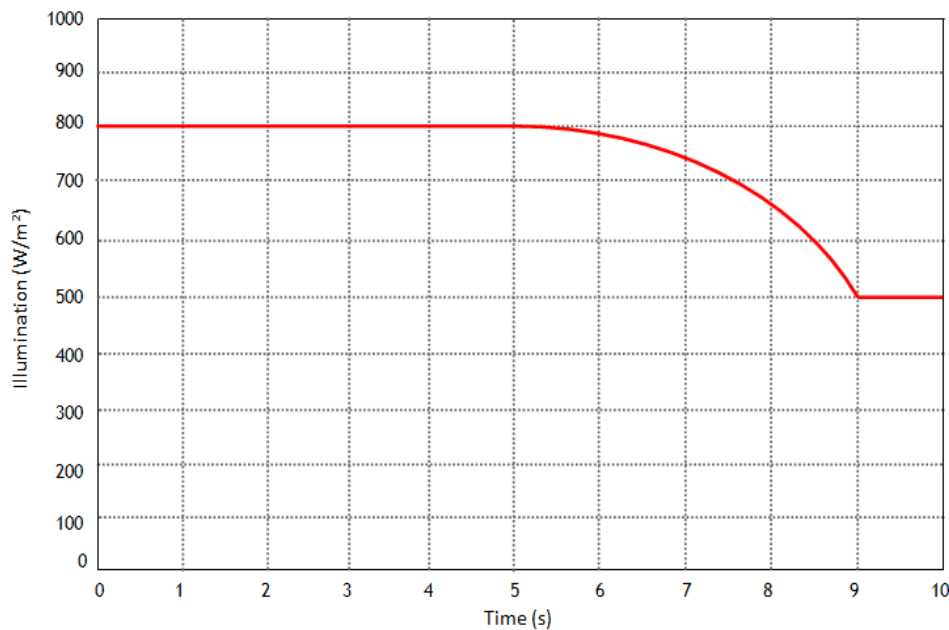
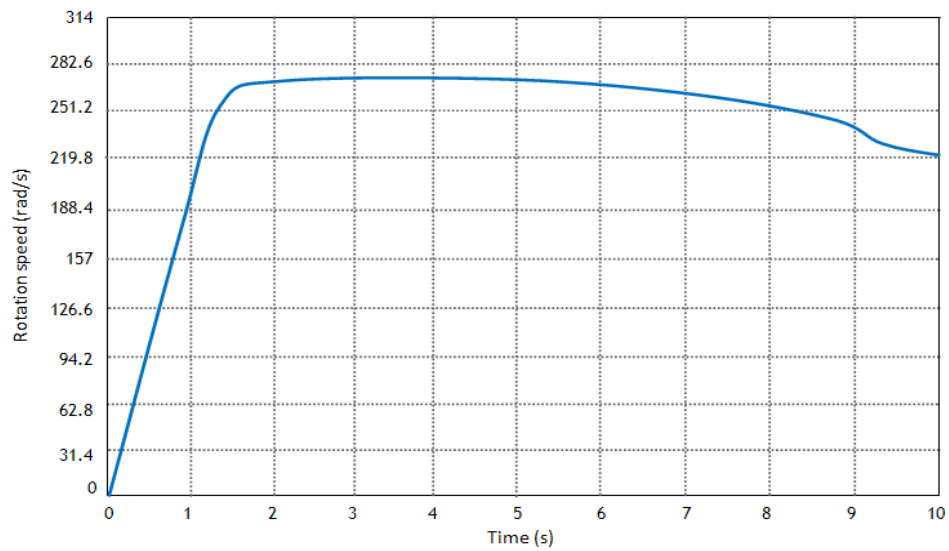
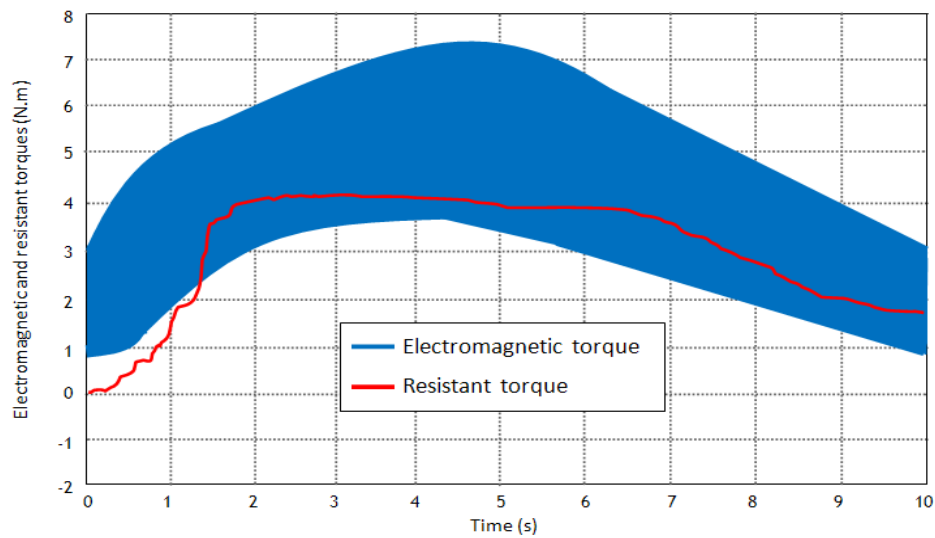


Figure 4. 35 Fall of irradiance

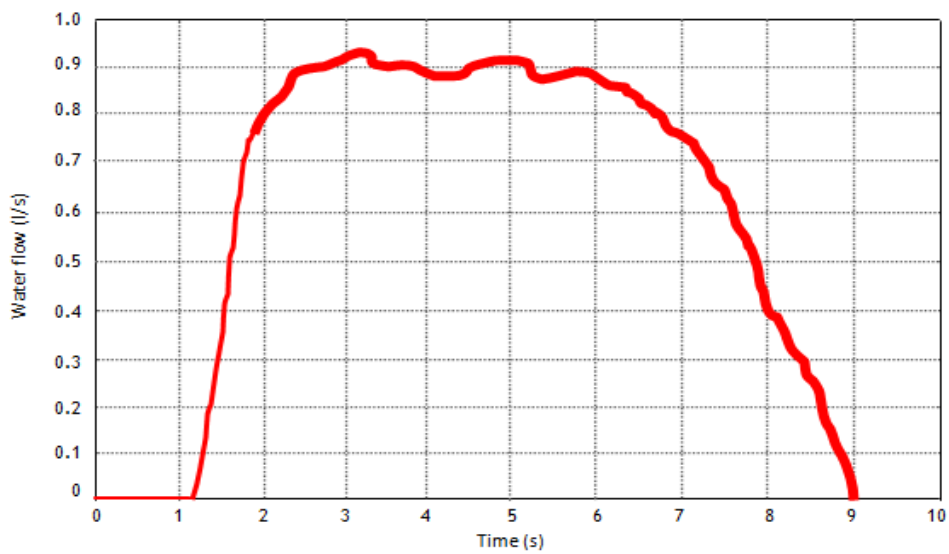
The benchmark of the pumping solar system for an operation with this irradiance profile is illustrated by the diagrams of the figure below. The latter defer the respective evolutions number of rotation speed, torques, water flow, terminal voltage of the PV, the current and the power output by the PV, and the prediction error of the optimal tension.



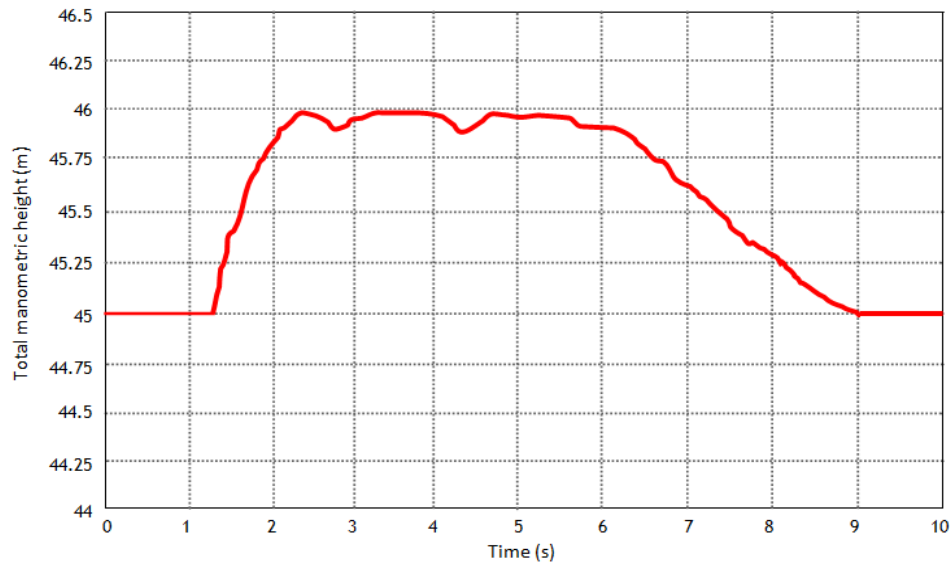
(a) Rotation speed



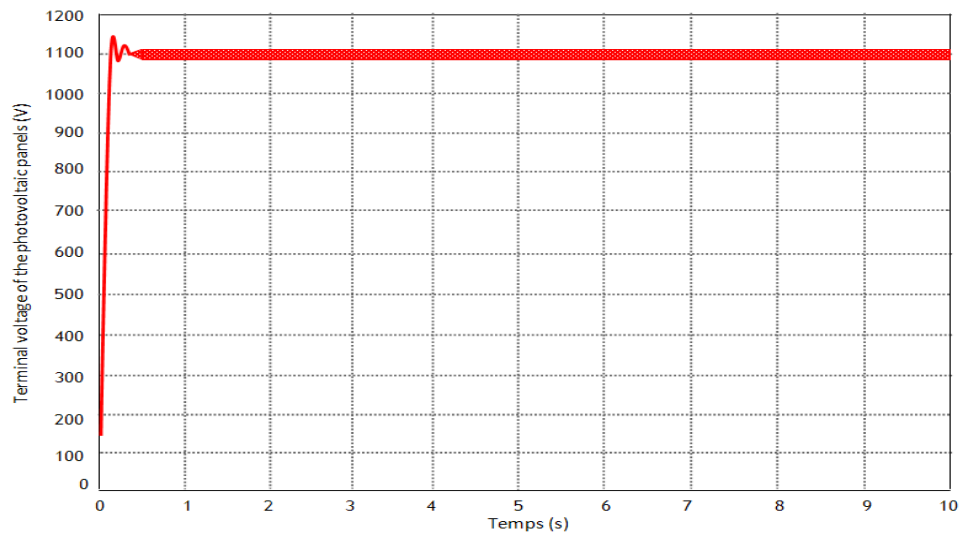
(b) Electromagnetic and resistant torque



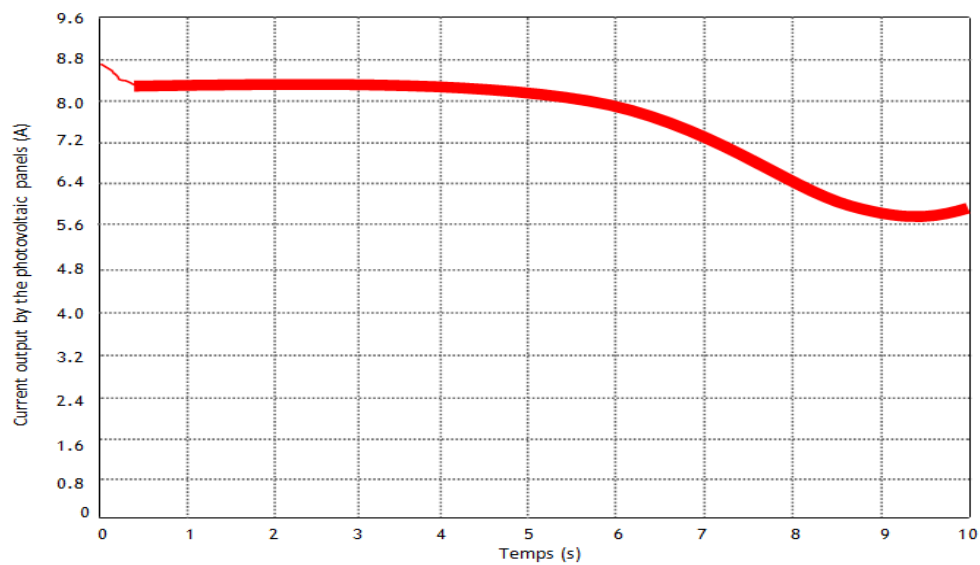
(c) Water flow



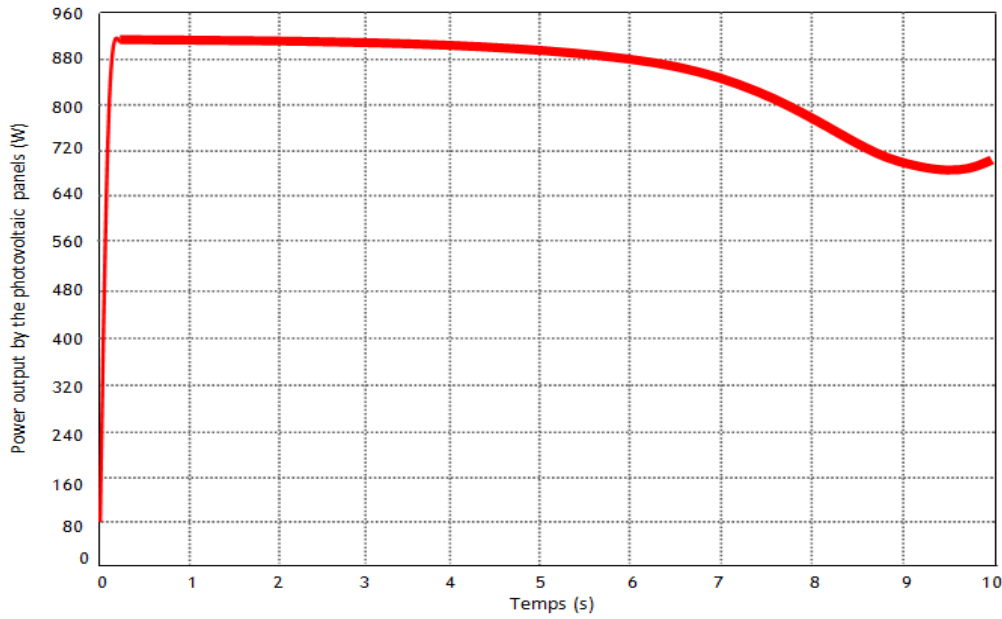
(d) Total manometric height



(e) Terminal voltage of the PV generator



(f) Current output by the PV generator



(g) Power output by the PV generator

Figure 4. 36 Performances test

According to the diagrams of figures 4.36 (a) and 4.36 (c), we note that the system had a shorter response time since the irradiance available was significant. But, as soon as this irradiance starts to decrease the rotation speed decreases by decreasing the water flow at the same time. At a certain time, the pump will not be able any more to convey water although the photovoltaic generator functions with its maximum of power.

According to the diagram figure 4.36 (g), the MPPT has been able to make function the generator with its maximum power, but in spite of that the pump could not output water when the irradiance decreased. We can rectify this situation by using other control laws for the synchronous motor.

4.5.3.3. CHARACTERISTIC PERFORMANCE AND SPEED OF THE PUMPING SYSTEM

The system performance is defined by:

$$\eta_{ppv} = \frac{E_H}{P_e} = \frac{\rho \cdot g \cdot Q \cdot H_m}{E \cdot N_s \cdot N_p \cdot S} \quad (4.23)$$

Q: The amount of water and is given by the following relationship:

$$Q = \begin{cases} 0 & \text{si } E < E_t \\ \frac{-b + \sqrt{b^2 + 4a(E - c)}}{2a} & \text{si } E > E_t \end{cases} \quad (4.24)$$

$E_t = 250 \text{ W/m}^2$; a, b and c are constants.

Figure (4.37) illustrates the shape of the yield, which is 100% for technical MPPT idealized cons by the direct coupling is characterized by low efficiency, especially for low values of illumination. But from $E = 900\text{W/m}^2$ and the values of performance will be close, this approximation shows good fit between the motor-pump and generator for the direct coupling of a strong illumination.

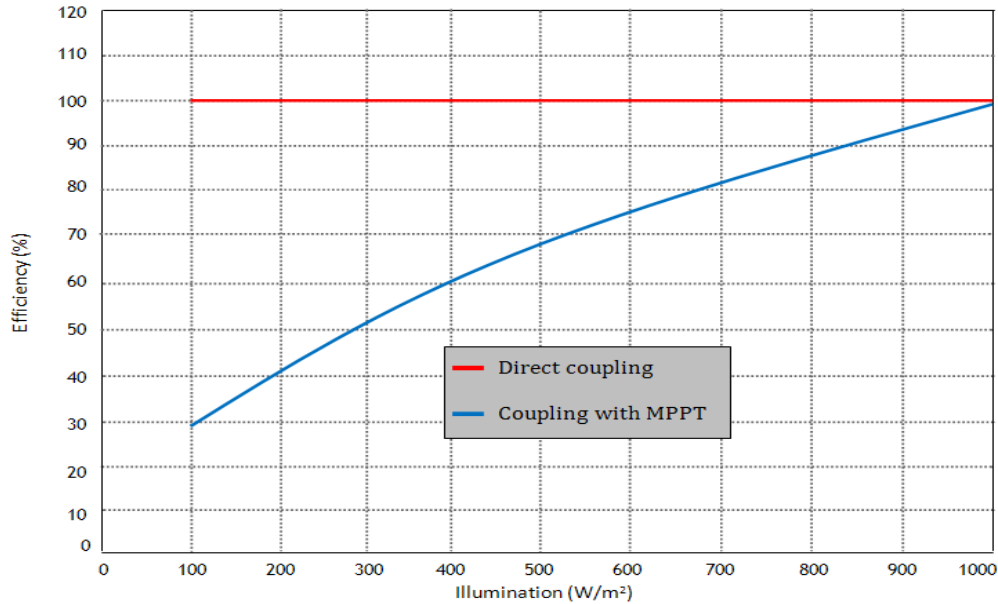


Figure 4. 37 Efficiency of photovoltaic pumping system

Figure (4.38) represents the gait speeds, the direct coupling with MPPT technology according to the illumination. In the case of the coupled system begins to deliver water at an illuminance of 280W/m^2 thus maximizing power to force the pump supplying water from 175W/m^2 .

