UMinho | 2014

Mohamed Tanta

Simulation and Implementation of Power Electronics for Educational Purposes - with SEPIC Converter for MPPT

Universidade do Minho
Escola de Engenharia

Mohamed Tanta

Simulation and Implementation of Power Electronics for Educational Purposes - with SEPIC Converter for MPPT

December 2014

Universidade do Minho
Escola de Engenharia

Mohamed Tanta

Simulation and Implementation of Power Electronics for Educational Purposes - with SEPIC Converter for MPPT

Thesis submitted at the University of Minho
for the degree of Master in
Industrial Electronics and Computer Engineering

Work performed under the supervision of
Professor João Luiz Afonso

December 2014

DECLARATION

Mohamed Tanta
E-mail address: mohamedtantaeng1320@gmail.com Telephone: 00351-938419012
Number of Identity:

Title of Thesis:

Simulation and Implementation of Power Electronics for Educational Purposes - with SEPIC Converter for MPPT

Supervisor:
Professor João Luiz Afonso.

Year of completion: 2014
Thesis submitted at the University of Minho for the degree of Master in Industrial Electronics and Computer Engineering.

University of Minho, ___/___/______

Signature: ____

To my family, my friends and all of my relatives.

To my country Syria, for Portugal and Portuguese people.

Acknowledgements

The completion of the work presented here would not have been possible without the support and the contribution of some people, to whom I send my sincere thanks:

My advisor, Professor **João Luiz Afonso** for his guidance and persistent help. Your professional and spiritual support helped me to identify and to understand Power Electronics. Thank you for your patience, for countless thoughtful long technical discussions and for your friendly attitude as it has greatly contributed to my professional and personal growth and made it possible to complete this work.

Special thanks for the professors **Júlio Martins** and **Manuel João Sepúlveda** for their kindness and excellent comments which helped me to correct many parts of this work.

To my colleagues in the laboratory of **GEPE** (Group of Energy and Power Electronics).

Dr. **José Gabriel Oliveira Pinto** for his guidance about the technical management which I used throughout this thesis and without his help, this work will not be completed.

PhD student Eng. **Bruno Exposto** for his guidance about technical support.

PhD student Eng. **Delfim Pedrosa** for his guidance in hardware materials that were used in this project.

Eng. Raul Almeida.

To my friends, research fellows.

Employees **Carlos Torres**, **Joel Almeida** and **Angela Macedo** who, as technical workshops of the Department of Industrial Electronics.

To all students who took the master's thesis in Power Electronics Laboratory, respect the environment and provided friendship.

In the end, special thanks for Program of "**Global Platform for Syrian Students**" which sponsored by President **Jorge Sampaio** and other financial institutions.

I am very grateful to Portugal and Portuguese people ......

Abstract

Nowadays, the importance and investments in electricity and renewable energy sources is significantly growing, so that the development and prosperity level of nations are measured accordingly with the strength and the efficiency of the power sector in the country.

Every day, the importance of renewable energy sources in the world is increasing to compensate the growing demand of energy in the future, especially with the global rise in oil prices and the environmental pollution. Therefore, renewable energy sources, such as wind, sun, biomass, waves and tides, will be the energy providers for our planet in the future.

Renewable energy sources are closely linked with power electronics, so that it is not possible to obtain the required electrical power without using semiconductor electronic elements, which have the capability to convert electrical power (for example, rectifiers can convert electrical power from AC to DC and the inverters do exactly the opposite). These elements give sufficient flexibility to control and convert the voltages according to our application, and in function of the load needs.

All of the above indicates the importance of power electronics area in the present time. Therefore, as a part of this project, a tutorial document on power electronics has been written for students and non-specialists who want to learn power electronics and know the basics of this area of Electrical Engineering. This document has an organizing strategy and arrangement in order to facilitate and give motivation for students to study power electronics, trying to provide, as much as possible, simple explanations and figures. Every circuit in this document was simulated by using the programs *PSIM* and *MATLAB*, which gives the possibility for students to change the circuit parameters, then monitoring the new results (with this document is made available a *CD* with the simulations models of the circuits). In addition, it contains worked examples with the most important ideas that must be known for every example. All figures and results of circuits are drawn to facilitate and clarify the figures as much as possible, using a plotting program named *KST*.

As a practical part of this Master thesis work, which also aims to merge renewable energy sources and power electronics applications, a battery charging system with MPPT circuit was implemented, to be used with a micro wind turbine, which can be employed in a boat in the future. This work used a micro wind turbine with a permanent magnet synchronous generator which converts mechanical energy into electrical energy.

The generator produces AC three-phase voltages that are rectified with an uncontrolled rectifier, PD3, which is then connected to a DC-DC converter (coupled inductor SEPIC converter), used here to increase or decrease the DC voltage value. In the output of the rectifier is used a capacitor to filter the DC voltage. The implemented control method uses a Maximum Power Point Tracker (MPPT), with perturbation and observation algorithm. This algorithm is ideal to use with intermittent wind energy resources. To operate at the optimal power point, the algorithm has to change the duty cycle of the SEPIC. This control was implemented in a microcontroller *ARDUINO ATMEGA UNO 328P*. All the developed system for energy production was simulated using *PSIM* program. This allowed to observe the behavior of the system when was used a passive load (resistive load) and an active load (battery).

Finally, with this work I hope to create benefits to my homeland Syria and to my second country, Portugal.

Keywords: SEPIC, Power Electronics, Maximum Power Point Tracker (MPPT), Micro Wind Turbine, Renewable Energy, Education, Simulation, Implementation, ADC, PWM.