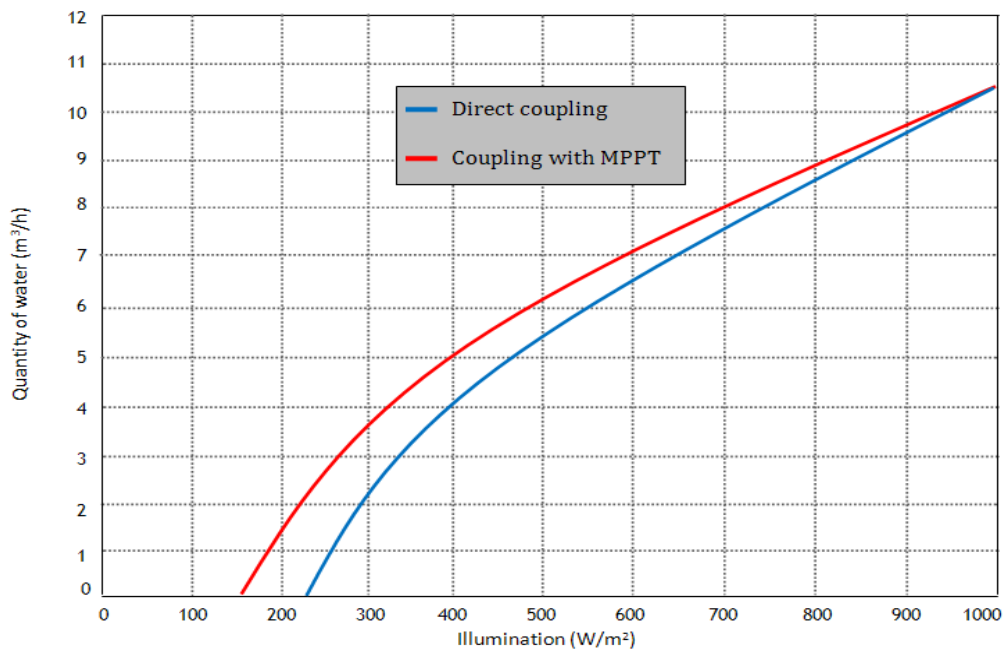


Figure 4. 38 Quantities of water according to illumination

4.6. CONCLUSION

A unified method for modeling of photovoltaic systems using bond graph energy-flow modeling. This modeling technique has been developed for simulation of photovoltaic system using MS1 environment. By using the bond graph formalism it is possible to combine linear and nonlinear circuits. Our study brought on the analysis of the photovoltaic systems intended for the insulated dwelling. Generally, this study brought the element necessary for the setting in devotement: it is likely to improve very quickly and with the help of an optimal cost the productivity and living conditions of the dwelling geographically dispersed.

In this study, a bond graph model is developed to represent the different components of a photovoltaic water pumping system. This methodology offers interesting solutions in terms of system analysis and reveals systematically all necessary functions needed for modeling, simulation, optimization, estimation, dimensioning, supervision, robustness testing or control laws development.

Part 3: Energy Production System Diagnosis

CHAPTER 5: Fault Detection and Isolation in Wind Energy Conversion System

CHAPTER 6: Fault Detection and Isolation in Photovoltaic System

***“We can’t solve problems by using the same kind of thinking we used when we created them”
Albert Einstein (1879-1955)***

CHAPTER 5: Fault Detection and Isolation in Wind Energy Conversion System

In this chapter the problem of fault detection in wind energy conversion (WEC) is addressed. One of the original points is that this work is the use of a new the fault detection and isolation method (FDI). The proposed method avoids the exploration of all the combinations for its application to the diagnostic of this system operation. The causal paths are used to generate the analytical redundancy relations (ARR) at each computation step based on the constitutive and structural junction relations. This is shown through an algorithm for monitoring the system by sensors placements on the corresponding bond graph model. The performance of the developed algorithm is evaluated on a model of a commercial sized 4.8 MW wind turbine.

5.1. INTRODUCTION

Modern complex conversion systems are deployed in environments where reliability and safety are of primary importance, which in turn calls for effective and sophisticated fault detection and isolation (FDI) algorithms. FDI methods can be broadly classified into two categories, namely, data driven approach and model based approach [178]. There is a method of fault diagnosis, which is based underlying structures and behavior of a system. Models serve as knowledge representation of a large amount of structural, functional and behavioral information and their relationship. This knowledge representation is used to create complex cause-effect reasoning to detect fault. There are two major types of model-based fault diagnosis broadly: quantitative and qualitative [179].

The problem of model-based fault diagnosis in wind turbines has just been recently addressed [180] mainly motivated because of importance of this technology for generating electricity is gained in many countries. So far, revising the literature, methods ranging from Kalman filters [181], observers [182] or parity equations [183] have been already suggested as possible model-based techniques for fault diagnosis of wind turbines. Model-based fault detection methods rely on the concept of analytical redundancy. The simplest analytical redundancy schema consists in comparing measurements of a system with corresponding analytically computed values that in turn are computed from measurements of other variables and/or from previous measurements of the same variable. The resulting differences are called residuals and are assumed to be indicative of faults in the system. Under ideal conditions, residuals are zero in the absence of faults and non-zero when a fault is present.

Although engineering processes are inherently non linear, the application of FDI to nonlinear system continues to apply linear methods based on the assumption that the disturbance caused by the fault is within a small region of the designed operating condition. Using an approximate linear model derived from a nonlinear model of the process, various algorithms have been proposed to obtain analytical redundancies, such as parity relations [184], [185], Kalman filters [186], [187] and parameter estimation [188], [189]. Excellent reviews on FDI can be found in [190] – [192].

The goal of the model-based fault diagnosis is to detect and localize faulty components in a system. Hence, the model used should incorporate structural information about the system and bond graph is such are presentation. In this work, a bond graph algorithm for fault detection and isolation in a WECS equipped with a permanent magnet synchronous generator (PMSG) is introduced. The proposed algorithm is based on analyzing the observed fault signatures on-line and matching them with the theoretical ones obtained using structural analysis. The advantages of the proposed technique over other techniques are that it has more flexibility and less complexity since it is fully software. Also, it has a very fast and accurate detection capability during wind speed variation which leads to a good control performance of the overall system.

In this chapter, a bond graph algorithm for fault detection and isolation in a WECS equipped with a permanent magnet synchronous generator (PMSG) is introduced. The proposed algorithm is based on analyzing the observed fault signatures on-line and

matching them with the theoretical ones obtained using structural analysis. The advantages of the proposed technique over other techniques are that it has more flexibility and less complexity since it is fully software. Also, it has a very fast and accurate detection capability during wind speed variation which leads to a good control performance of the overall system.

The method described herein is based on bond graph as a multidisciplinary tool for modeling, analysis, and ARR generation; all of which are required to monitor a process. First of all, some necessary substitutions are applied on the bond graph model in preferred differential causality to construct what we call here a diagnostic bond graph model. Inputs to a diagnostic bond graph model are the external sources and the sensor measurements, and its outputs are the residuals.

The innovative interest of the presented work consists in assigning detectors on junction nodes of bond graph without explicitly generating the ARRs. The original idea consists on analyzing the placement combination, which is a binary vector, in order to obtain the lines of the signature table, which is in turn a set of binary vectors.

5.2. FAULT DETECTION AND ISOLATION

Fault detection is a well studied area in many disciplines by the very nature that FD is essential to safe operations. The companion problem of fault isolation (FI) also has been studied and is a much more difficult problem.

Simply stated, a fault is a malfunction of the system because of some unexpected change. The malfunction disturbs normal operation and if unchecked may further deteriorate the system's performance. While a fault is considered non-normal behavior, in contrast, a failure is when a process is unable to perform its required functions. Generally, a fault is minor when compared to a failure, but most failures tend to stem from ignored or undetected faults.

The first step of the FDI procedure consists to generate a subset of equations called Analytical Redundancy Relations (ARRs) which express the difference between the model behavior and the actual reference given by data provided by the sensor [193]. ARRs are static or dynamic constraints which link the time evolution of known variables when the system operates according to its normal operation model. ARRs have to be sensitive to faults and insensitive to perturbations.

The residual represents the difference between an estimated value and a measured one, which should be zero during normal operation, but large in the presence of faults.

In practice, there is a distinction between the detection of fast-acting, possibly safety-critical faults, and faults which are non-safety-critical and slower to develop, for example due to wear. The former are most likely to be detected by state-estimation and instantaneous comparison of prediction with measurement, while the latter are detected using parameter estimation techniques which require a certain time window and excitation of the system. Probability analysis can be used to judge, from the residual values, when a fault or change has taken place. This work is concerned primarily with detection of fast-acting faults, detected via state estimation.

Isolation, in the literature, means diagnosis of the faulty component. If faults are allowed to occur simultaneously, then for a diagnosis, at least as many independent residual functions as faults considered are required. In practice, it is usually assumed that only one fault occurs at a time, which facilitates more robust fault diagnosis.

5.3. BOND GRAPH DIAGNOSIS OF PROCESS

5.3.1. TECHNICAL SPECIFICATIONS FOR SENSORS PLACEMENT

The quality and efficiency of a diagnosis system depends closely on the availability and relevance of the information it can retrieve from the diagnosed plant. The sensors distributed on the system are the source of the fault information. Previous diagnosis work has been done on the hypothesis of the sensors placed reasonably in advance. In reality, the number or cost of sensors available will be limited and this will, of course, places restrictions on the resolution of data. As a result, it would be necessary in practice to optimize the number and location of sensors for a given problem. The issue of determining the optimum number of sensors for a particular application, together with their best possible locations, has received considerable attention recently [103].

The goal of these sections is to provide an optimal sensor placement method on the bond graph model in order to make all components monitorable.

Let given a bond graph model obtained from physical process. We suppose that the sensors are not placed yet on the bond graph model.

Let x_i and y_j the boolean variables to express the potential sensor placement on the junction nodes such as:

$$x_i = \begin{cases} 1 & \text{if the } i^{\text{th}} \text{ sensor is placed on the } i^{\text{th}} \text{ "0"} \\ 0 & \text{otherwise} \end{cases} \quad (5.1)$$

$$y_j = \begin{cases} 1 & \text{if the } j^{\text{th}} \text{ sensor is placed on the } j^{\text{th}} \text{ "1"} \\ 0 & \text{otherwise} \end{cases} \quad (5.2)$$

N_0 number of “0” junctions, N_1 number of “1” junctions, n_i number of bonds around the i^{th} “0” junction ($i = 1, N_0$), m_j number of bonds around the j^{th} “1” junction ($j = 1, N_1$), In the following, “f” and “e” denote flow and effort vector, respectively

Equations of the i^{th} “0” junction are:

$$\begin{cases} \sum_{k=1}^{n_i} a_k f_k = 0 \\ e_k = e_{Ci} \end{cases} \quad \text{where } k = 1, n_i - 1 \quad a_i = \begin{cases} 1 & \text{if the half-arrow is toward junction} \\ 0 & \text{otherwise} \end{cases} \quad (5.3)$$

Equations of the j^{th} “1” junction are:

$$\begin{cases} \sum_{l=1}^{m_j} a_l f_l = 0 \\ f_l = f_{Rj} \end{cases} \quad \text{where } k = 1, m_j - 1 \quad a_l = \begin{cases} 1 & \text{if the half-arrow is toward junction} \\ 0 & \text{otherwise} \end{cases} \quad (5.4)$$

- The known variables are represented in the bond graph by the measured variables given by effort (De) and flow (Df) detectors, and the input variables which can be a

constant source of effort and flow S_e , S_f or a modulated source of effort and flow MS_e , MS_f . The set of known variables K is then obtained:

Let us define now, two sets of variables:

$$K = MS_e \cup MS_f \cup De \cup Df \cup u \quad (5.5)$$

- X the set of the unknown variables. The unknown variables are the power variables (flow and effort) which label the bonds. The vector X containing all the power variables is:

$$X(t) = \{e_1(t), f_1(t)\} \cup \{e_2(t), f_2(t)\} \dots \{e_n(t), f_n(t)\} \quad (5.6)$$

Where n is the number of bond graph R , C and I elements. The set of constraints can be decomposed into four sub sets according to the bond graph methodology.

- The behavioral constraints: gather the sets of algebraic and differential constraints, and describe the physical phenomena on the bond graph elements.
- The structural constraints: those constraints are independent from the metric notions and represent the laws of power and matter conservation on the system and are deduced from the junctions 0 and 1 on the bond graph model.
- The measurement constraints: describe the available measurement on the system. They express the manner the sensors transform some state variables of the process into output signals which can be used for system control and diagnosis. The sensor output represents the power variable common for all the inputs and outputs of the junction.
- The differentiation constraints: those constraints are not directly related to the physical system, thus they do not appear explicitly on the bond graph model. They are used to calculate the derivative of the known efforts and flows.

Based on causal properties of the bond graph modeling, the unknown variables can be calculated using covering causal paths.

For the “0” and the “1” junction, the unknown variable (based on fixed causality) is calculated as flows [194]:

$$\begin{cases} f_{C_i} = \phi_{C_i} \left[S \{ (1-x_i)(e_{C_i}) + x_i De_i \} \right] \\ e_{C_i} = \frac{1}{S} (1-x_i) \phi_{C_i}^{-1} (f_{C_i}) + x_i De_i \end{cases} \quad \text{avec } i = 1.N \quad (5.7)$$

$$\begin{cases} e_{R_j} = \phi_{R_j} \left[(1-y_j)(f_{R_j}) + y_j Df_j \right] \\ f_{R_j} = (1-y_j) \phi_{R_j} (e_{R_j}) + y_j Df_j \end{cases} \quad \text{avec } j = 1.N_1 \quad (5.8)$$

$$\begin{cases} e_{L_k} = \phi_{L_k} \left[(1-z_k)(f_{L_k}) + z_k Df_k \right] \\ f_{L_k} = (1-z_k) \phi_{L_k} (e_{L_k}) + z_k Df_k \end{cases} \quad \text{avec } k = 1.N_1 \quad (5.9)$$

The residuals are designed to be sensitive to a fault that comes from a specific sensor and as insensitive as possible to all the others sensor faults. This residual will permit us to treat not only with single faults but also with multiple and simultaneous faults.

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as insensitive as possible to all the others sensor faults. This residual will permit us to treat not only with single faults but also with multiple and simultaneous faults.

The input-output relationship of the system after being incorporated with a normal operation model can be described approximately as follows,

$$K = F(X) \quad (5.10)$$

X is the fault vector with each input x_i representing a measure of the fault level for fault (x_1 : fault in Df1, x_2 : fault in De13, ...). K is the state variable residual vector, with each input representing a particular state-variable residual. $F(X)$ is a nonlinear function defining the relationship between different faults at different levels and the state variable residuals k .

Fault diagnosis, which entails the determination of the kind and location of the detected fault from a list of possibilities, needs to use the resulting K (known) to find the causes X (unknowns).

The nonlinear equation (5.1) cannot get unique solutions for X for a given K if $m < n$ and may result in inconsistencies $n < m$, but it would not lose any generality to assume $m = n$. If $F(x)$ is known, multiple simultaneous fault diagnosis becomes easy. However, it is very difficult, if not impossible, to find $F(x)$. To simplify equation (5.1), the first two items of Maclaurin's series can be used to linearize the nonlinear equation.

Fault detection is a process of binary decision. This is an estimate positive or negative for the presence of a fault. This response is given by a decision criterion generally defined in an algorithm. The state detection, binary result of the detection process can be written in general

$$FD = \begin{cases} 1 & \text{if the criteria of decision is validated} \\ 0 & \text{otherwise} \end{cases} \quad (5.11)$$

The state of detection depends on one or more parameters. These parameters should then be adjusted according to measurement conditions, possibly as properties of the target roughness or defects sought.

Two cases for the actual presence of a fault are possible:

$$PF = \begin{cases} 0 & \text{if the signal does not correspond to a fault} \\ 1 & \text{if the signal corresponds to a fault} \end{cases} \quad (5.12)$$

Depending on the value of the state detection (det), four combinations are possible. Both errors are possible error detection and false alarm. False alarm is the erroneous detection of a fault. It may lead to the substitution of a piece yet intact, constituting an undue cost to the manufacturing process or revision of the device.

In this work we propose the application of simple thresholding algorithm. It gives a positive response to detection if, for at least one measuring point (n_i, n_j) , the value $s(n_i, n_j)$ the modulus of the signal is greater than the detection threshold θ fixed either

$$\text{det}(DC) = \begin{cases} 1 & \text{if } \exists(n_i, n_j), |s(n_i, n_j)| \geq DC \\ 0 & \text{otherwise} \end{cases} \quad (5.13)$$

DC is an adjustment of the decision criterion. It can be set for each set of measurement

conditions, while remaining the same for all assessments conducted under the same conditions. For our application $DC=0.22$ unite.

It may be possible to adjust the detection threshold based on the fault. The amplitude of the signal depends on the fault size. It is possible to consider that small faults are not harmful to the system. Its threshold value depends on the measurement conditions and the minimum fault size.

The algorithm developed in this section estimates the detection state $det=0$ or $det=1$ from any figure corresponding to a $PF=0$ or $PF=1$. This algorithm relies on a detection threshold DC whose value must be determined for each set of measurement conditions. The optimal threshold value is chosen by covering all possible threshold values and calculating their statistically representative set of images.

Sensitivity is the number of correct detections measured n_{CD} divided by the total number of correct detections possible on a statistically sufficient number of samples, or

$$Se = \frac{n_{CD}}{n_{CD} + n_{SD}} = \frac{n_{CD}}{n_{PF_1}} \quad PF_1 = PF \text{ (if the signal corresponds to a fault)} \quad (5.14)$$

The sensitivity is thus equal to the rate of correct detection and quantifies the ability of the detection process to respond correctly when the PF is 1.