Resumo

Hoje em dia, a importância e o investimento na energia elétrica e em fontes de energia renováveis tem uma grande preponderância nas nossas vidas. O grau de prosperidade e o desenvolvimento das nações pode ser aferido através do grau de importância do setor energético no país.

A cada dia que passa, a importância das fontes de energia renováveis aumenta, uma vez que existe uma procura cada vez maior de energia, isto tendo em conta o aumento mundial dos preços de combustível e a poluição ambiental. Tendo em conta isto, as fontes de energia renováveis, tais como o vento, o sol, a biomassa, as ondas e as marés, serão os fornecedores de energia para o nosso planeta num futuro próximo.

As fontes de energia renováveis estão intimamente ligadas com a eletrónica de potência, e não é possível obter a energia elétrica desejada sem usar elementos eletrónicos semicondutores, os quais têm a capacidade de realizar conversões (por exemplo os retificados podem converter tensão CA para CC, e os inversores o oposto).

Estes elementos dão flexibilidade suficiente para controlar e converter as tensões de acordo com a nossa aplicação, e conforme a carga.

Tudo o que é referido acima indica a importância da eletrónica de potência nos tempos atuais. Desta forma, como parte deste trabalho de Dissertação de Mestrado, foi escrito um tutorial de eletrónica de potência destinado aos estudantes e aos não-especialistas que querem aprender eletrónica de potência e perceber as bases desta área da Engenharia Eletrotécnica. Este documento apresenta uma certa estratégia e organização facilitadoras e motivadoras para que os alunos venham a estudar eletrónica de potência, contendo, dentro do possível, explicações e figuras simples. Cada circuito apresentado neste documento foi simulado usando os softwares *PSIM* e *MATLAB*, sendo oferecida a possibilidade aos estudantes para alterar os parâmetros dos circuitos e observarem os resultados (o documento é acompanhado de um CD com os modelos de simulação). Além disto, o documento contém exemplos trabalhados mostrando os conceitos mais importantes de cada circuito. Todas as figuras e resultados dos circuitos foram desenhados de forma a facilitar a sua compreensão, utilizando um programa designado *KST*.

Como parte prática deste trabalho, e envolvendo a fusão entre a eletrónica de potência e as aplicações de energias renováveis, foi implementado um circuito carregador de baterias com circuito MPPT, a ser usado com uma turbina micro-eólica, e que poderá ser empregado em barcos, no futuro. Neste projeto foi usada uma micro-turbina com um gerador síncrono de ímanes permanentes que converte a energia mecânica do vento em energia elétrica. O gerador produz tensões CA que necessitam de ser retificadas, e para isso é usado um retificador não controlado, PD3, ligado a um conversor DC-DC (conversor SEPIC com indutância de acoplamento mútuo). O conversor serve para aumentar ou diminuir a tensão de saída. Além disto, o retificador tem na sua saída um condensador de forma a filtrar a tensão. O método de controlo implementado foi um seguidor do ponto de máxima potência (*Maximum Power Point Tracker* - MPPT). O algoritmo do MPPT usado foi o da perturbação-observação. Este algoritmo é o ideal para utilizar com as fontes de energia intermitentes, como é o caso do vento. Para operar no ponto de máxima potência, o algoritmo tem que mudar constantemente o *duty-cycle* do conversor SEPIC. Este controlo foi implementado numa placa de desenvolvimento *ARDUINO ATMEGA UNO 328P*. O sistema para produção de energia desenvolvido foi todo simulado usando o software *PSIM*. Isto permitiu observar o comportamento desse sistema quando foi colocada na sua saída uma carga passiva (carga resistiva) e uma carga ativa (bateria).

Finalmente, com este trabalho, espero poder trazer benefícios ao meu país natal, a Síria, e ao meu segundo país, Portugal.

Palavras-Chave: SEPIC, Eletrónica de Potência, Rastreador de ponto de máxima potência (MPPT), Turbina micro-eolica, Energias Renováveis, Educação, Simulação, Implementação, ADC, PWM.

List of Contents

List of Figures

List of Tabels

List of Abbreviations and Acronyms

PE	*Power Electronics*
ESA	*European Space Agency*
CERN	*European Council for Nuclear Research*
SEPIC	*Single Ended Primary Inductance Converter*
MPPT	*Maximum Power Point Tracker*
PD3	*Three-phase rectifier bridge*
PD2	*Single phase rectifier bridge*
HVDC	*High Voltage Direct Current*
SCR	*Silicon Controlled Rectifier*
GTO	*Gate Turn-Off Thyristor*
BJT	*Bipolar junction Transistor*
PWM	*Pulse Width Modulation*
TSR	*Tip Speed Ratio*
EMI	*Electromagnetic Interference*
ICSP	*In-circuit serial programmer*
ADC	*Analogue to Digital Converter*
OTC	*Optimal Torque Control*
P&O	*Perturbation and Observation*
IGBT	*Insulated Gate Bipolar Transistor*
IEEE	*Institute of Electrical and Electronics Engineers*
DSP	*Digital Signal Processing*
PI	*Proportional Integrator*

Nomenclature

Symbol	Meaning	Unit
V_C , V_{Rec}	Average output voltage DC voltage – Rectified voltage	V
q	The number of circuit's branches	-
ψ, ψ_A, ψ_B	Firing angle of thyristor	Degree
ω , ω_b	Angular frequency	Rad/sec
K_1 , K_2 , K	Duty cycle	-
$v_o(t)$	Instantaneous value of output voltage	V
E	Electro-motive force	V
f , f_{in} , f_{out}	Frequency, input frequency, output frequency	Hz
R	Resistor	Ω
$R_{DS(on)}$	Resistor of Drain-Source junction in turn-on case	Ω
$v_{cut\text{-}in}$	Initial speed value	m/sec
$v_{cut\text{-}out}$	Final speed value	m/sec
v_{rated}	Rated speed value	m/sec
r	Radius of turbine blades	m
T_m	Mechanical torque	N.M
G	Gear ratio between the turbine shaft and the generator rotor shaft	-
β	Pitch angle of the wind turbine	Degree
C_P	Power coefficient function	-
$2P$	Number of poles	pole
η	Circuit efficiency	-
m	Factor between 20% and 40%	-
A	Rotor swept area	m^2
ρ	Air density	Kg/m^2
V	Wind speed	m/sec

V_m	Peak phase value of source voltage	V
V_s	Source voltage	V
V_D	Diode voltage dropping	V
V_{ref}	Reference voltage	V
V_{PK}	Peak line-to-line back EMF constant	V
V_i V_{eff}	RMS input voltage	V
L	Inductance	μH
C	Capacitor	μF
T	Period	sec
I_C	Output DC current	A
I_s , I_i	Source current	A
I_L, I_{L1} I_{L2}	Inductor current	A
ΔI_L	Inductor ripple current	A
I_Q	Current rating for MOSFET	A
P	Wind turbine output power	W
P_Q	Losses power in MOSFET	W
P_1	Output power of the rectifier	W
P_2	Input power of SEPIC	W

CHAPTER 1

Introduction

1.1. The History of Power Electronics

The amazing evolution in lots of technical fields these days was not achieved without the appearance of electronics and area of electrical engineering at the beginning of the twentieth century which is a continuously renewable field. Nowadays, the world depends more and more on renewable energy applications which are closely linked with Power Electronics (PE) area to convert the type of energy according to the purpose by using rectifiers, choppers, inverters and frequency converters to achieve the demand of global energy. In 1904 and in the same time when Wright brothers built the first plane ever, the British engineer John Ambrose Fleming was working in his modest laboratory to try to make a vacuum glass tube with the ability to pass the current in one direction (Electronic valve) and he actually succeeded to achieve his goal [1].

Nowadays, the effect of Fleming tube invention (electronic valve) on Humans well-being life is not less important than the effect of Wright brothers' plane invention.

All of PE circuits contain semiconductor elements where the basic purpose of these elements, or electronic valves, is to pass the current in one direction through a small current or voltage value which is applied on the gate pin. This simple function is exploited to do more complex functions and according to this feature, lots of complicated devices and circuits were built to play an important role in people's life. Therefore, the transistor invention was considered as the greatest invention in the twenty century. Consequently, the transistor inventors received a Nobel prize in 1956 even before that its applications started to appear.

In the beginning of 20th century, new applications needing to convert the type of power form AC to DC and the opposite started to appear, so the electronics area was expanded to include PE branch which has many applications in the field of power conversion and transmission.

Nowadays lots of researchers work in the field of optical electronics to study the possibility of manufacturing optical transistors, where the light is the holder of the signals instead of the electrons, and that means increasing the speed of information processing because the transference speed of light is greater than the transference speed of electrons.

The importance of PE area in our life needs to find new educational ways to learn PE, especially for academicals students and specialists. The area of PE mainly consists of four blocks as shown in Figure 1.1 and with PE help, it is possible to make a power conversion with high performance and less components volume.

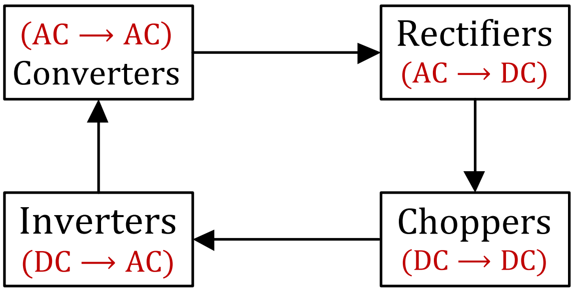


Figure 1.1 - Power Electronics structure loop.

1.2. The Importance and Needing of New Ways to Learn Power Electronics

Unfortunately, during the past few years most of the world's energy is generated by traditional ways by burning the fossil fuels and that caused environmental pollution problems, so it was very necessary to find a final solution for this problem by using a renewable energy system which is closely linked with PE applications.

PE deals with converting the type of power according to the final application with the help of semiconductor devices (switchers), so the efficiency of PE circuits can be very high (more than 90%). With advanced technology and low cost of elements, the size became smaller with high and acceptable performance.

PE applications became increasingly important with the appearance of renewable energy system which has environmentally clean resources like wind, solar, hydro, biofuels and wave energy. In addition to that, PE nowadays are used in lots of important fields for example, in the European organization for nuclear research (CERN) which is interested in fundamental structure of the universe, they are using the most complex scientific instruments to study the basics of the matter. Therefore, they need very huge magnetic field values more than earth magnetic value by 100 000 as shown in Figure 1.2 which is produced by using PE.

European Space Agency (ESA) is also using PE to feed and store surplus power in the spacecraft's batteries until needed [2].