Specificity is the number of non-correct detections measured divided by the total number of non-correct detections possible, on a statistically sufficient number of samples, or

$$S_p = \frac{n_{NCD}}{n_{NCD} + n_C} = \frac{n_{NCD}}{n_{PF_0}} \quad , \quad PF_0 = PF \text{ (if the signal does not correspond to a fault)} \quad (5.15)$$

Precision is the total number of states detection consistent with the hypothesis assessed divided by the total number of samples, or

$$P_r = \frac{n_{CD} + n_{NCD}}{n_{PF_0} + n_{PF_1}} \quad (5.16)$$

For our application, the equations in junctions are given by:

Junction 0_1

$$\begin{cases} e_1 = e_3, e_{60} = e_3 \\ f_1 - f_3 - f_{60} = 0 \\ f_{C1} = f_3 = \phi_{C1} \left[s \left[(1-x_1)e_{C1} + x_1 D e_1 \right] \right] \\ e_{C1} = e_3 = \frac{1}{s} (1-x_1) \phi_{C1}^{-1} f_{C1} + x_1 D e_1 \end{cases} \quad (5.17)$$

Junction 0_2

$$\begin{cases} e_7 = e_{31}, e_{20} = e_7 \\ f_7 - f_{31} - f_{20} = 0 \\ f_{C2} = f_{31} = \phi_{C2} \left[s \left[(1-x_2)e_{C2} + x_2 D e_2 \right] \right] \\ e_{C2} = e_{31} = \frac{1}{s} (1-x_2) \phi_{C2}^{-1} f_{C2} + x_2 D e_2 \end{cases} \quad (5.18)$$

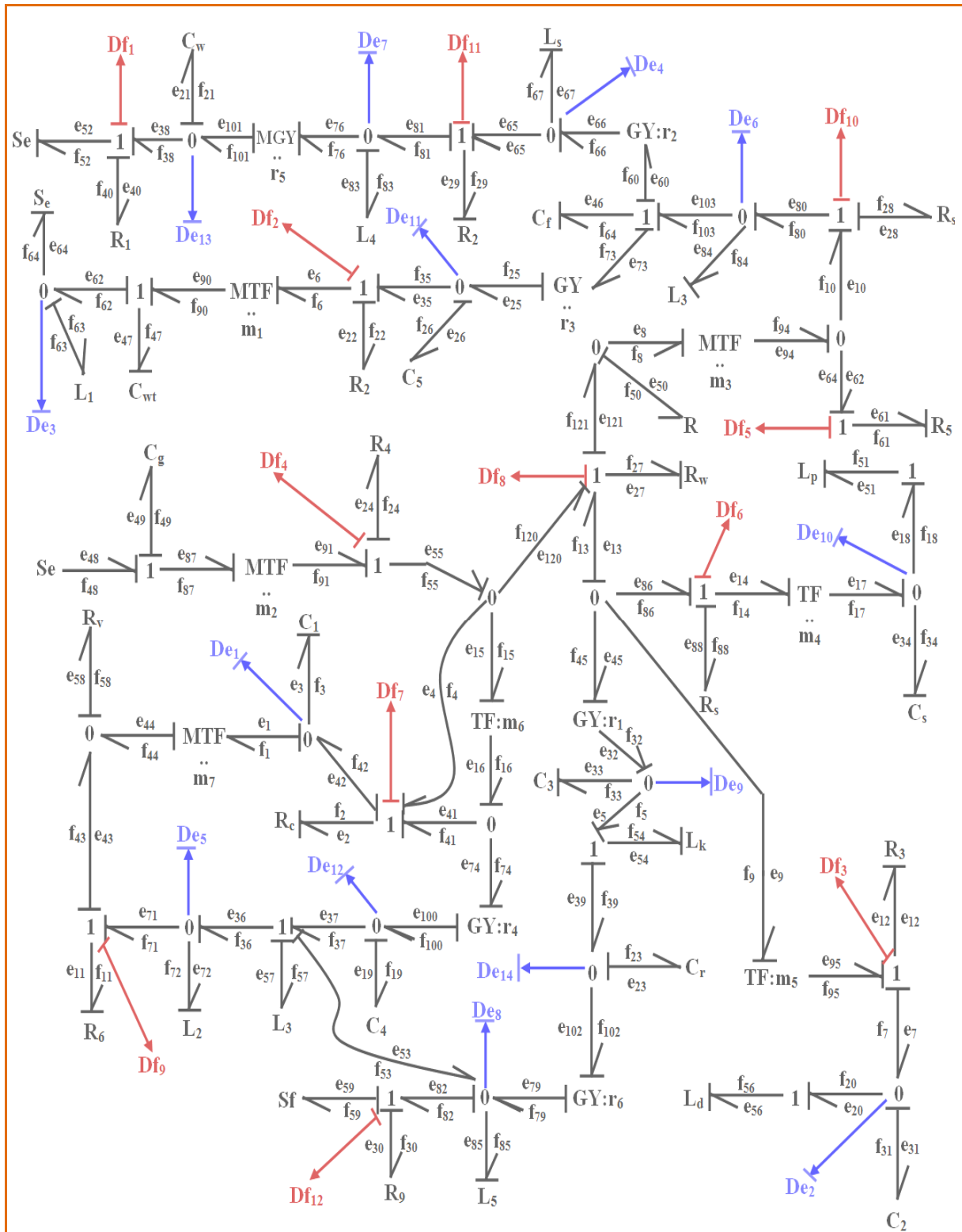


Figure 5. 1 Bond graph model with sensors placement

Junction 0₃

$$\begin{cases} e_{64} = e_{62}, e_{63} = e_{62} \\ f_{62} - f_{63} - f_{64} = 0 \\ f_{L1} = f_{63} = \phi_{L1}^{-1} \left[\frac{1}{s} [(1-x_8)e_{L1} + x_8 De_3] \right] \\ e_{L1} = e_{63} = s(1-x_8)\phi_{L1} f_{L1} + z_1 De_3 \end{cases} \quad (5.19)$$

Junction 0₄

$$\begin{cases} e_{66} = e_{65}, e_{67} = e_{65} \\ f_{65} - f_{66} - f_{67} = 0 \\ f_{Ls} = f_{67} = \phi_{Ls}^{-1} \left[\frac{1}{s} [(1-x_9)e_{Ls} + x_9 De_4] \right] \\ e_{Ls} = e_{67} = s(1-x_9)\phi_{Ls} f_{Ls} + x_9 De_4 \end{cases} \quad (5.20)$$

Junction 0₅

$$\begin{cases} e_{36} = e_{71}, e_{72} = e_{71} \\ f_{71} - f_{72} - f_{36} = 0 \\ f_{L2} = f_{72} = \phi_{L2}^{-1} \left[\frac{1}{s} [(1-x_{10})e_{L2} + x_{10} De_5] \right] \\ e_{L2} = e_{72} = s(1-x_{10})\phi_{L2} f_{L2} + x_{10} De_5 \end{cases} \quad (5.21)$$

Junction 0₆

$$\begin{cases} e_{84} = e_{80}, e_{103} = e_{80} \\ f_{80} - f_{103} - f_{84} = 0 \\ f_{L3} = f_{84} = \phi_{L3}^{-1} \left[\frac{1}{s} [(1-x_{11})e_{L3} + x_{11} De_6] \right] \\ e_{L3} = e_{84} = s(1-x_{11})\phi_{L3} f_{L3} + x_{11} De_6 \end{cases} \quad (5.22)$$

Junction 0₇

$$\begin{cases} e_{18} = e_{18}, e_{17} = e_{18} \\ f_{18} - f_{18} - f_{17} = 0 \\ f_{L4} = f_{18} = \phi_{L4}^{-1} \left[\frac{1}{s} [(1-x_{12})e_{L4} + x_{12} De_7] \right] \\ e_{L4} = e_{18} = s(1-x_{12})\phi_{L4} f_{L4} + x_{12} De_7 \end{cases} \quad (5.23)$$

Junction 0₈

$$\begin{cases} e_{85} = e_{82}, e_{120} = e_{82} \\ f_{120} - f_{53} - f_{120} = 0 \\ f_{L5} = f_{85} = \phi_{L5}^{-1} \left[\frac{1}{s} [(1-x_{13})e_{L5} + x_{13} De_8] \right] \\ e_{L5} = e_{85} = s(1-x_{13})\phi_{L5} f_{L5} + z_6 De_8 \end{cases} \quad (5.24)$$

Junction 0₉

$$\begin{cases} e_{32} = e_{33}, e_5 = e_{33} \\ f_{32} - f_{33} - f_5 = 0 \\ f_{C3} = f_{33} = \phi_{C3} \left[s \left[(1-x_3) e_{C3} + x_3 D e_9 \right] \right] \\ e_{C3} = e_{33} = \frac{1}{s} (1-x_3) \phi_{C3}^{-1} f_{C3} + x_3 D e_9 \end{cases} \quad (5.25)$$

Junction 0₁₀

$$\begin{cases} e_{17} = e_{18}, e_{34} = e_{18} \\ f_{17} - f_{18} - f_{34} = 0 \\ f_{Cs} = f_{18} = \phi_{Cs} \left[s \left[(1-x_4) e_{Cs} + x_4 D e_{10} \right] \right] \\ e_{Cs} = e_{18} = \frac{1}{s} (1-x_4) \phi_{Cs}^{-1} f_{Cs} + x_4 D e_{10} \end{cases} \quad (5.26)$$

Junction 0₁₁

$$\begin{cases} e_{25} = e_{26}, e_{35} = e_{26} \\ f_{25} - f_{26} - f_{35} = 0 \\ f_{C5} = f_{26} = \phi_{C5} \left[s \left[(1-x_5) e_{C5} + x_5 D e_{11} \right] \right] \\ e_{C5} = e_{26} = \frac{1}{s} (1-x_5) \phi_{C5}^{-1} f_{C5} + x_5 D e_{11} \end{cases} \quad (5.27)$$

Junction 0₁₂

$$\begin{cases} e_{100} = e_{19}, e_{37} = e_{19} \\ f_{100} - f_{19} - f_{37} = 0 \\ f_{C4} = f_{19} = \phi_{C4} \left[s \left[(1-x_6) e_{C4} + x_6 D e_{12} \right] \right] \\ e_{C4} = e_{19} = \frac{1}{s} (1-x_6) \phi_{C4}^{-1} f_{C4} + x_6 D e_{12} \end{cases} \quad (5.28)$$

Junction 0₁₃

$$\begin{cases} e_{101} = e_{21}, e_{38} = e_{21} \\ f_{101} - f_{21} - f_{38} = 0 \\ f_{Cw} = f_{21} = \phi_{Cw} \left[s \left[(1-x_7) e_{Cw} + x_7 D e_{13} \right] \right] \\ e_{Cw} = e_{21} = \frac{1}{s} (1-x_7) \phi_{Cw}^{-1} f_{Cw} + x_7 D e_{13} \end{cases} \quad (5.29)$$

Junction 0₁₄

$$\begin{cases} e_{102} = e_{23}, e_{39} = e_{23}; f_{102} - f_{23} - f_{39} = 0 \\ f_{Cr} = f_{23} = \phi_{Cr} \left[s \left[(1-x_8) e_{Cr} + x_8 D e_{14} \right] \right] \\ e_{Cr} = e_{23} = \frac{1}{s} (1-x_8) \phi_{Cr}^{-1} f_{Cr} + x_8 D e_{14} \end{cases} \quad (5.30)$$

Junction TF₁

$$\begin{cases} e_6 = m_1 e_{190} \\ f_{90} = m_1 f_6 \end{cases} \quad (5.31)$$

Junction TF₂

$$\begin{cases} e_{87} = m_2 e_{91} \\ f_{91} = m_2 f_{87} \end{cases} \quad (5.32)$$

Junction TF₃

$$\begin{cases} e_8 = m_3 e_{94} \\ f_{94} = m_3 f_8 \end{cases} \quad (5.33)$$

Junction TF₄

$$\begin{cases} e_9 = m_4 e_{95} \\ f_{95} = m_4 f_9 \end{cases} \quad (5.34)$$

Junction TF₅

$$\begin{cases} e_{17} = \frac{1}{m_5} e_{14} \\ f_{14} = \frac{1}{m_5} f_{17} \end{cases} \quad (5.35)$$

Junction TF₆

$$\begin{cases} e_{15} = m_6 e_{16} \\ f_{16} = m_6 f_{15} \end{cases} \quad (5.36)$$

Junction TF₇

$$\begin{cases} e_1 = m_7 e_{44} \\ f_{44} = m_7 f_1 \end{cases} \quad (5.37)$$

Junction 1₁

$$\begin{cases} e_{52} - e_{40} - e_{38} = 0 \\ f_{52} = f_{40}, f_{38} = f_{40} \\ e_{R1} = e_{40} = \phi_{R1} [(1 - y_1) f_{R1} + y_1 Df_1] \\ f_{R1} = f_{40} = (1 - y_1) \phi_{R1}^{-1} e_{R1} + y_1 Df_1 \end{cases} \quad (5.38)$$

Junction 1₂

$$\begin{cases} e_6 - e_{22} - e_{35} = 0 \\ f_6 = f_{22}, f_{35} = f_{22} \\ e_{R2} = e_{22} = \phi_{R2} [(1 - y_2) f_{R2} + y_2 Df_2] \\ f_{R2} = f_{22} = (1 - y_2) \phi_{R2}^{-1} e_{R2} + y_2 Df_2 \end{cases} \quad (5.39)$$

Junction 1₃

$$\begin{cases} e_{95} - e_{12} - e_7 = 0 \\ f_{95} = f_{12}, f_7 = f_{12} \\ e_{R3} = e_{12} = \phi_{R3} [(1 - y_3) f_{R3} + y_3 Df_3] \\ f_{R3} = f_{12} = (1 - y_3) \phi_{R3}^{-1} e_{R3} + y_3 Df_3 \end{cases} \quad (5.40)$$

Junction 1₄

$$\begin{cases} e_{55} - e_{24} - e_{91} = 0 \\ f_{55} = f_{24}, f_{91} = f_{24} \\ e_{R4} = e_{24} = \phi_{R4} \left[(1 - y_4) f_{R4} + y_4 Df_4 \right] \\ f_{R4} = f_{24} = (1 - y_4) \phi_{R4}^{-1} e_{R4} + y_4 Df_4 \end{cases} \quad (5.41)$$

Junction 1₅

$$\begin{cases} e_4 - e_{61} = 0 \\ f_4 = f_{61} \\ e_{R5} = e_4 = \phi_{R5} \left[(1 - y_5) f_{R5} + y_5 Df_5 \right] \\ f_{R5} = f_4 = (1 - y_5) \phi_{R5}^{-1} e_{R5} + y_5 Df_5 \end{cases} \quad (5.42)$$

Junction 1₆

$$\begin{cases} e_{86} - e_{14} - e_{88} = 0 \\ f_{14} = f_{88}, f_{86} = f_{88} \\ e_{R6} = e_{88} = \phi_{R6} \left[(1 - y_6) f_{R6} + y_6 Df_6 \right] \\ f_{R6} = f_{88} = (1 - y_6) \phi_{R6}^{-1} e_{R6} + y_6 Df_6 \end{cases} \quad (5.43)$$

Junction 1₇

$$\begin{cases} f_4 = f_{42}, f_2 = f_{42}, f_{41} = f_{42} \\ e_4 + e_{41} - e_2 - e_{42} = 0 \\ e_{Rc} = e_2 = \phi_{Rc} \left[(1 - y_7) f_{Rc} + y_7 Df_7 \right] \\ f_{Rc} = f_2 = (1 - y_7) \phi_{Rc}^{-1} e_{Rc} + y_7 Df_7 \end{cases} \quad (5.44)$$

Junction 1₈

$$\begin{cases} f_{13} = f_{120}, f_{27} = f_{120}, f_{121} = f_{120} \\ e_{13} + e_{121} - e_{27} - e_{120} = 0 \\ e_{Rw} = e_{27} = \phi_{Rw} \left[(1 - y_8) f_{Rw} + y_8 Df_8 \right] \\ f_{Rw} = f_{27} = (1 - y_8) \phi_{Rw}^{-1} e_{Rw} + y_8 Df_8 \end{cases} \quad (5.45)$$

Junction 1₉

$$\begin{cases} f_{27} = f_{71}, f_{43} = f_{71}, f_{11} = f_{71} \\ e_{27} + e_{43} - e_{11} - e_{71} = 0 \\ e_{R6} = e_{11} = \phi_{R6} \left[(1 - y_9) f_{R6} + y_9 Df_9 \right] \\ f_{R6} = f_{11} = (1 - y_9) \phi_{R6}^{-1} e_{R6} + y_9 Df_9 \end{cases} \quad (5.46)$$

Junction 1₁₀

$$\begin{cases} e_{10} - e_{28} - e_{80} = 0 \\ f_{10} = f_{80}, f_{28} = f_{80} \\ e_{R7} = e_{28} = \phi_{R7} \left[(1 - y_{10}) f_{R7} + y_{10} Df_{10} \right] \\ f_{R7} = f_{28} = (1 - y_{10}) \phi_{R7}^{-1} e_{R7} + y_{10} Df_{10} \end{cases} \quad (5.47)$$

Junction 1₁₁

$$\begin{cases} e_{65} - e_{29} - e_{81} = 0 \\ f_{65} = f_{81}, f_{29} = f_{81} \\ e_{R8} = e_{29} = \phi_{R8} \left[(1 - y_{11}) f_{R8} + y_{11} Df_{11} \right] \\ f_{R8} = f_{29} = (1 - y_{11}) \phi_{R8}^{-1} e_{R8} + y_{11} Df_{11} \end{cases} \quad (5.48)$$

Junction 1₁₂

$$\begin{cases} e_{41} - e_{30} - e_{82} = 0 \\ f_{41} = f_{82}, f_{30} = f_{82} \\ e_{R9} = e_{30} = \phi_{R9} \left[(1 - y_{12}) f_{R9} + y_{12} Df_{12} \right] \\ f_{R9} = f_{30} = (1 - y_{12}) \phi_{R9}^{-1} e_{R9} + y_{12} Df_{12} \end{cases} \quad (5.49)$$

Junction GY₁

$$\begin{cases} f_{32} = (1 / r_1) e_{45} \\ f_{45} = (1 / r_1) e_{32} \end{cases} \quad (5.50)$$

Junction GY₂

$$\begin{cases} f_{60} = \frac{1}{r_2} e_{66} \\ f_{66} = \frac{1}{r_2} e_{60} \end{cases} \quad (5.51)$$

Junction GY₃

$$\begin{cases} f_{25} = \frac{1}{r_3} e_{73} \\ f_{73} = \frac{1}{r_3} e_{25} \end{cases} \quad (5.52)$$

Junction GY₄

$$\begin{cases} f_{100} = \frac{1}{r_4} e_{74} \\ f_{74} = \frac{1}{r_4} e_{100} \end{cases} \quad (5.53)$$

Junction GY₅

$$\begin{cases} f_{101} = \frac{1}{r_5} e_{76} \\ f_{76} = \frac{1}{r_5} e_{101} \end{cases} \quad (5.54)$$

Junction GY₆

$$\begin{cases} f_{102} = \frac{1}{r_6} e_{79} \\ f_{79} = \frac{1}{r_6} e_{102} \end{cases} \quad (5.55)$$

5.3.2. ANALYTICAL REDUNDANCY RELATIONS GENERATION

The Analytical Redundancy Relations ARR are symbolic equations representing constraints between different known process variables (parameters, measurements and sources). ARR are obtained from the behavioral model of the system through different procedures of the unknown variables elimination.

From equations of junctions we generate the following analytical redundancy relation:

$$\begin{aligned}
 ARR_1 &= [\phi_{R1} [(1-y_1)f_{R1} + y_1Df_1]] \\
 ARR_2 &= [\phi_{R2} [(1-y_2)f_{R2} + y_2Df_2]] \\
 ARR_3 &= [\phi_{R3} [(1-y_3)f_{R3} + y_3Df_3]] \\
 ARR_4 &= \frac{1}{s}(1-x_2)\phi_{C2}^{-1}f_{C2} + \phi_{R4} [(1-y_4)f_{R4} + y_4Df_4] + \left(\phi_{C5}Df_1^* + \frac{1}{s}(1-x_1)\phi_{C1}^{-1}f_{C1} + x_1De_1 \right) - \phi_{R7}Df_7 \\
 ARR_5 &= (1-y_5)\phi_{R5}^{-1}e_{R5} - y_5Df_5 + \phi_{C1} [s[(1-x_1)e_{C1} + x_1De_1]] \\
 ARR_6 &= \frac{1}{s}(1-x_1)\phi_{C1}^{-1}f_{C1} + x_1De_1 - \phi_{R5} [(1-y_5)f_{R5} + y_5Df_5] \\
 ARR_7 &= \phi_{C2} [s[(1-x_2)e_{C2} + x_2De_2]] \\
 ARR_8 &= \phi_{R5} [(1-y_6)f_{R5} + y_6Df_6] + m_1m_2^*Df_1 \\
 ARR_9 &= s(1-x_8)\phi_{L1}f_{L1} + x_8De_3 + \phi_{Rc} [(1-y_7)f_{Rc} + y_7Df_7] + se \\
 ARR_{10} &= r_1.r_7^*De_1(1-y_7)\phi_{Rc}^{-1}e_{Rc} - \phi_{L1}^{-1} [s[(1-x_8)e_{L1} + x_8De_3]] - [s(1-x_3)\phi_{C3}^{-1}f_{C3} + x_3De_9] \\
 ARR_{11} &= s\phi_{C3}(1-x_3)e_{C3} + \phi_{C3}x_3De_9 + [s(1-x_8)\phi_{L1}f_{L1} + x_8De_3] \\
 ARR_{12} &= \phi_{Rw} [(1-y_8)f_{Rw} + y_8Df_8] - s(1-x_9)\phi_{L5}f_{L5} + x_9De_4 + m_7Df_2^* \quad (5.56) \\
 ARR_{13} &= \frac{r_6}{m_1.m_4}Df_2^* + \phi_{L5}^{-1} \left[\frac{1}{s} [(1-x_9)e_{L5} + x_9De_4] \right] + \frac{1}{s}(1-x_4)\phi_{C5}^{-1}f_{C5} + x_4De_{10} + r_3^*De_3^* - Df_1 \\
 &+ (1-y_8)\phi_{Rw}^{-1}e_{Rw} + y_8Df_8 \\
 ARR_{14} &= s(1-x_9)\phi_{L5}f_{L5} + x_9De_4 - s\phi_{C5} [(1-x_4)e_{C5} + x_4De_{10}] \\
 ARR_{15} &= s(1-x_{10})\phi_{L2}f_{L2} + x_{10}De_5 + \phi_{R6} [(1-y_9)f_{R6} + y_9Df_9] \\
 ARR_{16} &= s\phi_{L2}^{-1} [(1-x_{10})e_{L2} + x_{10}De_5] + (1-y_9)\phi_{R6}^{-1}e_{R6} + \frac{1}{s}(1-x_5)\phi_{C5}^{-1}f_{C5} + x_5De_{11} + y_9Df_9 \\
 ARR_{17} &= s(1-x_{10})\phi_{L2}f_{L2} + x_{10}De_5 + s\phi_{C5} [(1-x_5)e_{C5} + x_5De_{11}] \\
 ARR_{18} &= s(1-x_{11})\phi_{L3}f_{L3} + x_{11}De_6 + \phi_{R7} [(1-y_{10})f_{R7} + y_{10}Df_{10}] - s(1-x_{12})\phi_{L4}f_{L4} + x_{12}De_7 \\
 ARR_{19} &= \frac{1}{s}(1-x_6)\phi_{C4}^{-1}f_{C4} + x_6De_{12} + (1-y_{10})\phi_{R7}^{-1}e_{R7} + y_{10}Df_{10} - \phi_{L3}^{-1} \left[\frac{1}{s} [(1-x_{12})e_{L3} + x_{12}De_6] \right] \\
 ARR_{20} &= s(1-x_{12})\phi_{L4}f_{L4} + x_{12}De_7 - \phi_{C4} [s[(1-x_6)e_{C4} + x_6De_{12}]] \\
 ARR_{21} &= \phi_{R8} [(1-y_{11})f_{R8} + y_{11}Df_{11}] - s(1-x_{13})\phi_{L4}f_{L4} + x_{13}De_7 - s(1-x_{11})\phi_{L3}f_{L3} + x_{11}De_6 \\
 ARR_{22} &= s(1-x_7)\phi_{Cw}^{-1}f_{Cw} + x_7De_{13} - (1-y_{11})\phi_{R8}^{-1}e_{R8} + y_{11}Df_{11} - \phi_{L4}^{-1} [s[(1-x_{13})e_{L4} + x_{13}De_7]]
 \end{aligned}$$

$$ARR_{23} = s(1-x_{14})\phi_{L5}f_{L5} + x_{14}De_8 - s(1-x_{13})\phi_{L4}f_{L4} + x_{13}De_7 + s\phi_{Cw}[(1-x_7)e_{Cw} + x_7De_{13}]$$

$$ARR_{24} = \frac{1}{r_3}Df_1^* + Sf + \phi_{R9}[(1-y_{12})f_{R9} + y_{12}Df_{12}] - [s(1-x_{14})\phi_{L5}f_{L5} + x_{14}De_8]$$

$$ARR_{25} = \phi_{R9}Df_{12} + \frac{m_5}{r_6}\left[\frac{1}{s}(1-x_8)\phi_{Cr}^{-1}f_{Cr} + x_8De_{14}\right] - \frac{1}{s}\phi_{L5}^{-1}[(1-x_{14})e_{L5} + x_{14}De_8]$$

$$ARR_{26} = s(1-x_7)\phi_{Cw}^{-1}f_{Cw} + x_7De_{13} - s(1-x_{14})\phi_{L5}f_{L5} + x_{14}De_8 + s\phi_{Cr}[(1-x_8)e_{Cr} + x_8De_{14}]$$

Now, we will study, the combinatorial problematic of sensor placement. We have shown that to each sensor position, a binary variable (0–1) can be associated. The optimal solution is then a binary vector in which “1” value indicates that a sensor has to be placed.

From junctions equations we obtains ARRs and according to binary variables x_i, y_j and we finds the final structure of the system to be supervised. The question which arises then, can we supervise the global model of system with twenty tree sensors? And which would be the combination which ensures this property?

$$\text{For } [y_1 y_2 y_3 y_4 x_1 y_5 x_2 y_6 y_7 x_3 y_8 x_{10} x_4 y_9 x_{11} x_5 y_{10} x_{12} x_6 y_{11} x_{13} x_7 y_{12} x_{14} x_8] = [11110111010111111111111111]$$

The results of this placement are represented by the system of equations (5.57).

$$ARR_1 = \phi_{R1}Df_1 + \frac{r_1}{r_5}(Df_1^* + Df_2^*)$$

$$ARR_2 = \phi_{R2}Df_2 - m_6De_2^*$$

$$ARR_3 = -r_1Df_2^* + Sf + \phi_{R3}Df_3$$

$$ARR_4 = m_7\phi_{C1}Df_1^* - s\phi_{C1}De_1 + \phi_{R4}Df_2^* + Se - \phi_{R4}Df_4$$

$$ARR_5 = \frac{-m_1m_3}{r_2}De_1^* - \phi_{C1}De_1 - \phi_{R5}Df_5 + Sf$$

$$ARR_6 = s\phi_{C2}De_2 + Se$$

$$ARR_7 = -\phi_{R5}Df_6 + Df_1^* - De_1^*$$

$$ARR_8 = De_1^* + Df_2^* + \phi_{Rc}Df_1^* - \frac{1}{s}\phi_{L1}De_8 + \phi_{C3}De_3.$$

$$ARR_9 = \frac{m_3}{m_1}Df_2^* - \frac{1}{r_1}\phi_{Rw}Df_8 - m_6De_{10}^*$$

$$ARR_{10} = Df_8 - r_2s\phi_{L5}De_9$$

$$ARR_{11} = Se - s\phi_{Cs}De_{10}$$

$$ARR_{12} = m_1De_3^* - \phi_{R6}Df_9 \tag{5.57}$$

$$ARR_{13} = m_5(Df_2^* + De_1^*) - s\phi_{L2}De_5$$

$$ARR_{14} = De_1^* + Sf - m_3De_{12} + s\phi_{C5}De_{11}$$

$$ARR_{15} = Se - \phi_{R7}Df_{10} - De_6$$

$$ARR_{16} = Df_{10} - s\phi_{L3}De_6 - r_4De_{12}$$

$$ARR_{17} = \frac{1}{r_5} De_6 + s\phi_{C4} De_{12} - De_2^*$$

$$ARR_{18} = De_8 - Df_2^* + \phi_{R8} Df_{11} - De_7^*$$

$$ARR_{19} = \frac{1}{m_1} Df_{11} - s\phi_{L4} De_7$$

$$ARR_{20} = s\phi_{Cw} De_{13} + Se - m_1 Df_1^*$$

$$ARR_{21} = Sf - \phi_{R9} Df_{12}$$

$$ARR_{22} = Df_{12} - \phi_{L5}^{-1} \frac{1}{s} De_8 - \frac{1}{r_6} De_{14}^*$$

$$ARR_{23} = r_3 r_6 Df_1^* - s\phi_{Cr} De_{14} - De_1^* + \frac{m_1}{m_2 + m_7} De_5$$

The matrix of corresponding signature of the failures is represented by the table (5.1).

Table 5. 1 Signature matrix of the failures

	R1	R2	R3	R4	R5	R6	R7	R8	R9	Rc	Rs	Rw	C1	C2	C3	C4	C5	Cr	Cs	Cw	L1	L2	L3	L4	L5	Ls
ARR1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 4	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 5	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 6	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
ARR 7	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 8	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
ARR 9	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
ARR 11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
ARR 12	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
ARR 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
ARR 15	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
ARR 17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
ARR 18	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
ARR 20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
ARR 21	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
ARR 23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0

It is noticed that the structures of the residues are different and the signatures of faults are not different (R_c , L_1 and C_3) and no-null. Thus components R_c , L_1 and C_3 are detectable but not isolable then not monitoring. What takes us along to saying that the total system is not monitoring.

For $[y_1 y_2 y_3 y_4 x_1 y_5 x_2 y_6 y_7 x_9 x_3 y_8 x_{10} x_4 y_9 x_{11} x_5 y_{10} x_{12} x_6 y_{11} x_{13} x_7 y_{12} x_{14} x_8] = [11110111101101101101101101]$

The results of this placement are represented by the system of equations (5.58).

$$\begin{aligned}
 ARR_1 &= m_1 m_5 De_2 + \phi_{R1} Df_1 \\
 ARR_2 &= m_1 De_1^* - \phi_{R2} Df_2 \\
 ARR_3 &= \phi_{R3} Df_3 - m_2 De_1^* \\
 ARR_4 &= \phi_{C1} De_1^* + \frac{1}{r_2} \phi_{R7} Df_1^* + s \phi_{C1} De_1 + \phi_{R4} Df_4 \\
 ARR_5 &= \frac{1}{s} \phi_{Cr}^{-1} f_{Cr} - \phi_{Rr} Df_5 \\
 ARR_6 &= Sf + Df_1^* - s \phi_{C2} De_2 \\
 ARR_7 &= Sf + \phi_{R5} Df_6 \\
 ARR_8 &= Vsa + De_3^* - \phi_{Rsa} Df_7 - s \phi_{Isa} f_{Isa} \\
 ARR_9 &= \frac{1}{r_1} s \phi_{Isa} f_{Isa} - \phi_{Csa} s De_9 - \phi_R^{-1} De_4^* \\
 ARR_{10} &= m_6 (De_1^* - De_2^*) + \phi_{Rw} Df_8 - s \phi_{Ls} De_1^* \\
 ARR_{11} &= \frac{m_1}{m_3 m_2} s \phi_{Ls} De_1^* - \phi_{Cs} De_{10} \\
 ARR_{12} &= Sf + De_1^* - \phi_{R6} Df_9 - \frac{1}{s} \phi_{L2} De_1^* \\
 ARR_{13} &= \frac{1}{s} \phi_{L2} De_1^* - s \phi_{C5} De_{11} - \frac{1}{r_1} \phi_{R7} De_6^* \\
 ARR_{14} &= \frac{r_1}{r_2} (Df_1^* + Df_2^*) + \phi_{R7} Df_{10} - s \phi_{L3} f_{L3} \\
 ARR_{15} &= s \phi_{L3} f_{L3} + r_3 s \phi_{C4} De_{12} \\
 ARR_{16} &= m_1 \phi_{R8} Df_{11} - \frac{m_2}{r_4} s \phi_{L4} f_{L4} + \phi_{R9} Df_{12} \\
 ARR_{17} &= s \phi_{L4} f_{L4} - \frac{1}{s} \phi_{Crb} De_3 + m_5 Df_1 \\
 ARR_{18} &= De_1^* - \phi_{R9} Df_{12} - \frac{1}{s} \phi_{L5} De_{14} \\
 ARR_{19} &= r_1 m_1 De_1^* \frac{1}{s} \phi_{L5} De_{14} + s \phi_{Cr} De_{14} - De_1^*
 \end{aligned} \tag{5.58}$$

The matrix of corresponding signature of the failures is represented by the table (5.2).

Table 5. 2 Signature matrix of the failures

	R1	R2	R3	R4	R5	R6	R7	R8	R9	Rc	R5	Rw	C1	C2	C3	C4	C5	Ct	Cs	Cw	L1	L2	L3	L4	L5	Ls
ARR1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 4	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 5	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 6	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
ARR 7	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ARR 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
ARR 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
ARR 10	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
ARR 11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
ARR 12	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
ARR 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0
ARR 14	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
ARR 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0
ARR 16	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
ARR 17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0
ARR 18	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
ARR 19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0

The matrix of corresponding signature of the failures is represented by the table (5.2). It is noticed that the structures of the residues are different and the signatures of the defects are also different and no-null. Then all the components are detectable and isolable thus monitoring with nineteen sensors only.

5.4. ANALYSIS TOOLS AND SIMULATION PROCEDURE

Software SYMBOLS (SYstem Modeling by Bond graph Language and Simulation), created by Indian Institute of Technology, Consultants HighTech, is a software of simulation modeling and control of various systems for scientific applications variety and of engineer. A SYMBOLS is object oriented hierarchical hybrid modeling, simulation and control analysis software. It allows users to create models using bond graph, block-diagram and equation models. Large number of advanced sub-models called Capsules is available for different engineering and modeling domains. It automatically derives completely reduced system equations. Differential causalities and algebraic loops are solved using its powerful symbolic solution engine. Non-linearity and user code can be integrated in single editing IDE. It creates high-level C language code and allows any external code embedding. The simulator module has both online and post-display facilities. Event handlers and online event notification and variation of parameters are key features of this advanced simulator. It has a well-developed controls module that automatically transforms state-space modules from graph or blocks

diagram models and converts them to analog or digital transfer functions. Most control charts and high-level control analysis can be performed. In this section, we will give the results obtained from the developed method for one or more sensor faults.

5.4.1. SINGLE FAULT

For the faults detection of our system we use the precedent Analytical Redundancy Relations (ARRs). We create the faults on monitoring components with this software fault here is considered in the total absence or the deviation of the nominal value given out by the component to monitor.

The numeric values of components are not considered, only their presence or absences in the relation are taken in account with evaluation term the operators (+, -). It is the qualitative approach for bond graph monitoring.

5.4.1.1. SENSITIVITY OF DETECTOR DF1

In the first time, we create a fault between the instant $t = 4$ h and $t = 6$ h in the first sensor (DF1). The default on the wind turbine depends especially on the environment. For example, for the wind sites-often in mountain-snow, or falls of branches can cause damage.

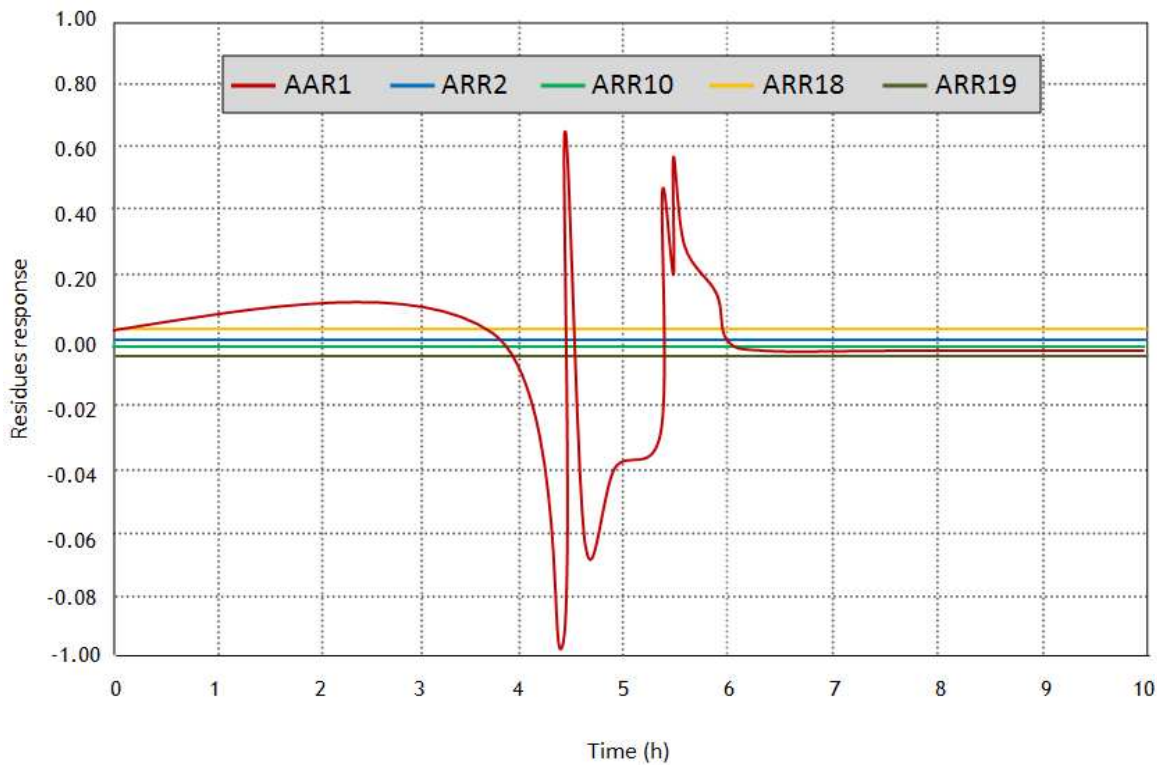


Figure 5. 2 Sensitivity of detector Df1

In figure (5.2) we present five residuals, the failure on R1 is characterized by the presence of the detector Df1 in the analytical redundancy relation ARR1. We note that the residual ARR1 is sensitive to the failures which affect R1, but residuals ARR2, ARR10, ARR18 and ARR19 are equals to zero.

5.4.1.2. SENSITIVITY OF DETECTOR DE13

We create a fault between the instant $t = 4$ h and $t = 6$ h in the thirteenth sensor (DE13). A stator winding fault in the generator was simulated on the test rig by simultaneously shorting 3 coils installed on the stator of the generator. When the connection state of the coils was changed periodically, the torque and rotational speed signals were collected from the generator shaft. The time-waveforms of the signals are shown in figure (5.3).