By talking about PE in academicals field, most of students still have difficulties with studying it because some circuits have a complex structure and work mechanism like Cyclo converter and Matrix converter. In addition, PE area is closely linked with other fields of Electrical Engineering like Electromagnetics and Electric Machines, so the new ways of presenting PE for students in a simple way to understand and study must be represented in a motivating and organized way with staying faraway from boring mathematical equations which are necessary in some cases. Therefore, as a part of this work, an Educational Power Electronics document, written in a motivating way, is presented for students and for non-specialists to help them to understand PE and develop new ideas in the future. For more information, the chapter 2 in this thesis speaks about the modern ways to learn PE.

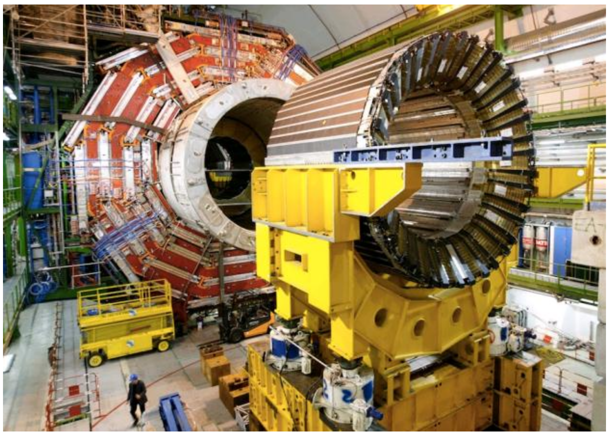


Figure 1.2 -Tesla superconducting magnet – CERN **[**3**].**

1.3. Implementation of Power Electronics Circuits

An MPPT (Maximum Power Point Tracker) system for micro wind power using SEPIC (Single-Ended Primary-Inductor Converter) converter has been implemented to be used in boats to charge the batteries, and to observe the differences between simulation results (theoretical results) and practical results (implementation results).

This system contains a micro wind turbine with a synchronous generator, a PD3 (three-phase full bridge rectifier) uncontrolled rectifier bridge and a coupled inductor SEPIC converter to increase or decrease the output voltage (the duty cycle) according to the wind speed. The control method used here, MPPT with perturbation and observation, is controlled by using the microcontroller *ATMEGA UNO* 328*P*.

Coupled inductor SEPIC converter is used as a charging system for the batteries. The idea is to drive the boats in two ways through a combustion engine and an electric one. When the combustion engine is working, the wind turbine is connected with synchronous generator to produce AC power which is rectified by PD3 bridge to DC power. The duty cycle of SEPIC is changed according to the input voltage of SEPIC (output voltage of the rectifier) to generate the electricity and charge the batteries, as shown in the diagram of Figure 1.3. This system uses a 450 W wind turbine (*SilentWind* 24 V) with permanent magnet synchronous generator.

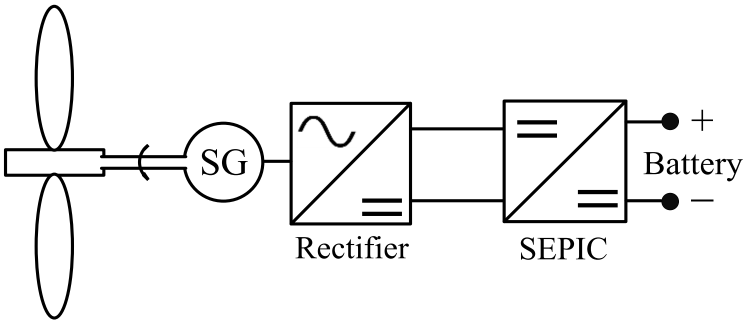


Figure 1.3 - Micro wind power application using SEPIC converter.

This study is a direct application about the relation between Power Electronics converters and what is described in the written Educational Power Electronics document, because this study uses two types of converters, AC→DC converter (PD3 rectifier) and DC →DC SEPIC converter (chopper).

1.4. Motivations

Learning and presenting Power Electronics for the students in a motivating, organized and easy way to study, with the possibility of getting knowledge through simulation results, are the main motivations for this Master thesis work. The implementation of a batteries charging system using a micro wind turbine, with permanent magnet synchronous generator, three-phase uncontrolled rectifier, coupled inductor SEPIC converter, and digital controller, are another important motivation.

1.5. Objectives and Contributions

The objectives and contributions of this work are the following:

- Presenting an Educational Power Electronics document for students with theoretical explanations and with simulations of all the circuits by using *PSIM* and *MATLAB* programs.
- Providing the models of the simulated circuits on a CD, which gives the possibility to check results and change circuits parameters.
- Making a copy of the Educational Power Electronics document in 16:9 dimensions to be used on multimedia devices.

- Implementing a batteries charging system with MPPT for micro wind turbine using a coupled inductor SEPIC converter.

1.6. Thesis Organization

Chapter 1 is an introduction for the main purpose which gives an idea about needing new motivating ways to learn Power Electronics for the students and the implemented circuits.

Chapter 2 handles the traditional and modern resources to learn Power Electronics these days which includes journals, books, video conferencing and Power Electronics websites.

Chapter 3 handles with Educational Power Electronics document and gives an idea about its content, presentation and multipurpose Power Electronics circuits.

Chapter 4 talking about simulation of Power Electronics circuits, the ways of simulation, *MATLAB* and *PSIM* programs.

Chapter 5 describes the theoretical information about micro wind power turbine using SEPIC converter charging batteries system which includes MPPT control, calculation design for SEPIC converter, driving circuit of MOSFET and *ATMEGA* 328*p* microcontroller.

Chapter 6 contains the experimental results for the system and also makes a comparison between the theoretical and experimental results for the system.