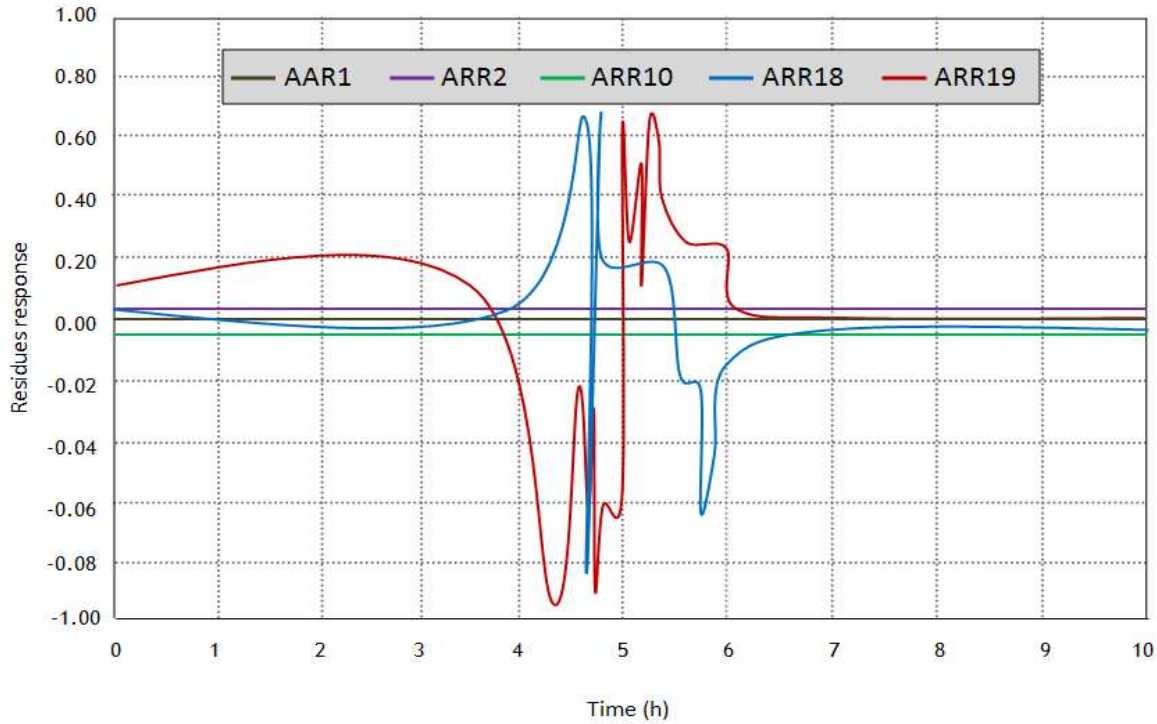


Figure 5. 3 Sensitivity of detector De13

The figure (5.3) shows the response of the residues. It is noted that residue ARR18 present a short change compared to its initial state between $t_1=4$ h and $t_2=6.5$ h but turns over in their initial state from $t=10$ h and same thing for ARR19, but other residues ARR1, ARR2 and ARR10 remain invariant.

If we refers to the signature of the Irc component given to table (5.2) we notes that this result is in conformity with what is envisaged; i.e. that in the event of failure of the Irc component the residues ARR18 and ARR19 will are sensitive.

5.4.2. MULTIPLE FAULTS

5.4.2.1. SENSITIVITY OF DETECTORS DF1 AND DE13

We create tow fault, the first fault between the instant $t = 4$ h and $t = 9$ h in the first sensor (DF1) and the second fault between the instant $t = 7$ h and $t = 9$ h in the thirteenth sensor (DE13). The fault at the first sensor (DF1) is still occurred when the fault at thirteenth sensor (DE13) has been introduced.

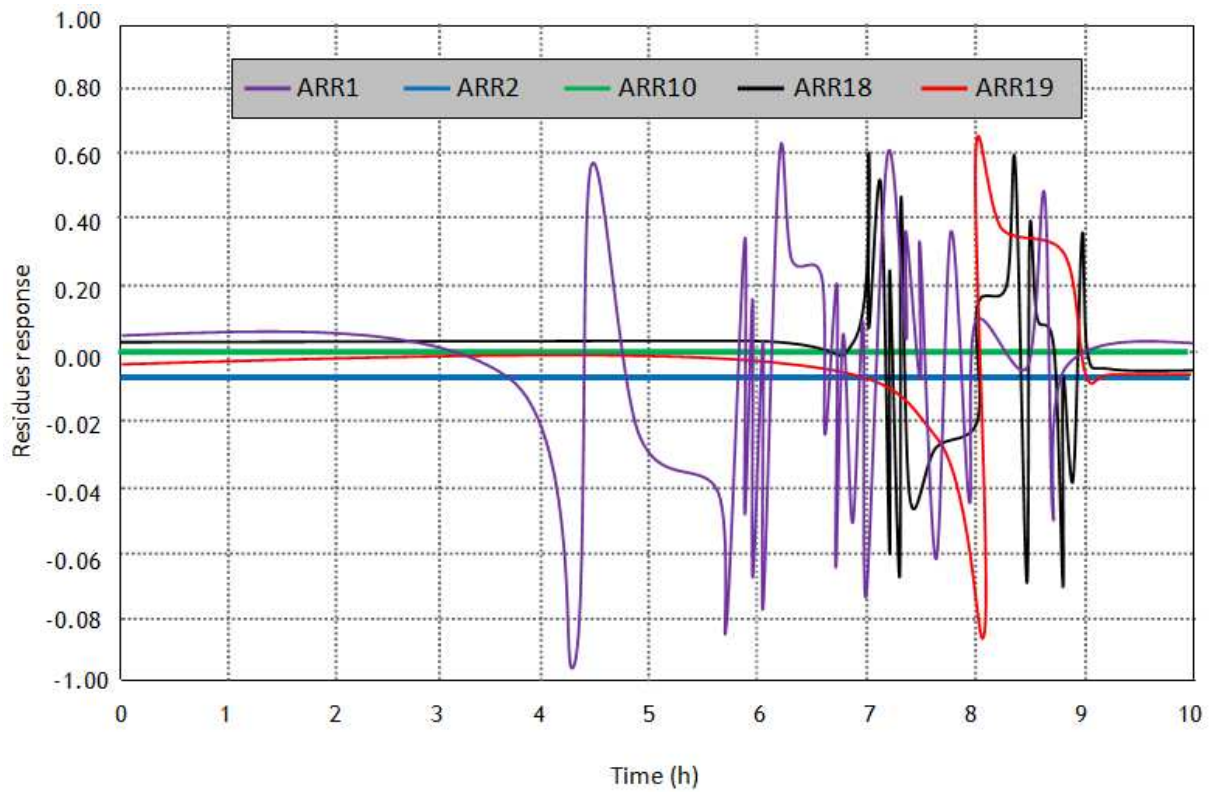


Figure 5. 4 Sensitivity of detectors Df1 and De13

Figure (5.4) shows the five residuals (ARR1, ARR2, ARR10, ARR18 and ARR19) where after the initialization, they have a constant value until $t=4$ h. There, all the residuals retain their initial values and only the residual ARR1 that corresponds at the first sensor stays to the new value.

At time $t=7$ h, where the second fault has been entered, the residuals that corresponds to the thirteenth sensor (ARR18 and ARR19) change from his initial value. It stays at the new value until $t=9$ h but the other two residuals (ARR2 and ARR10) retain their initial value. The first residual (ARR1), which corresponds to the first sensor where the first fault still occurs, has not been affected by the new fault.

5.4.3. SIMULTANEOUS FAULTS

We illustrate the case where more than one faults occur at the same time on the system or briefly the simultaneous faults. We have applied two faults: one on the first sensor (DF1) and one on the thirteenth sensor (DE13) at the same time $t=4$ h ($t=4$ h until $t=6$ h).

In figure (5.5), we give the five residuals (ARR1, ARR2, ARR10, ARR18 and ARR19) and we can see that their values are equal to a constant value until $t=4$ h where the two faults occur on the system. At that time, only the residual associated to the first sensor (ARR1) and this residuals correspond to the thirteenth sensor (ARR18 and ARR19) change from his initial value and stays to their new value until $t=6$ h; the other two residuals (ARR2 and ARR10) retain their initials values.

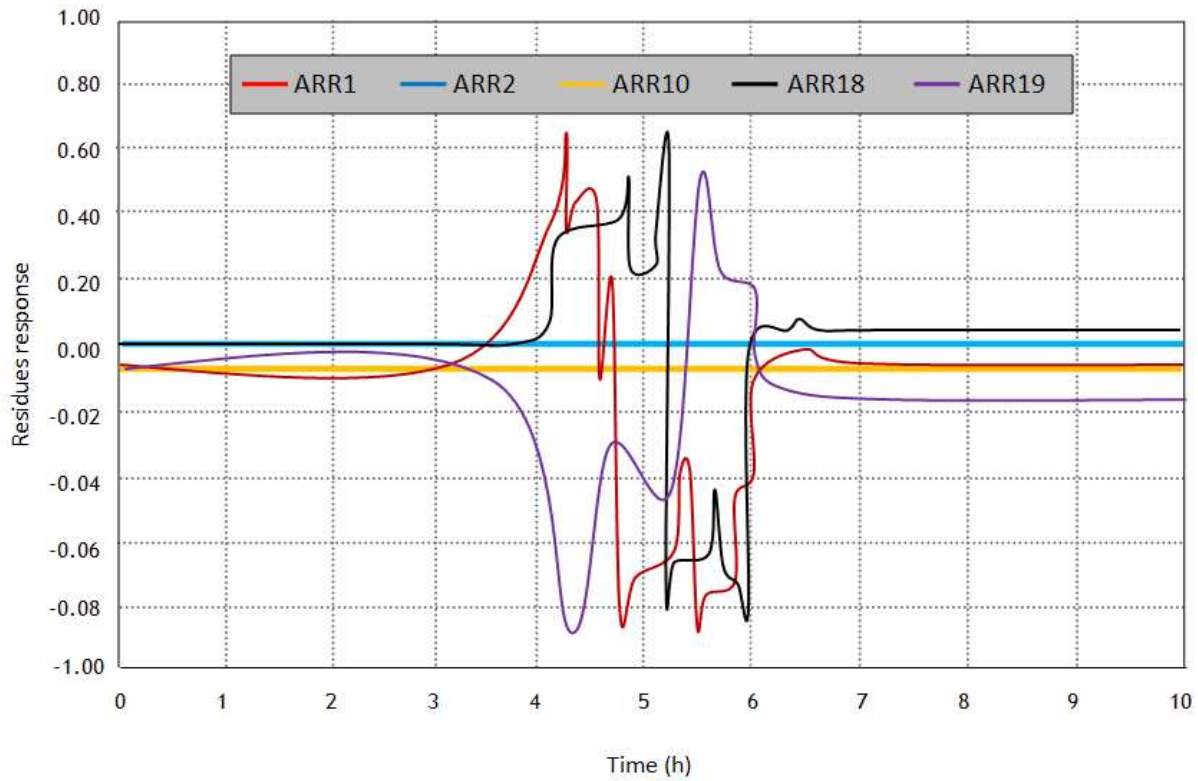


Figure 5. 5 Sensitivity of detectors Df1 and De13

5.5. CONCLUSION

The diagnostic strategy and the form in which knowledge is available conditioned the method used to design the monitoring algorithm. According to the type of knowledge, the criterion of classification of the monitoring method distinguishes between two types of approaches: methods with or without model. Our contribution relates to the methods containing model. The results found here are proven interesting because the simulation of faults in quite precise moments were confirmed by the simulation software starting from the sensitivity of the indicators installed.

The generation of the analytical redundancy relations by the bond graph approach shows some interesting characteristics:

- They are simple to include/understand, since they correspond to relations and variables which are posted by the model bond graph image of the physical process, these relations are deduced directly from the graphic representation.
- They can be generated in form symbolic system and thus adapted to a data-processing implementation.

CHAPTER 6: Fault Detection and Isolation in Photovoltaic System

The use of renewable energy is growing significantly around the world. In front of the growing demand for electricity essentially for the remote and deserted locations needs. Photovoltaic systems, especially water pumping systems, begin to find great applications. Unfortunately these systems have encountered a number of problems even nowadays: a problem of maintenance. Therefore, we have conducted a study with an aim to design a tool for the diagnosis and repair, which uses the methodology of case-based reasoning, in order to ensure proper operation and ease of maintenance strategies.

6.1. INTRODUCTION

The fast evolution of the renewable energy sources during the two last decades had as consequence the installation of many systems in the world. The disadvantage of the latter is the high cost of installation. The good dimensioning of a PV installation is very important initially for the optimization of its size and its cost. Then, it is important to continuously follow and control the performances of this PV installation. Electrical faults and the aging of PV modules cause a malfunction of the photovoltaic system. Several research laboratories were interested about the renewable energy sources [195], [196] and various techniques were developed either for dimensioning, the regulation to have a maximum of power [197], or for the fault detection [198] - [201]. The monitoring and the control of the performances of system state and their produced powers are the higher importance to evaluate them continuously, to monitor the evolution of their capabilities, and to detect the faults. In this chapter, we present a technique which contributes to the detection of the faults and to monitoring the degradation of the performances of a PV system.

In recent years we have found in the literature a lot of methods of faults diagnosis of PV panels [202] - [206]. K-H. Chao and al. [200] use a software package called "PSIM" for the fault detection. This software package not only makes it possible to diagnose the fault but also to give the characteristic curves of $I(V)$ and $P(V)$ at variable surface temperatures of PV panels. Another technique has been developed by Y. Yagi and al [204] called "Learning method" to diagnose faults on PV panels, this technique uses criteria of database and then analyzes the data obtained from the photovoltaic system and determines if the installation functions correctly. These criteria are updated monthly for each site location of PV panels. Moreover, this method also makes it possible to check if the PV panels are shaded.

In recent years, the impact of partial shading on the photovoltaic array performance has been widely discussed [207] - [211]. With a physical photovoltaic module it is difficult to study the effects of partial shading since the field testing is costly, time consuming and depends heavily on the prevailing weather conditions. Moreover, it is difficult to maintain the same shade under varying numbers of shaded and fully illuminated cells throughout the experiment. However it is convenient to carry out the simulation study with the help of a computer model. In most of the studies [212] - [219], the effect of partial shading in reducing the output power of the photovoltaic has been discussed. But little attention has been paid to the power dissipated by the shaded cells affecting the array life and utilization of the array for the worst shaded case.

The investigation into mismatch problems of PV arrays can be traced back to as early as late eighties when Bishop [220] proposed a voltage sweeping method to draw the current-voltage ($I-V$) curve of a PV array with shaded cells. Since then, studies on mismatch of PV arrays, in particular those caused by partial shading, have become active. Shortly later, Abete et al. [221] applied Bishop's method to study the behaviour of a mismatched PV array in presence of bypass diodes. We note that both Bishop [220] and Abete et al. [221] avoided solving nonlinear implicit equations governing PV cell circuits by sweeping the diode voltage to obtain the corresponding $I-V$ curves of PV cells. On the other hand, the Newton-Raphson

method, a widely applied iterative numerical method for solving nonlinear equations, was not used for the analysis of PV array networks until the work of Quaschning and Hanitsch [222], subsequent to which Kawamura et al. [223], Alonso-Garcia et al. [224] and Wang and Hsu [225] also adopted the Newton-Raphson method for analyzing mismatched PV arrays.

6.2. FAULT DIAGNOSIS OF PHOTOVOLTAIC PANELS

The default on the photovoltaic panels depends especially on the environment. For example, for the isolated sites-often in mountain-snow, or falls of branches can cause damage.

Urban installations can be touched by projectiles. The lightning can also deteriorate the installations. Connections and the weldings connectors can also be degraded with time.

Another very frequent phenomenon was the cause of much deterioration on the first generation of photovoltaic panels: Hot Spot [226]-[229]. This phenomenon appears when a shade comes to cover one or more cells of the panel. This shade can for example, come from an electric pole near the panel or a dead sheet which comes to be stuck to the panel. This cell then does not produce electricity anymore and behaves like a receiver. The cells composing a panel are all connected in series and when a cell does not produce electricity any more, the current produced by the others which crosses this cell converted into heat. This phenomenon creates important rises in temperature which frequently involve the deterioration of the cell.

To remove this problem, the manufacturers place a diode in parallel all the 18 cells, therefore two diodes for a standard panel of 36 cells. These By-pass diodes derive the current of the line from cells having the shade.

6.3. PROBLEM STATEMENT

Several conditions impair the performance of PV arrays, including partial shading, module soiling, inverter failure, and mismatch due to variation in manufacturing or aging of PV modules. In general, faults result in a characteristic pattern in which the faulty module (s) form a cluster in I-V space, while the rest of the string in which the fault occurs forms another cluster, and the remaining un affected modules in the other strings form a third cluster. This paper focuses on the detection of ground and arc faults.

6.3.1. GROUND FAULT

A ground fault occurs when a PV array develops an unintentional low-resistance path to ground, such as when wire insulation is compromised, leaving it in contact with adjacent conductors. This shorts one or more modules in a string, leaving the rest of the modules to make up the difference in voltage.

Some modules are shorted and operate at a higher current and much lower voltage than their MPP, while the rest of the string operates at a higher voltage and lower current than their MPP.

6.3.2. ARC FAULT

An arc fault is the unintended flow of current through air or another dielectric. Arc faults are generally divided into two categories: series and parallel arcs. A series arc occurs when a short break is created in a conductor, such as when a connect or pulls a part due to aging or thermal stress. A parallel arc occurs when two conductors of widely differing voltage are placed near one another, for instance when the insulation on a cable running over a steel frame is compromised. The current through a series arc is generally limited by the circuit with which it is in series, while a parallel arc can theoretically consume as much power as a source is able to supply.

Several models exist which attempt to describe the behavior of an electric arc. One extremely simple approach is the Cassie model, which describes an arc as a time-varying conductance with constant steady-state voltage. The Mayr model takes a similar approach but assigns an arc constant steady-state power dissipation. The Habedank model [230] consists of Cassie and Mayr arcs in series with one another.

6.4. TECHNICAL SPECIFICATIONS FOR SENSORS PLACEMENT

We assume that the faults are not multiple and may affect only components. Let given a bond graph model obtained from physical process (figure 6.1), these figure present the bond graph model simplified of the experimental step (figure 4.23) . We suppose that the sensors are not placed yet on the bond graph model. For this application, the equations in junctions are given by:

For 0_1 junction:

$$\begin{cases} e_4 = e_1, e_4 = e_2, e_4 = e_3 \\ Msf - f_2 - f_3 - f_4 = 0 \end{cases} \quad (6.1)$$

For 1_1 junction:

$$\begin{cases} f_4 = f_5, f_4 = f_6 \\ e_4 - e_5 - e_6 = 0 \\ e_{R_{S1}} = \phi_{R_{S1}} \left[(1 - y_1) f_5 + y_1 Df_1 \right] \\ f_{R_{S1}} = (1 - y_1) \phi_{R_{S1}}^{-1} e_5 + y_1 Df_1 \end{cases} \quad (6.2)$$

For 0_2 junction:

$$\begin{cases} e_9 = e_6, e_9 = e_7, e_9 = e_8 \\ f_6 - f_7 - f_8 - f_9 = 0 \end{cases} \quad (6.3)$$

For 1_2 junction:

$$\begin{cases} f_9 = f_{10}, f_9 = f_{11} \\ e_9 - e_{10} - e_{11} = 0 \\ e_{R_{S2}} = \phi_{R_{S2}} \left[(1 - y_2) f_{10} + y_2 Df_2 \right] \\ f_{R_{S2}} = (1 - y_2) \phi_{R_{S2}}^{-1} e_{10} + y_2 Df_2 \end{cases} \quad (6.4)$$

For 0_3 junction:

$$\begin{cases} e_{14} = e_{11}, e_{14} = e_{12}, e_{14} = f_{13} \\ f_{11} - f_{12} - f_{13} - f_{14} = 0 \end{cases} \quad (6.5)$$

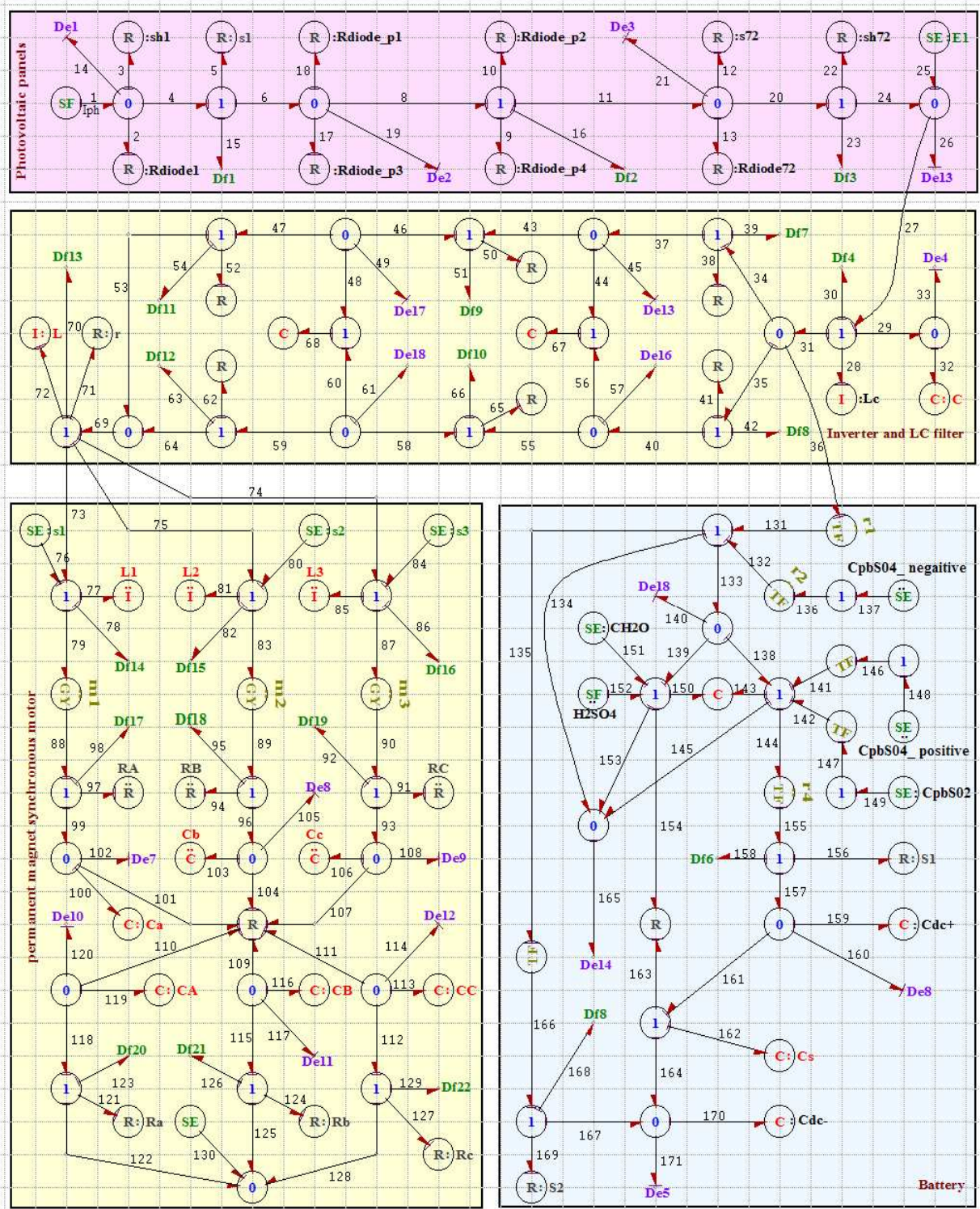


Figure 6. 1 Bond graph model with sensors placement

For 1_3 junction:

$$\begin{cases} f_{14} = f_{15}, f_{14} = f_{16} \\ e_{14} - e_{15} - e_{16} = 0 \\ e_{R_{S72}} = \phi_{R_{S72}} \left[(1 - y_3) f_{15} + y_3 Df_3 \right] \\ f_{R_{S72}} = (1 - y_3) \phi_{R_{S72}}^{-1} e_{15} + y_3 Df_3 \end{cases} \quad (6.7)$$

For 0₄ junction:

$$\begin{cases} e_{17} = e_{16}, e_{17} = e_{18} \\ f_{16} + f_{17} - f_{18} = 0 \end{cases} \quad (6.8)$$

For 1₄ junction:

$$\begin{cases} f_{20} = f_{18}, f_{20} = f_{19}, f_{20} = f_{21} \\ e_{18} - e_{19} - e_{20} - e_{21} = 0 \\ e_{L_c} = \phi_{L_c} \left[(1 - z_1) f_{19} + z_1 Df_4 \right] \\ f_{L_c} = (1 - z_1) \phi_{L_c}^{-1} e_{19} + z_1 Df_4 \end{cases} \quad (6.9)$$

For 0₅ junction:

$$\begin{cases} e_{22} = e_{21} \\ f_{21} - f_{22} = 0 \\ f_{C_c} = \phi_{C_c} \left[S \{ (1 - x_1) e_{22} + x_1 D e_1 \} \right] \\ e_{L_c} = \frac{1}{S} (1 - x_1) \phi_{C_c}^{-1} f_{22} + x_1 D e_1 \end{cases} \quad (6.10)$$

For 0₆ junction:

$$\begin{cases} e_{20} = e_{23}, e_{20} = e_{24}, e_{20} = e_{25} \\ f_{20} - f_{23} - f_{24} - f_{25} = 0 \end{cases} \quad (6.11)$$

For TF₁ junction:

$$\begin{cases} e_{25} = r_1 \cdot e_{23} \\ f_{26} = r_1 \cdot f_{25} \end{cases} \quad (6.12)$$

For 1₅ junction:

$$\begin{cases} f_{30} = f_{26}, f_{30} = f_{27}, f_{30} = f_{29}, f_{30} = f_{52} \\ -e_{30} + e_{26} + e_{27} + e_{29} + e_{52} = 0 \end{cases} \quad (6.13)$$

For TF₂ junction:

$$\begin{cases} e_{28} = r_2 \cdot e_{27} \\ f_{27} = r_2 \cdot f_{28} \end{cases} \quad (6.14)$$

For TF₃ junction:

$$\begin{cases} e_{30} = r_3 \cdot e_{31} \\ f_{31} = r_3 \cdot f_{30} \end{cases} \quad (6.15)$$

For 1₆ junction:

$$\begin{cases} f_{32} = f_{31}, f_{32} = f_{33} \\ e_{31} - e_{32} - e_{33} = 0 \\ e_{R_{SS2}} = \phi_{R_{SS2}} \left[(1 - y_4) f_{32} + y_4 Df_5 \right] \\ f_{R_{SS2}} = (1 - y_4) \phi_{R_{SS2}}^{-1} e_{32} + y_4 Df_5 \end{cases} \quad (6.16)$$

For 0₇ junction:

$$\begin{cases} e_{34} = e_{33}, e_{34} = e_{35} \\ f_{33} - f_{34} - f_{35} = 0 \\ f_{C_{dc^-}} = \phi_{C_{dc^-}} \left[S \{ (1-x_2) e_{34} + x_2 D e_5 \} \right] \\ e_{C_{dc^-}} = \frac{1}{S} (1-x_2) \phi_{C_{dc^-}}^{-1} f_{34} + x_2 D e_5 \end{cases} \quad (6.17)$$

For 1₇ junction:

$$\begin{cases} f_{36} = f_{35}, f_{36} = f_{37}, f_{36} = f_{38} \\ e_{35} - e_{36} - e_{37} - e_{38} = 0 \end{cases} \quad (6.18)$$

For 0₈ junction:

$$\begin{cases} e_{39} = e_{38}, e_{39} = e_{40} \\ -f_{38} - f_{39} + f_{40} = 0 \\ f_{C_{dc^+}} = \phi_{C_{dc^+}} \left[S \{ (1-x_3) e_{39} + x_3 D e_6 \} \right] \\ e_{C_{dc^+}} = \frac{1}{S} (1-x_3) \phi_{C_{dc^+}}^{-1} f_{39} + x_3 D e_6 \end{cases} \quad (6.19)$$

For 1₈ junction:

$$\begin{cases} f_{41} = f_{40}, f_{41} = f_{42} \\ -e_{40} - e_{41} + e_{42} = 0 \\ e_{R_{SS1}} = \phi_{R_{SS1}} \left[(1-y_5) f_{41} + y_5 D f_6 \right] \\ f_{R_{SS1}} = (1-y_5) \phi_{R_{SS1}}^{-1} e_{41} + y_5 D f_6 \end{cases} \quad (6.20)$$

For TF₄ junction:

$$\begin{cases} e_{43} = r_4 \cdot e_{42} \\ f_{42} = r_4 \cdot f_{43} \end{cases} \quad (6.21)$$

For 1₉ junction:

$$\begin{cases} f_{43} = f_{44}, f_{43} = f_{45}, f_{43} = f_{46}, f_{43} = f_{47}, f_{43} = f_{49} \\ -e_{43} + e_{44} + e_{45} + e_{46} + e_{47} + e_{49} = 0 \end{cases} \quad (6.22)$$

For TF₅ junction:

$$\begin{cases} e_{50} = r_5 \cdot e_{49} \\ f_{49} = r_5 \cdot f_{50} \end{cases} \quad (6.23)$$

For TF₆ junction:

$$\begin{cases} e_{48} = r_6 \cdot e_{47} \\ f_{47} = r_6 \cdot f_{48} \end{cases} \quad (6.24)$$

For 0₉ junction:

$$\begin{cases} e_{51} = e_{45}, e_{51} = e_{52} \\ -f_{45} - f_{52} + f_{51} = 0 \end{cases} \quad (6.25)$$

For 0₁₀ junction:

$$\begin{cases} e_{54} = e_{29}, e_{54} = e_{44} \\ f_{54} - f_{29} - f_{44} = 0 \end{cases} \quad (6.26)$$

For 1₁₁ junction:

$$\begin{cases} f_{56} = f_{23}, f_{56} = f_{55} \\ e_{23} - e_{55} - e_{56} = 0 \\ e_{R_{D1}} = \phi_{R_{D1}} \left[(1 - y_6) f_{55} + y_6 Df_7 \right] \\ f_{R_{D1}} = (1 - y_6) \phi_{R_{D1}}^{-1} e_{55} + y_6 Df_7 \end{cases} \quad (6.27)$$

For 1₁₂ junction:

$$\begin{cases} f_{57} = f_{24}, f_{57} = f_{58} \\ e_{24} - e_{57} - e_{58} = 0 \\ e_{R_{D4}} = \phi_{R_{D4}} \left[(1 - y_7) f_{57} + y_7 Df_8 \right] \\ f_{R_{D4}} = (1 - y_7) \phi_{R_{D4}}^{-1} e_{57} + y_7 Df_8 \end{cases} \quad (6.28)$$

For 0₁₁ junction:

$$\begin{cases} e_{56} = e_{61}, e_{56} = e_{62} \\ f_{56} - f_{61} - f_{62} = 0 \end{cases} \quad (6.29)$$

For 0₁₂ junction:

$$\begin{cases} e_{58} = e_{59}, e_{58} = e_{67} \\ f_{58} + f_{59} - f_{67} = 0 \end{cases} \quad (6.30)$$

For 1₁₃ junction:

$$\begin{cases} f_{59} = f_{60}, f_{59} = f_{61} \\ -e_{59} - e_{60} + e_{61} = 0 \end{cases} \quad (6.31)$$

For 1₁₄ junction:

$$\begin{cases} f_{64} = f_{62}, f_{64} = f_{63} \\ e_{62} - e_{63} - e_{64} = 0 \\ e_{R_{D2}} = \phi_{R_{D2}} \left[(1 - y_8) f_{63} + y_8 Df_9 \right] \\ f_{R_{D2}} = (1 - y_8) \phi_{R_{D2}}^{-1} e_{63} + y_8 Df_9 \end{cases} \quad (6.32)$$

For 1₁₅ junction:

$$\begin{cases} f_{68} = f_{67}, f_{68} = f_{69} \\ e_{67} - e_{68} - e_{69} = 0 \\ e_{R_{D5}} = \phi_{R_{D5}} \left[(1 - y_9) f_{68} + y_9 Df_{10} \right] \\ f_{R_{D5}} = (1 - y_9) \phi_{R_{D5}}^{-1} e_{68} + y_9 Df_{10} \end{cases} \quad (6.33)$$

For 0₁₃ junction:

$$\begin{cases} e_{64} = e_{65}, e_{64} = e_{73} \\ f_{64} - f_{65} - f_{73} = 0 \end{cases} \quad (6.34)$$

For 0₁₄ junction:

$$\begin{cases} e_{66} = e_{69}, e_{66} = e_{70} \\ f_{66} + f_{69} - f_{70} = 0 \end{cases} \quad (6.35)$$

For 1₁₆ junction:

$$\begin{cases} f_{66} = f_{65}, f_{66} = f_{84} \\ e_{65} - e_{66} - e_{84} = 0 \end{cases} \quad (6.36)$$

For 1₁₇ junction:

$$\begin{cases} f_{74} = f_{73}, f_{74} = f_{75} \\ e_{73} - e_{74} - e_{75} = 0 \\ e_{R_{D3}} = \phi_{R_{D3}} \left[(1 - y_{10}) f_{74} + y_{10} Df_{11} \right] \\ f_{R_{D3}} = (1 - y_{10}) \phi_{R_{D3}}^{-1} e_{74} + y_{10} Df_{11} \end{cases} \quad (6.37)$$

For 1₁₈ junction:

$$\begin{cases} f_{71} = f_{70}, f_{71} = f_{72} \\ e_{70} - e_{71} - e_{72} = 0 \\ e_{R_{D6}} = \phi_{R_{D6}} \left[(1 - y_{11}) f_{71} + y_{11} Df_{12} \right] \\ f_{R_{D6}} = (1 - y_{11}) \phi_{R_{D6}}^{-1} e_{71} + y_{11} Df_{12} \end{cases} \quad (6.38)$$

For 1₁₉ junction:

$$\begin{cases} f_{78} = f_{76}, f_{78} = f_{77}, f_{78} = f_{79}, f_{78} = f_{80}, f_{78} = f_{81} \\ e_{76} - e_{77} - e_{78} - e_{79} - e_{80} - e_{81} = 0 \end{cases} \quad (6.39)$$

For 1₂₀ junction:

$$\begin{cases} f_{81} = f_{82}, f_{81} = f_{83}, f_{81} = f_{85} \\ e_{81} - e_{82} + e_{83} - e_{85} = 0 \\ e_{L_1} = \phi_{L_1} \left[(1 - z_3) f_{82} + z_3 Df_{14} \right] \\ f_{L_1} = (1 - z_3) \phi_{L_1}^{-1} e_{82} + z_3 Df_{14} \end{cases} \quad (6.40)$$

For 1₂₁ junction:

$$\begin{cases} f_{80} = f_{86}, f_{80} = f_{87}, f_{80} = f_{90} \\ e_{80} + e_{87} - e_{86} - e_{90} = 0 \\ e_{L_2} = \phi_{L_2} \left[(1 - z_4) f_{86} + z_4 Df_{15} \right] \\ f_{L_2} = (1 - z_4) \phi_{L_2}^{-1} e_{86} + z_4 Df_{15} \end{cases} \quad (6.41)$$

For 1₂₂ junction:

$$\begin{cases} f_{79} = f_{88}, f_{79} = f_{89}, f_{79} = f_{91} \\ e_{79} + e_{88} - e_{89} - e_{91} = 0 \\ e_{L_3} = \phi_{L_3} \left[(1 - z_5) f_{89} + z_5 Df_{16} \right] \\ f_{L_3} = (1 - z_5) \phi_{L_3}^{-1} e_{89} + z_5 Df_{16} \end{cases} \quad (6.42)$$

For GY₁ junction:

$$\begin{cases} e_{85} = m_1 \cdot f_{92} \\ e_{92} = m_1 \cdot f_{85} \end{cases} \quad (6.43)$$

For GY₂ junction:

$$\begin{cases} e_{95} = m_2 \cdot f_{97} \\ e_{97} = m_2 \cdot f_{95} \end{cases} \quad (6.44)$$

For GY₃ junction:

$$\begin{cases} e_{98} = m_3 \cdot f_{100} \\ e_{100} = m_3 \cdot f_{98} \end{cases} \quad (6.45)$$

For 1₂₂ junction:

$$\begin{cases} f_{93} = f_{92}, f_{93} = f_{94} \\ e_{92} - e_{93} - e_{94} = 0 \\ e_{R_A} = \phi_{R_A} \left[(1 - y_{12}) f_{93} + y_{12} Df_{17} \right] \\ f_{R_A} = (1 - y_{12}) \phi_{R_A}^{-1} e_{93} + y_{12} Df_{17} \end{cases} \quad (6.47)$$

For 1₂₃ junction:

$$\begin{cases} f_{96} = f_{95}, f_{96} = f_{97} \\ e_{95} - e_{96} - e_{97} = 0 \\ e_{R_B} = \phi_{R_B} \left[(1 - y_{13}) f_{96} + y_{13} Df_{18} \right] \\ f_{R_B} = (1 - y_{13}) \phi_{R_B}^{-1} e_{96} + y_{13} Df_{18} \end{cases} \quad (6.48)$$

For 1₂₄ junction:

$$\begin{cases} f_{99} = f_{98}, f_{99} = f_{100} \\ e_{98} - e_{99} - e_{100} = 0 \\ e_{R_C} = \phi_{R_C} \left[(1 - y_{14}) f_{99} + y_{14} Df_{19} \right] \\ f_{R_C} = (1 - y_{14}) \phi_{R_C}^{-1} e_{99} + y_{14} Df_{19} \end{cases} \quad (6.49)$$

For 0₁₅ junction:

$$\begin{cases} e_{101} = e_{94}, e_{101} = e_{104} \\ -f_{101} - f_{104} + f_{94} = 0 \\ f_{C_a} = \phi_{C_a} \left[S \{ (1 - x_4) e_{101} + x_4 D e_7 \} \right] \\ e_{C_a} = \frac{1}{S} (1 - x_4) \phi_{C_a}^{-1} f_{101} + x_4 D e_7 \end{cases} \quad (6.50)$$

For 0₁₆ junction:

$$\begin{cases} e_{102} = e_{97}, e_{102} = e_{105} \\ -f_{102} - f_{105} + f_{97} = 0 \\ f_{C_b} = \phi_{C_b} \left[S \{ (1 - x_5) e_{102} + x_5 D e_8 \} \right] \\ e_{C_b} = \frac{1}{S} (1 - x_5) \phi_{C_b}^{-1} f_{102} + x_5 D e_8 \end{cases} \quad (6.51)$$