Chapter 7 contains the conclusion, the problems that should be solved and the suggestions for the future.

CHAPTER 2

What Exists for Learning Power Electronics

2.1. Introduction

Power Electronics (PE) is in constant innovation and renewal, so the researchers and people who are interested in this field should know always more and more about the fundamentals of electronics and electrical power areas.

As a result of the importance of PE at the present time, there are many educational sources for the people who are interested to learn PE and expand their horizons of knowledge in this field, and because of we are in the age of scientific and technological evolution, both of computer and the internet grid are appeared to use as a trendy methods to get as much information as possible about any subject. In addition to that, the electronics copies of educational books to learn PE which prepared with animated figures are very suitable for students to analyze and recognize very well the work mechanism for any complex circuit, also one of the sources to learn PE is the scientific journals which publish the newest applications of science and the most important scientific achievements. Also we do not have to ignore the role of traditional PE books which are also the primary source to learn PE.

As a result, the available options to study PE can be classified as:

1- Electronic Learning Sources, which are Divided into:

1- PE websites and interactive forums.

2- Video conferencing and educational videos.

3- Electronic books which provided with animated figures.

4- Specific educational books written by the manufacturer.

5- Social network websites which include a content of interactive groups.

2- Traditional Learning Sources, which Divided into:

1- Scientific journals.

2- Traditional books.

3- Modeling and Simulation Programs

2.2. Electronic Learning Sources

Electronic learning nowadays using all of multimedia devices which include lots of available information on the internet grid in different fields to facilitate students realizing for scientific subjects according to their abilities at any time.

The education in age of communication and information technology is a worthy commodity, so it is important these days to realize that we have to deal with education process in a different way from the past, so that is possible today to exchange the information, develop the communication between people, gathering and analysis information to find good solutions for many problems.

Some benefits for electronic educational sources [4]:

1- The big effectiveness for electronic educational sources that increase the ability of learning and recall the information.
2- Less costs and saving more time because of the student does not have to go every day to a university or any educational institute.
3- More flexibility than traditional learning sources which means that the student can access to his educational program at any time.
4- The possibility to choose the level of education, whether for beginner students, professional students or for craftsmen.

2.2.1. Power Electronics Websites and Interactive Forums

These websites are designed to help people, especially students, job seekers and working engineers who need information about PE completely from the basics to advanced levels. In addition, these websites have forums for discussion about any scientific idea with specialists and experts opinions that will confirm and make the educational process more interesting.

Also one of the features for these websites is they are always constantly in innovation and evolution for the information which fitting with the development of technology. These websites are often associated with researching centers or the universities and they are among the easiest and cheapest ways to study PE.

Some examples for tutorial PE websites, which are completely free, are shown in Figure 2.1.

“www.completepowerelectronics.com” and “www.powerelectronics.com”.

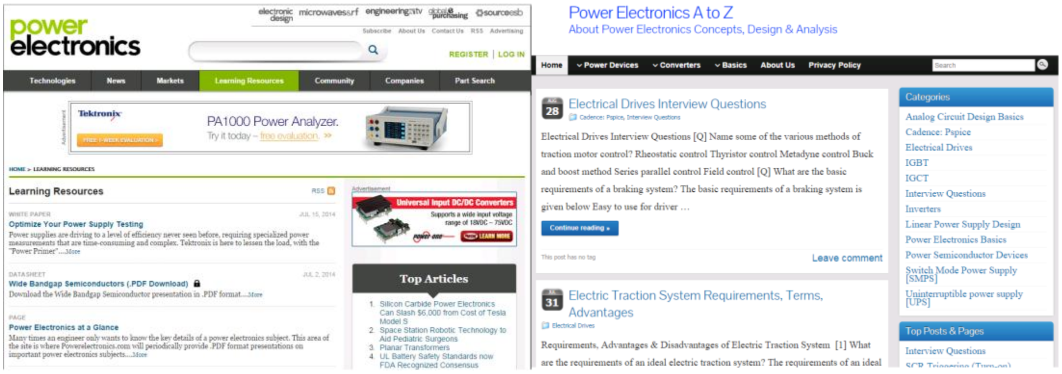


Figure 2.1- Some examples of tutorial power electronics websites.

2.2.2. Video Conferencing and Educational Videos

The video conference is a broadcasting live lectures from a site to several sites which separated by distances. The process of sending and receiving information will be as an interactive and direct process between members by using the internet grid, cameras and monitors.

This way gives the best opportunity to learn PE for as many people as possible, also one of the most modern applications for video conference which is related to with engineering science is a telemedicine system which allows for doctors to confer or doing some surgical operations through video and robot system [5].

The differences between learning PE through video conference system and normal educational videos is that video conference system is a real time system or synchronous information delivery system as shown in Figure 2.2, while normal educational videos is an asynchronous information delivery system (later time).

Both ways are very preferable to learn PE and any other fields because this way is very interesting and motivating for students, also it helping for reminding the new concepts for a long time more than other ways, in addition of increasing the ability to understand new difficult ideas.

Figure 2.2 - Video conference system [6].

2.2.3. Electronic Books which are Provided with Animated Figures

Animated figures are defined as a group of drawings which are displayed behind each other in sequential mode and regular presentation speed to give at the end a sense of motion on screen, making the learning process interesting and motivating for students to increase the ability of realizing new concepts.

It is possible to give the movement for the most of photos and graphics to clarify most of unclear points or to explain some difficult ideas, so the movement of drawings here gives the motivation for student to learn more and leads to increasing the physical sense for learners, also it can provide this motion accompanied with sounds and clarification texts and in this case will be similar to videos. In PE field, there are lots of circuits with complex work mechanism (for example: cycloconverter and multi-level inverter) that present their work mechanisms in this way leads to simplify the learning process and make easier cognition for students whatever the circuit was complex.

This learning method is still a modern method and has a limited spread comparing with other methods, also most of electronics books which provided with animated figures are not free and expensive but it is possible to find some websites on the internet which provide the explanation for some simple electronic circuits and it is completely free.

2.2.4. Special Educational Books Written by the Manufacturer

These books are normally written by the company that manufactured the device and the main purpose of these books is to describe and explain about the products, how to use it, and product advantages, so these books are not for a category of beginner students who want to learn the basics in PE. It is more for a category of engineers and specialist people because these books are talking about a specific application and the achievements of company in this field to facilitate product marketing process.

The main features of these books are:

1- Usually these books are accompanied with real clarification figures of products.
2- They includes the designing values of product (datasheet).
3- Explanations about work mechanism and the product installation.
4- Keep up with the last version of product.
5- Most of these books are completely free (download from the company website).

For example: a book about HVDC (High Voltage Direct Current) for beginners and beyond is written by *ALSTOM* company (*ALSTOM* is a French multinational company which holds interests in the electricity generation and rail transport markets), so this book is an educational book about specific application (HVDC) and in the same time it aims to marketing the product [7].

Another book from *ABB* company (*ABB* is a multinational corporation *headquartered in Zurich*, *Switzerland*, operating mainly in robotics and the power and automation technology areas) talking about the solutions for photovoltaic protections as shown in Figure 2.3 [8].

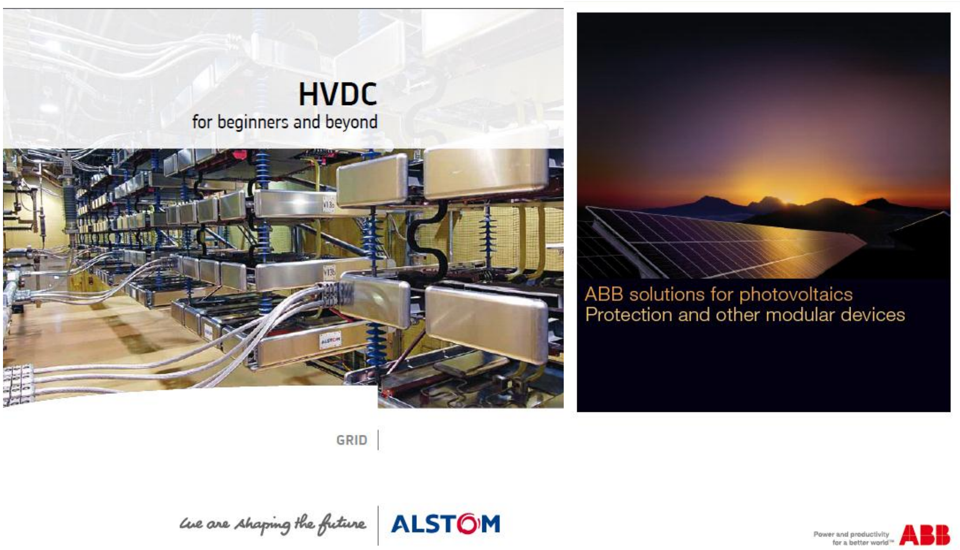


Figure 2.3 – HVDC book written by *ALTSOM* and Photovoltaic book written by *ABB* [7] [8].

2.2.5. Social Network Websites which Include a Content of Interactive Groups

Social websites started recently to spread very rapidly between people and they are known as “the new social media”, which are always in development and in continuous widespread.

These websites are the newest communication technology products and the most popular websites on the internet. Although these websites were established for social communication between people, nowadays they are also being used for scientific activities.

Some of the most famous social websites are *Facebook* and *Twitter*, and the first social website in the world is a *Facebook* with more than 700 million members. It normally consists of some social groups and pages which have specific targets and some of them are specialized about PE with different levels for students.

In this case, the student’s responsibility is only to join for one of these educational groups which talking about PE before being able to discuss in any topic.

The features of these websites are:

1- Full possibility to ask any question for members.
2- Speed responding, especially if the group has lots of members.
3- The possibility of discussion about any topic with members.
4- Most of these groups have permanent updating for the information.

The disadvantages of this way to learn PE is a lack of information reliability, by another meaning, the student must be careful to choose the true information when a scientific discussion happens between members because most of those members are not specialized people.

2.3. Traditional Learning Sources

Every work in this life has positive and negative sides, and that also applying for electronic learning way which depends on computer and internet grid.

The internet grid is an open information system where any user can have his own website which includes lots of inaccurate information and that leads to damage and harm the academic integrity. Therefore, the importance of traditional learning sources which usually are not free and not available for all categories like books and scientific journals that these sources characterized by a full accurate information and still preferable for some people in spite of a widespread of electronic learning sources and that for sure applying for any field of study, including PE. We will talk later in some details about the traditional sources to learn PE.

2.3.1. Power Electronics Journals

PE journals have two kinds, one of them called educational journals which interested in publishing the recent news and applications of PE area in a simple way for normal people and non-specialists and the second one called academic journals which published for researchers and academic people (specialist people).

Normally, these journals have two published ways, virtual journal contains a collection of previously published paper in a scientific style, and hard copy journal to facilitate its spread between people as much as possible. The headline and the main topics for every copy of this journal are determined by an editorial team according to their relevance. Therefore, it is not necessary that the journal be always restricted to specific topics.