For 0₁₇ junction:

$$\begin{cases} e_{103} = e_{100}, e_{103} = e_{106} \\ -f_{106} - f_{103} + f_{100} = 0 \\ f_{C_c} = \phi_{C_c} \left[S \{ (1-x_6) e_{103} + x_6 D e_9 \} \right] \\ e_{C_c} = \frac{1}{S} (1-x_6) \phi_{C_c}^{-1} f_{103} + x_6 D e_9 \end{cases} \quad (6.52)$$

For 0₁₈ junction:

$$\begin{cases} e_{110} = e_{107}, e_{110} = e_{111} \\ -f_{111} - f_{110} + f_{107} = 0 \\ f_{C_a} = \phi_{C_a} \left[S \{ (1-x_7) e_{110} + x_7 D e_{10} \} \right] \\ e_{C_a} = \frac{1}{S} (1-x_7) \phi_{C_a}^{-1} f_{110} + x_7 D e_{10} \end{cases} \quad (6.53)$$

For 0₁₉ junction:

$$\begin{cases} e_{114} = e_{108}, e_{114} = e_{115} \\ -f_{115} - f_{114} + f_{108} = 0 \\ f_{C_b} = \phi_{C_b} \left[S \{ (1-x_8) e_{114} + x_8 D e_{11} \} \right] \\ e_{C_b} = \frac{1}{S} (1-x_8) \phi_{C_b}^{-1} f_{114} + x_8 D e_{11} \end{cases} \quad (6.54)$$

For 0₂₀ junction:

$$\begin{cases} e_{118} = e_{109}, e_{118} = e_{119} \\ -f_{119} - f_{118} + f_{109} = 0 \\ f_{C_c} = \phi_{C_c} \left[S \{ (1-x_9) e_{118} + x_9 D e_{12} \} \right] \\ e_{C_c} = \frac{1}{S} (1-x_9) \phi_{C_c}^{-1} f_{118} + x_9 D e_{12} \end{cases} \quad (6.55)$$

For 1₂₅ junction:

$$\begin{cases} f_{112} = f_{111}, f_{112} = f_{113} \\ e_{111} - e_{112} - e_{113} = 0 \\ e_{L_a} = \phi_{L_a} \left[(1-z_6) f_{112} + z_6 D f_{20} \right] \\ f_{L_a} = (1-z_6) \phi_{L_a}^{-1} e_{112} + z_6 D f_{20} \end{cases} \quad (6.56)$$

For 1₂₆ junction:

$$\begin{cases} f_{116} = f_{115}, f_{116} = f_{117} \\ e_{115} - e_{116} - e_{117} = 0 \\ e_{L_b} = \phi_{L_b} \left[(1-z_7) f_{116} + z_7 D f_{21} \right] \\ f_{L_b} = (1-z_7) \phi_{L_b}^{-1} e_{116} + z_7 D f_{21} \end{cases} \quad (6.57)$$

For 1₂₇ junction:

$$\begin{cases} f_{120} = f_{119}, f_{120} = f_{121} \\ e_{119} - e_{120} - e_{121} = 0 \\ e_{L_c} = \phi_{L_c} \left[(1-z_8) f_{120} + z_8 D f_{22} \right] \\ f_{L_c} = (1-z_8) \phi_{L_c}^{-1} e_{120} + z_8 D f_{22} \end{cases} \quad (6.58)$$

For 0_{21} junction:

$$\begin{cases} e_{122} = e_{121}, e_{122} = e_{113}, e_{122} = e_{117} \\ f_{113} + f_{117} + f_{121} + f_{122} = 0 \end{cases} \quad (6.59)$$

From equations of junctions we generate the following analytical redundancy relation:

$$\begin{aligned} ARR_1 : De_1^* - \phi_{R_{S1}} \left[(1-y_1) f_{R_{S1}} + y_1 Df_1 \right] - De_2^* &= 0 \\ ARR_2 : De_2^* - \phi_{R_{S2}} \left[(1-y_2) f_{R_{S2}} + y_2 Df_2 \right] - De_3^* &= 0 \\ ARR_3 : De_3^* - \phi_{R_{S72}} \left[(1-y_3) f_{R_{S72}} + y_3 Df_3 \right] - De_4^* &= 0 \\ ARR_4 : -De_{13}^* + Se_1 - \phi_{L_C} \left[(1-z_1) f_{19} + z_1 Df_4 \right] - \phi_{R_{D1}} \left[(1-y_6) f_{55} + y_6 Df_7 \right] &= 0 \\ ARR_5 : (1-z_1) \phi_{L_C}^{-1} e_{19} + z_1 Df_4 - \phi_{C_C} \left[S \{ (1-x_1) e_{C_C} + x_1 De_4 \} \right] &= 0 \\ ARR_6 : \frac{1}{r_3} De_{14}^* - \phi_{R_{SS2}} \left[(1-y_4) f_{32} + y_4 Df_4 \right] - \frac{1}{S} (1-x_2) \phi_{C_{dc}^-}^{-1} f_{34} - x_2 De_5 &= 0 \\ ARR_7 : y_5 Df_6 - \phi_{C_{dc}^-} \left[S \{ (1-x_2) e_{34} + x_2 De_5 \} \right] + \phi_{C_{dc}^+} \left[S \{ (1-x_3) e_{39} + x_3 De_6 \} \right] - (1-y_5) \phi_{R_{SS1}}^{-1} e_{41} \\ + (1-y_4) \phi_{R_{SS2}}^{-1} e_{32} + y_4 Df_5 &= 0 \\ ARR_8 : -\phi_{C_{dc}^-} \left[S \{ (1-x_2) e_{34} + x_2 De_5 \} \right] + (1-y_4) \phi_{R_{SS2}}^{-1} e_{32} + y_4 Df_5 - \phi_{C_{dc}^+} \left[S \{ (1-x_3) e_{39} + x_3 De_6 \} \right] \\ + (1-y_5) \phi_{R_{SS1}}^{-1} e_{41} + y_5 Df_6 &= 0 \\ ARR_9 : \frac{1}{r_4} \left(-De_{14}^* + De_{15}^* - \frac{1}{r_6} Se_4 - \frac{1}{r_4} Se_5 \right) - \phi_{R_{SS1}} \left[(1-y_5) f_{41} + y_5 Df_6 \right] - \frac{1}{S} (1-x_3) \phi_{C_{dc}^+}^{-1} f_{39} \\ - x_3 De_6 &= 0 \\ ARR_{10} : -Se_1 + \phi_{L_C} \left[(1-z_1) f_{19} + z_1 Df_4 \right] - \phi_{R_{D1}} \left[(1-y_6) f_{55} + y_6 Df_7 \right] + \frac{1}{S} (1-x_1) \phi_{C_C}^{-1} f_{22} - De_{13}^* \\ + x_1 De_4 &= 0 \\ ARR_{11} : -Se_1 + \phi_{L_C} \left[(1-z_1) f_{19} + z_1 Df_4 \right] - \phi_{R_{D4}} \left[(1-y_7) f_{57} + y_7 Df_8 \right] - De_{16}^* + \frac{1}{S} (1-x_1) \phi_{C_C}^{-1} f_{22} \\ + x_1 De_4 &= 0 \\ ARR_{12} : De_{13}^* - \phi_{R_{D2}} \left[(1-y_8) f_{63} + y_8 Df_9 \right] - De_{17}^* &= 0 \\ ARR_{13} : De_{16}^* - \phi_{R_{D5}} \left[(1-y_9) f_{68} + y_9 Df_{10} \right] - De_{18}^* &= 0 \\ ARR_{14} : De_{17}^* - \phi_{R_{D3}} \left[(1-y_{10}) f_{74} + y_{10} Df_{11} \right] - De_{19}^* &= 0 \\ ARR_{15} : De_{18}^* - \phi_{R_{D6}} \left[(1-y_{11}) f_{71} + y_{11} Df_{12} \right] - De_{19}^* &= 0 \end{aligned} \quad (6.60)$$

$$ARR_{16} : \phi_{L_3} \left[(1-z_5) f_{89} + z_5 Df_{16} \right] - \phi_{L_1} \left[(1-z_3) f_{82} + z_3 Df_{14} \right] - De_{19}^* - m_1 (1-y_{12}) \phi_{R_A} e_{93} + y_{12} Df_{17} \\ + Se_1 + r \cdot f_{77} + \frac{1}{L} f_{78} - \phi_{L_2} \left[(1-z_4) f_{86} + z_4 Df_{15} \right] = 0$$

$$ARR_{17} : \phi_{L_3} \left[(1-z_5) f_{89} + z_5 Df_{16} \right] + \phi_{L_1} \left[(1-z_3) f_{82} + z_3 Df_{14} \right] + De_{19}^* - m_2 (1-y_{13}) \phi_{R_B} e_{96} + y_{13} Df_{18} \\ + Se_2 + r \cdot f_{77} + \frac{1}{L} f_{78} - \phi_{L_2} \left[(1-z_4) f_{86} + z_4 Df_{15} \right] = 0$$

$$ARR_{18} : -\phi_{L_3} \left[(1-z_5) f_{89} + z_5 Df_{16} \right] + \phi_{L_1} \left[(1-z_3) f_{82} + z_3 Df_{14} \right] + De_{19}^* - m_3 (1-y_{14}) \phi_{R_C} e_{99} + r \cdot f_{77} \\ + \frac{1}{L} f_{78} + \phi_{L_2} \left[(1-z_4) f_{86} + z_4 Df_{15} \right] + y_{14} Df_{19} + Se_3 = 0$$

$$ARR_{19} : -\phi_{R_A} \left[(1-y_{12}) f_{93} + y_{12} Df_{17} \right] - \phi_{C_a} \left[S \left\{ (1-x_4) e_{101} + x_4 De_7 \right\} \right] - m_1 (1-z_3) \phi_{L_1}^{-1} e_{82} + z_3 Df_{14} = 0$$

$$ARR_{20} : -\phi_{R_B} \left[(1-y_{13}) f_{96} + y_{13} Df_{18} \right] - \phi_{C_b} \left[S \left\{ (1-x_5) e_{102} + x_5 De_8 \right\} \right] - m_2 (1-z_4) \phi_{L_2}^{-1} e_{86} + z_4 Df_{15} = 0$$

$$ARR_{21} : -\phi_{R_C} \left[(1-y_{14}) f_{99} + y_{14} Df_{19} \right] - \phi_{C_c} \left[S \left\{ (1-x_6) e_{103} + x_6 De_9 \right\} \right] - m_3 (1-z_5) \phi_{L_3}^{-1} e_{89} + z_5 Df_{16} = 0$$

$$ARR_{22} : -\phi_{C_a} \left[S \left\{ (1-x_7) e_{110} + x_7 De_{10} \right\} \right] - (1-z_6) \phi_{L_a}^{-1} e_{112} + z_6 Df_{20} + Df = 0$$

$$ARR_{23} : -\phi_{C_b} \left[S \left\{ (1-x_8) e_{114} + x_8 De_{11} \right\} \right] - (1-z_7) \phi_{L_b}^{-1} e_{116} + z_7 Df_{21} + Df = 0$$

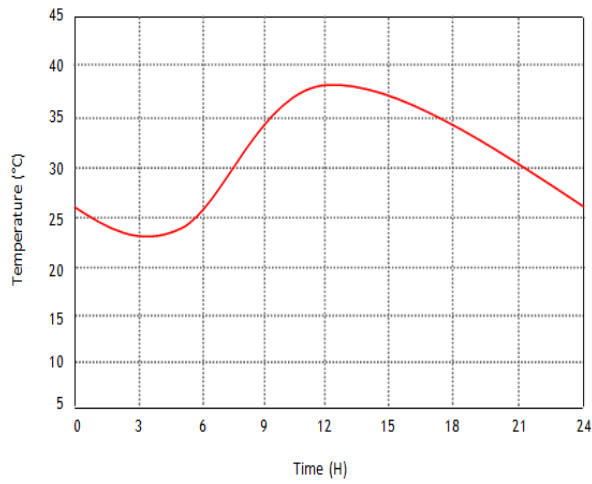
$$ARR_{24} : -\phi_{C_c} \left[S \left\{ (1-x_9) e_{118} + x_9 De_{12} \right\} \right] - (1-z_8) \phi_{L_c}^{-1} e_{120} + z_8 Df_{22} + Df = 0$$

$$ARR_{25} : -\phi_{L_a} \left[(1-z_6) f_{112} + z_6 Df_{20} \right] - \frac{1}{S} (1-x_7) \phi_{C_a}^{-1} f_{110} + x_7 De_{10} + Se = 0$$

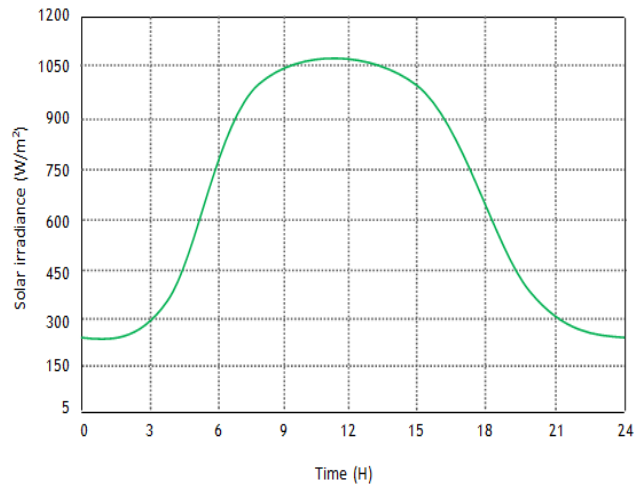
$$ARR_{26} : -\phi_{L_b} \left[(1-z_7) f_{116} + z_7 Df_{21} \right] - \frac{1}{S} (1-x_8) \phi_{C_b}^{-1} f_{114} + x_8 De_{11} + Se = 0$$

$$ARR_{27} : -\phi_{L_c} \left[(1-z_8) f_{120} + z_8 Df_{22} \right] - \frac{1}{S} (1-x_9) \phi_{C_c}^{-1} f_{118} + x_9 De_{12} + Se = 0$$

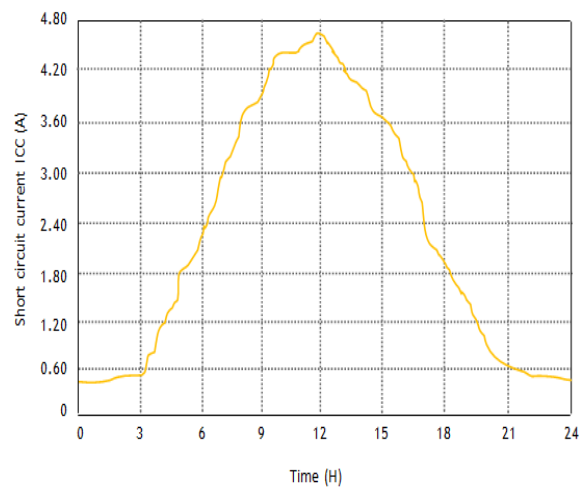
We can now simulate the normal production (without defect) of a photovoltaic installation according to the manufacturer data of the solar irradiation and the outside temperature. In the following case (figure 6.2), we will find the temperature, the luminous flow, the short-circuit current, the open circuit voltage, and the power delivered by the panels.



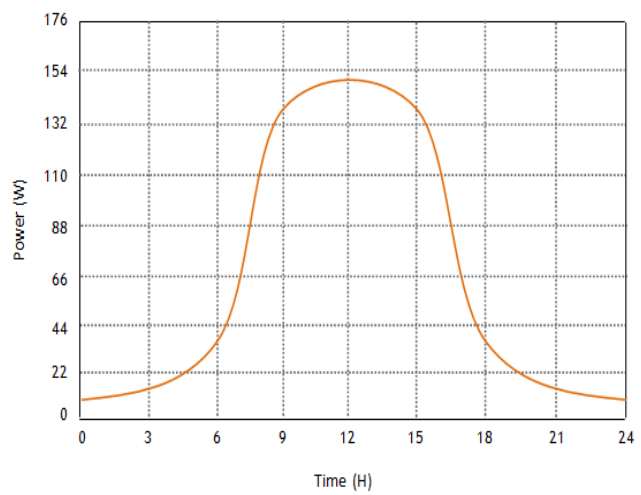
(a) Temperature



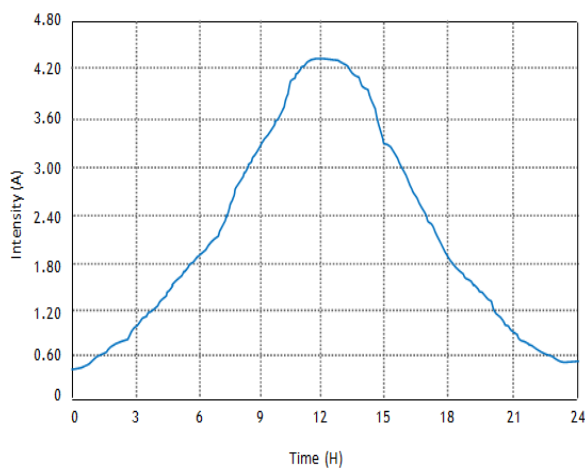
(b) Solar irradiance



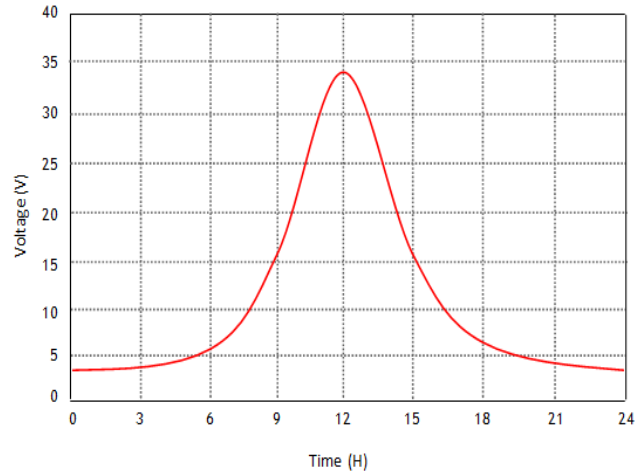
(c) Icc



(d) Pmax,



(f) Intensity



(g) Voltage

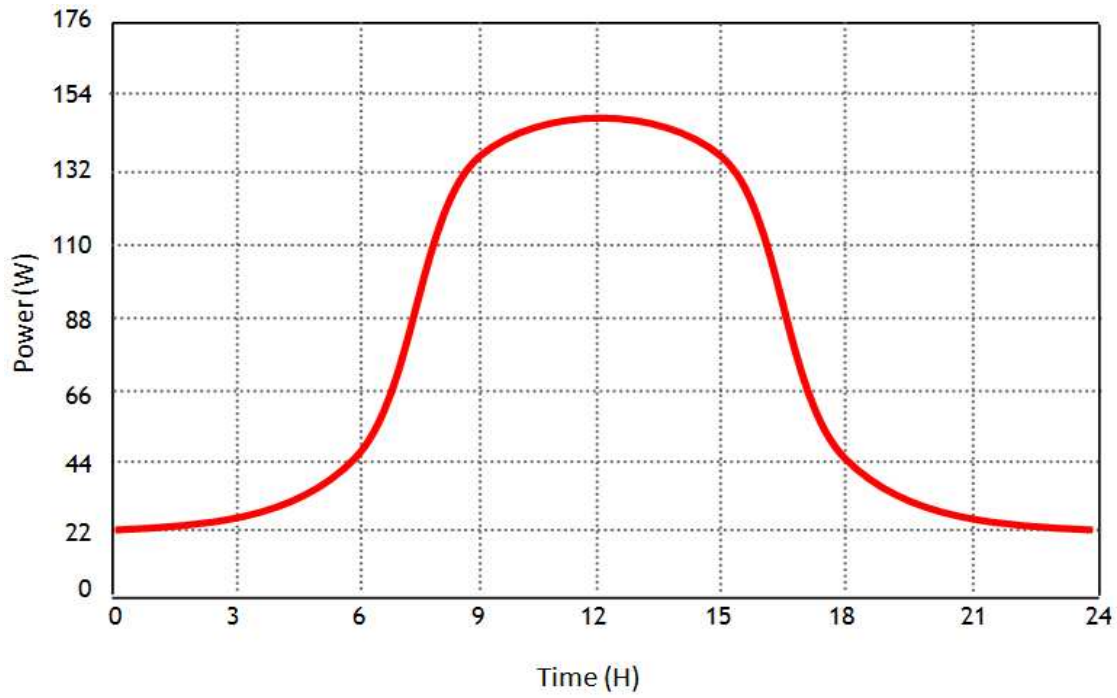
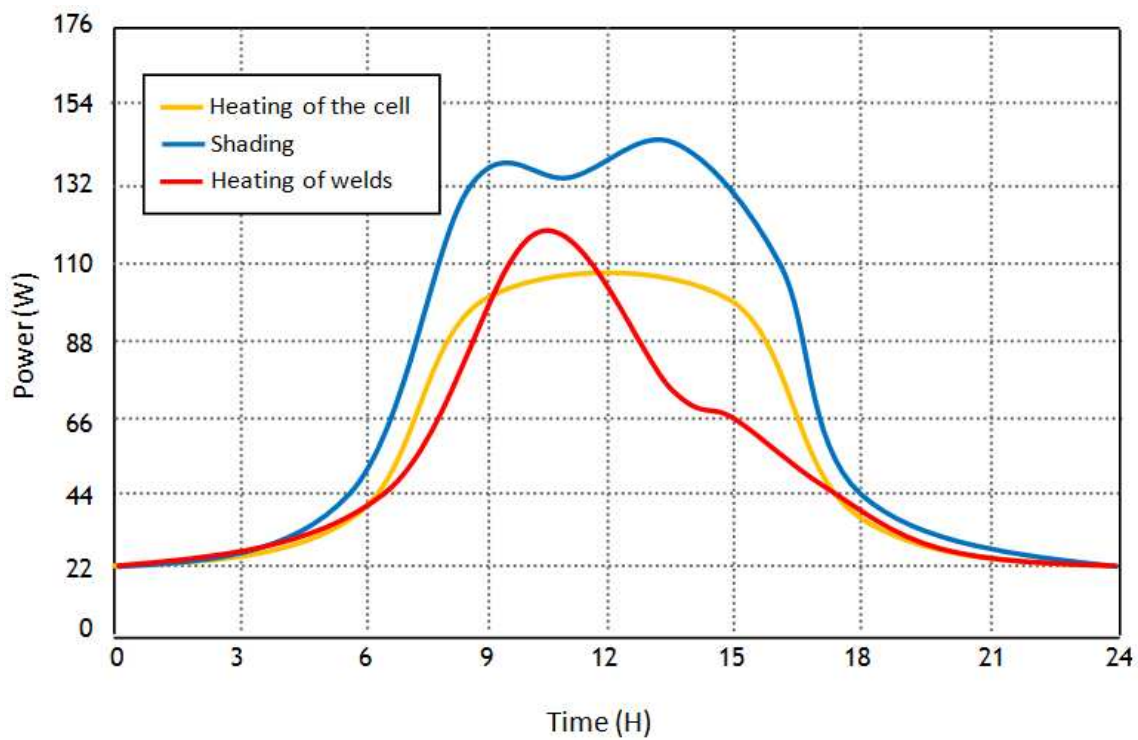


Figure 6. 2 Characteristics of installation without faults

In figure 6.2, the highest curve corresponds to the normal functioning meaning “not default”, then the following curve corresponds to a panel in default.



The default on the photovoltaic panels depends especially on the environment. For example, for the isolated sites often in mountain-snow, or branches falls can cause damage. We create a fault between the instant $t_1=4$ s and $t_2=10$ s. The generated ARR's reaction is very fast see figures (6.4) and (6.5). The numeric values of components are not considered, only their presence or absence in the relation are taken account with evaluation term the operators (+, -). It is the qualitative approach for bond graph monitoring.

The deviation of the relations ARR2 and ARR3 in this time is normal (constant value). We see that residuals ARR1 and ARR4 are sensitive (seen the presence of De2 in this relation).

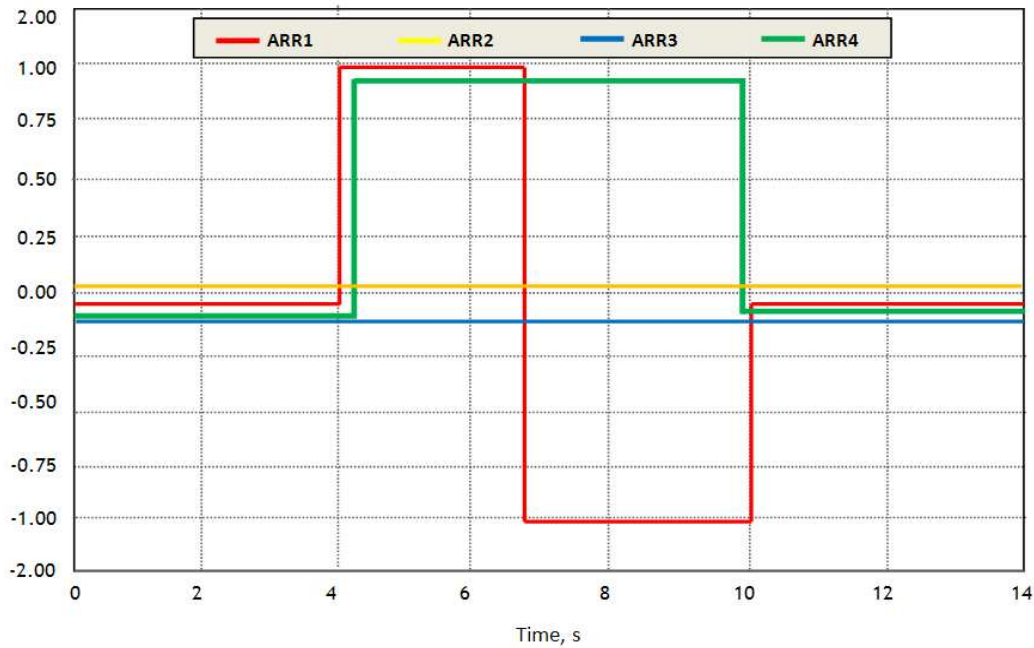


Figure 6. 4 Sensitivity of the detector De2

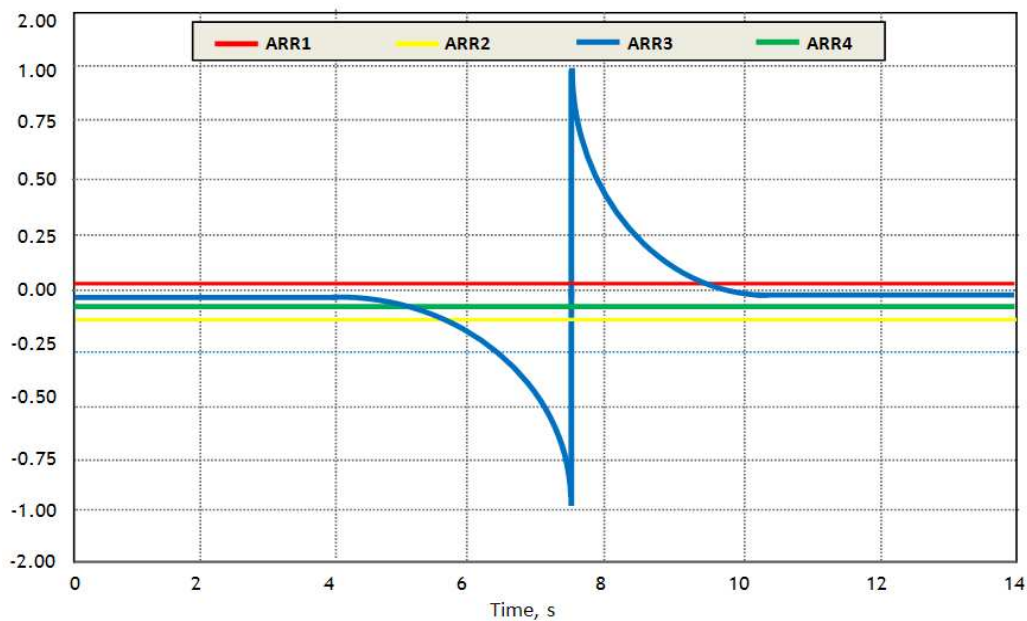


Figure 6. 5 Sensitivity of the detector Df2

The figure (6.4) shows the response of the residuals. It is noted that residual ARR3 presents a short change compared to its initial state between $t_1=4.1s$ and $t_2=10s$ but turns over in their initial state from $t=10s$ and other residuals ARR1, ARR2 and ARR4 remain invariant.

The results obtained are very promising, but it would be necessary to carry out many measurements by the different climatic conditions on various sites to be able to conclude on the relevance of our methodology. That would also enable us to fix a threshold corresponding to the number of variables not belonging to the zone of normal functioning above which it is considered that the installation has indeed a default.

6.5. CONCLUSION

The diagnostic strategy and the form in which knowledge is available conditioned the method used to design the monitoring algorithm. According to the type of knowledge, the criterion of classification of the monitoring method distinguishes between two types of approaches: methods with or without model. Our contribution relates to the methods containing model.

We used only one tool for modeling, the generations of the indicators of failures (residuals), the analysis of the monitorability and the sensors placement in order to satisfy the technical specifications for the monitoring.

The photovoltaic system modeling constitutes a search object always for topicality seen that the complexity of these systems is more and more increasing, adoption of a common modeling tool to several disciplines represent an asset in the search for a good solution on design level. Moreover, this methodology offers interesting solutions in terms of system analysis and reveals systematically all necessary functions to answer that an objective of modeling, simulation, estimation, dimensioning, supervision, robustness study or synthesis of control laws. Unfortunately, the application of this approach in the renewable energy field had crossed important steps but did not deepened to have all these advantages.

General Conclusion

The main conclusions and originalities for this thesis are listed here (in order of appearance in the thesis):

- Environmentally friendly and sustainable alternative energy systems will play more important roles in the future electricity supply.
- Dynamic models have been developed for the following: variable speed wind energy conversion systems, photovoltaic power generation systems, power electronic interfacing devices, battery. These dynamic models are suitable for both detailed fast transient and large time scale performance evaluation studies. They can be used to expedite the research processes in the related alternative energy areas, such as system control, performance optimization studies and diagnosis.
- A novel Maximum Power Point Tracker (MPPT) algorithm (BG-MPPT), which solves some problems within the standard algorithms with tracking the MPP during rapid changes in the weather conditions, is proposed. The algorithm initially locates the global MPP by sweeping (scanning) the voltage-current characteristic of the PV module.
- Control of the pumping photovoltaic systems is investigated. MPPT-BG controller using bond graph is designed. The validity of the proposed control schemes over a large operating range was verified through simulations and experimental.
- A new procedure for automatic detection of main faults in PV systems have been developed. The fault detection procedure have been verified in real conditions of work of a grid connected PV system. The results obtained were the expected in all cases and faults present in the PV system were detected by using this method.

Future Works

The attempts made in this thesis to contribute to the improvement of modeling, MPPT technique and diagnostics of energy production system (photovoltaic and wind energy) have far from finished the task in these subjects. There were topics found to be unanswered or left for further studies.

- ✓ Improvements on the equations used to determine the parameters of the nonlinear PV generator model, like *R-diode* should be made in order to increase the accuracy of the model.
- ✓ Implementing the proposed algorithm in a real microcontroller-based wind system,

- ✓ Applied to mobile-based PV systems which need fast MPPT relatively due to movements,
- ✓ Although the PV panels used for experimental tests of the diagnostic methods presented here contain 72 cells and 4 bypass diodes, which can be considered as a small-scale representation of a photovoltaic array, a full-scale residential PV system should be also considered for field testing.
- ✓ As has been previously mentioned, the models and diagnostic functions used in this work consider crystalline silicone PV cells. It would be an interesting topic to test their validity on amorphous silicone cells.
- ✓ And advanced analysis of process and measurement noises in a PV power electronic device.

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Fact Sheets

We give in this appendix the characteristics of different devices that were used in the simulation and in the development of the test bench.

Table A.1. Parameters of PMSG

Number of poles	4
Rated speed	157 rad/s
Nominal power	600 W
Nominal current	4.18 A
Nominal voltage	90 V
Armature resistance	0.425 Ω
Magnetic flux linkage	0.433 wb
Stator inductance	4 mH
Rated torque	40 Nm

Table A.2. Parameters of boost

Power	2kVA
IGBT Switching	5KHz
Carrier frequency	10 kHz
Frequency reference signals	50 Hz
Efficiency	0.95
Ratio	0.8

Table A.3. Parameters of VSI

Grid voltage	220V
DC link voltage	750V
Current	16A
Switching frequency	8kHz
Grid frequency	50Hz
Converter side inductor in LCL-filter	2.5mH
Grid side inductor in LCL-filter	2mH
Capacitor in LCL-filter	1 μ F

Table A.4. Parameters of storage battery

Nominal voltage	12V
Maximum charging voltage	13.7V
Limited voltage	14.1 V
Minimal tension of discharge	12V

Maximum tension of discharge	11.2V
Rated capacity	100A/h
Coefficient of discharge	0.0001
x.Li ⁺ amount in the cathode of the battery	0.2 mole
LixH amount in the cathode of the battery	0.2 mole
x.Li ⁺ amount in the anode of the battery	0.2 mole
LixH amount in the anode of the battery	0.2 mole
Battery capacity (chemical C)	0.4 mole
Capacity of the double layer of the battery	0.001 mole
Diffusion resistance (relaxation)	10 Ω
Diffusion capacity C (relaxation)	0.000104 mole

Table A.5. Parameters of centrifugal pump

Mechanical power absorbed	521 W
Nominal manometric height	14.11 m
Flow after trimming	2.59 l/s
Nominal speed	314 rd/s
Input radius of the wheel	0.042 m
Output radius of the wheel	0.051 m
Input width of dawn	0.01 m
Output width of dawn	0.01 m
Output angle of dawn	0.5235 rd
Geometric Lift height	7.430 m
Constant pressure drop of the pipe	1223216.3
Number of blades	7
Volumetric efficiency	0.95
Thickness	0.003 m
Specific speed	21 Trs/min

Table A.6. Parameters of hydraulic system

Depth of the well	45 m
Pipe diameter	4 cm
Roughness Index	0.015 mm
Singular head loss modulus	13.642
Temperature	25 °C

Abstract: In this thesis, a contribution to modeling and fault detection and isolation of energy production system (photovoltaic and wind systems) is proposed. Firstly an overview is given on the world energy demand, electricity consumption and their development trend in the near future, secondly this work deals with the modeling of photovoltaic and wind turbine generation systems by bond graph approach for integration in power systems studies. The modeling of the photovoltaic generator, the wind phenomenon, the turbine mechanical system and the electrical machine, along with the corresponding converter and electrical grid is described. In the third part, we show a new methodology for fault detection and isolation of PV and wind systems, based mainly on optimal placement of sensors. This supposes the possibility to build a dynamic model of the system by using the bond graph tool, and the existence of a degradation model in order to predict its future health state. The choice of bond graph is motivated by the fact that it is well suited for modeling physical systems where several types of energies are involved.

Key-words: Modeling, Diagnosis, Photovoltaic, Wind Energy Conversion, Production Energy System.

المخلص: في هذه الأطروحة، نقترح مساهمة في النمذجة، الكشف عن الخطأ وعزل نظام إنتاج الطاقة (النظم الكهروضوئية وطاقة الرياح). أولاً قمنا بتقديم لمحة عامة على الطلب العالمي على الطاقة، استهلاك الكهرباء واتجاه التنمية في المستقبل القريب، وثانياً يتناول هذا العمل وضع نماذج من أنظمة توليد الطاقة الكهروضوئية وتوربينات الرياح بواسطة أداة الرسم البياني لتحقيق التكامل في دراسات أنظمة الطاقة. نمذجة مولد الكهروضوئي، يتم وصف ظاهرة الرياح، ونظام ميكانيكي التوربينات والآلة الكهربائية، جنباً إلى جنب مع مقابل التحويل المقابل. في الجزء الثالث، إقترحنا منهجية جديدة للكشف عن الخطأ وعزله في الأنظمة الكهروضوئية وطاقة الرياح، تقوم أساساً على الوضع الأمثل لأجهزة الاستشعار. هذا يفترض إمكانية بناء نموذج ديناميكي للنظام باستخدام أداة الرسم البياني، مع وجود نموذج تدهور من أجل التنبؤ بحالة النظام في المستقبل. والدافع وراء اختيار الرسم البياني من حقيقة أنه مناسب تماماً لنمذجة النظم الفيزيائية التي تشارك فيها عدة أنواع من الطاقات.

كلمات البحث: النمذجة، التشخيص، الطاقة الكهروضوئية، توربينات الرياح، نظام إنتاج الطاقة.

Résumé: Dans cette thèse, une contribution à la modélisation, la détection et isolation de défauts dans le système de production d'énergie (système photovoltaïque et éolien) est proposé. Tout d'abord un aperçu sur la demande mondiale d'énergie, la consommation d'électricité et de leur tendance de développement dans un avenir proche est donné, d'autre part ce travail traite de la modélisation d'un système photovoltaïque et d'un système éolien par une approche graphique. La modélisation du générateur photovoltaïque, le phénomène de vent, le système mécanique de la turbine et la machine électrique, en même temps que le convertisseur correspondant est décrite. Dans la troisième partie, nous montrons une nouvelle méthodologie pour la détection et localisation de défauts des systèmes photovoltaïques et éoliens, basée principalement sur le placement optimal de capteurs. Cela suppose la possibilité de construire un modèle dynamique du système en utilisant l'outil bond graph, et l'existence d'un modèle de dégradation afin de prédire son état de futur. Le choix de l'approche bond graph est motivée par le fait qu'il est bien adapté à la modélisation de systèmes physiques où plusieurs types d'énergies sont impliqués.

Mots-clés: Modélisation, Diagnostic, Photovoltaïque, Conversion de l'énergie Eolienne, Système de production d'énergie.