Usually most of these journals are not free because it contains lots of innovation and updated information in PE field and some of these academic journals are related to research bodies and the universities around the world, so these journals are not a good choice for people who want to learn the basics in PE but on the opposite, it is a good reference for specialists and researchers.

The advantages of these virtual journals are [9]:

1- Quick access to the previously published papers in a scientific style.
2- Valuable commentary that provided by researchers and academic team.
3- Provide the links for full-text articles and the reference journal.
4- Comfortable browse and links to previous issues.

Some examples of PE academic journal is an *International Journal of Advancements in Power Electronics & Digital Devices* which includes original research and innovation ideas, applications from all over the world.

Also one of the most important and popular journal in the world is a journal which followed by the *Institute of Electrical and Electronics Engineers IEEE* as shown in Figure 2.4 which has a lot of various topics (not only about Power Electronics) like bioengineering, robotics, control systems and nuclear engineering.

Figure 2.4 – some power electronics journals [10].

2.3.2. Traditional Educational Books

The most important option and reference these days to learn PE are still the traditional books which not possible to ignore their roles whatever the other educational methods are developed and increased due to these books contain the feature of information reliability, illustrative examples, and recent studies. The researches nowadays indicated that reading electronics books is harder than reading traditional ones.

Sometimes, the traditional books are more preferable to read for students and researchers, but that does not mean ignoring the electronic learning sources. Despite of the fact that electronic books have recently spread very quickly, but they still need lots of time to eliminate the effect of traditional books which are indispensable for anyone because they supposed as a permanent reference and can be stored for a long time on the opposite of electronic storage tools which can be damaged at any time.

Both traditional and electronic books have their own features. For example, the electronic books can contain animation figures which increase the ability of realizing the new ideas, while the traditional books are more organized, have a logical sequence of ideas, and suitable for all student levels. Also it is important to know that these books are always updated to new editions to avoid old mistakes and keep up with the latest developments in PE, so it can be found the same book of the same author with different editions.

2.4. Modeling and Simulation Programs

According to these programs, a student can simulate any circuit and detect both of transient and stable results. Usually these programs consist of a dialogic interface with student which allows for student to make a simulation and observe the results before they are applied on reality.

Circuits simulation is a one of the newest way of self-learning PE because it helps the student to predict and conclude the results, on the other hand, usually the simulation is accompanied with the other previous learning ways, for example student can study any circuit and see its work mechanism results before doing the simulation which must to confirm the same results.

Nowadays, lots of simulation programs are available to do the simulation for electrical circuits and the most popular program for simulation and modeling is a *MATLAB* which consists of lots of libraries and every library is responsible for a specific purpose. *Simulink* and *Simpowersystem* libraries are using to simulate Power Electronics circuits and every model could be accompanied with editor file as a definition file to define the variables which including inside the model file.

Also one of the most popular simulation programs is *PSIM*, and the main feature of this program that it accepts the simulation with *C+* language, in order to simulate a microcontroller program. *MULTISIM* program, from *National Instruments* company, is also a popular program to make simulations of PE circuits.

2.5. Conclusion

After making a review about PE learning sources, traditional and modern ones, it is very clear that every option has its own advantages and disadvantages, and that there is no perfect option to learn PE.

The most important point which the student must know is that any information source must be accurate, recommended and reliable, in order to learn PE. Although traditional PE sources are more reliable and trusty, at the same time they can be boring for students, because they usually contain lots of theoretical information and mathematical equations (which in some cases are unnecessary).

In the end, the learner must choose the best option to learn PE according to many points, like his skills and the level of his previous knowledge. Although the traditional ways are typically the slowest ways to understand and remember new ideas, it is not possible to ignore them, because they are references for teaching and learning processes.

CHAPTER 3

Theory of Power Electronics Circuits

3.1. Introduction

This chapter presents the Educational Power Electronics document, which was prepared in the scope of this Master thesis for students and people who are not specialists in Power Electronics, to make this area of Electrical Engineering as much available as possible. Also, this chapter presents theory of PE circuits, as well as multi-purpose PE circuits that can work in many possibilities, according to the driving way of semiconductor elements.

3.2. Multi-Purpose Power Electronics Circuit

This chapter gives an idea about the simulation of PE circuits and multi-purposes circuits which described in PE document:

1- AC ⟶ DC converters (Rectifiers) P-PD-S groups.
2- Rectifier groups (ways of linking) Dual converter, 12,18,24 pulse converter.
3- DC ⟶ DC converters (Choppers).
4- DC ⟶ AC converters (Inverters).
5- AC ⟶ AC converters voltage regulators, cycloconverter, and matrix converter.

Inside these five parts there are multi-purpose circuits that can work depending on driving method of semiconductor elements like *Graetz* bridge or *H* bridge can work as an rectifier, chopper, or full bridge inverter. In addition, dualconverter and cycloconverter have exactly the same circuit topology but driving method for the elements is completely different.

3.3. Graetz Bridge (*H* Bridge)

This bridge is a symmetrical bridge, and Figure 3.1 shows the feeding points for this bridge (A,B for AC side and D,C for DC side) so it can work on three groups of converters:

1- AC ⟶ DC converters (Rectifiers).

a- Full controlled bridge.

b- Symmetrical half controlled bridge

c- Asymmetrical half controlled bridge.

2- DC ⟶ DC converters (Choppers) full bridge chopper.

3- DC ⟶ AC converters (Inverters) full bridge inverter.

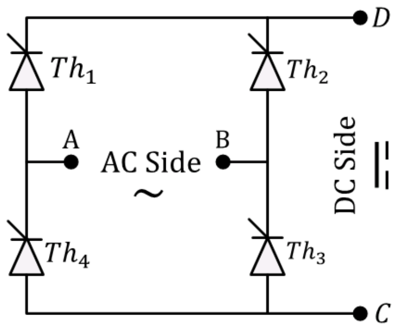


Figure 3.1 - Graetz bridge feeding points.

3.3.1. Graetz Bridge Rectifier

Graetz bridge rectifier could be full controlled (4 SCR – Silicon Controlled Rectifier), half controlled (2 SCR, 2 Diodes) or uncontrolled (4 diodes) depending on the type of semiconductor elements and it is also called full-wave rectifier which convert the whole of the input voltage to DC voltage with the same polarity, to achieve that, we need four semiconductor elements, each two of them work in a half of the cycle (positive and negative one).

3.3.1.1.Full controlled Greaetz Bridge Rectifier

It is possible to change the value of firing angle by using SCRs instead of diodes but to achieve single phase bridge rectifier, it should to create two AC signals with shift angle between them equals to 180°, so using center tapped transformer leads to get double output voltage. Figure 3.2 shows center tapped transformer with PD2 (single-phase rectifier) bridge and Figure 3.3 shows the results at resistive load and firing angle ψ =120°.

Work mechanism for this bridge is completely depending on naturally commutated process between the elements.

The average output voltage V_C is given by the equation:

$$V_C = \frac{q}{\pi}\ \frac{V_m}{2}\ sin\frac{\pi}{q}\ cos\,\psi \qquad (3.1)$$

q: number of branches and here $q = 2$.

V_m : peak value for phase to phase source voltage.

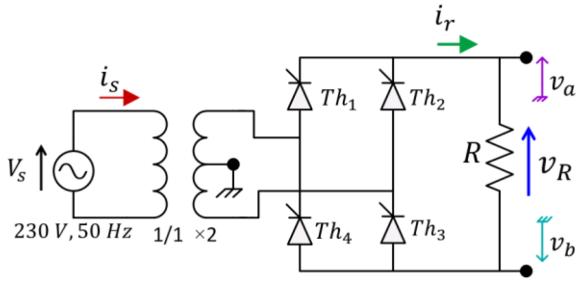


Figure 3.2 - Center tapped transformer with PD2 full controlled bridge.

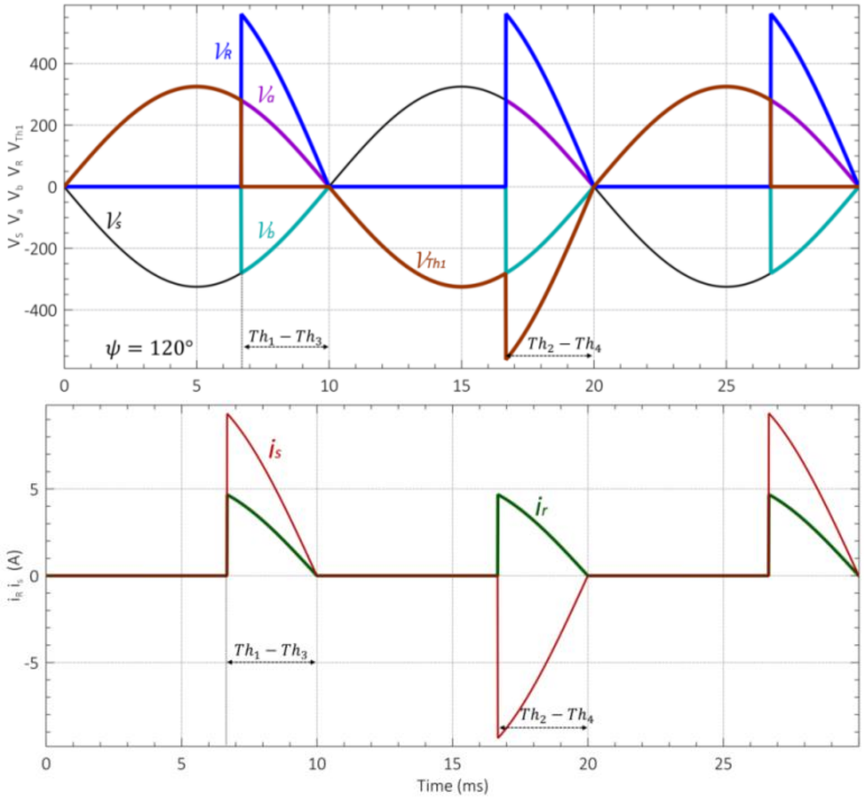


Figure 3.3 - PD2 full controlled Graetz rectifier results at ψ=120°.

Table 3.1 - Work mechanism for PD2 Graetz rectifier.

The angle	Th_1 , Th_3	Th_2 , Th_4
0 → 120°	0	0
120°→ 180°	1	0
180° → 300°	0	0
300° → 360°	0	1

3.3.1.2. Half Controlled Symmetrical Graetz Bridge Rectifier

Symmetrical PD2 bridge means that one of load voltage points is always connected to the common cathodes point, which is related to the same type of semiconductor elements and the other load voltage point is always connected to the common anodes point which is also related to the same type of semiconductor elements as shown in Figure 3.4. Therefore, this bridge means that, there are always common anodes or cathodes point which is related to the same type of semiconductor elements.

Work mechanism for this bridge during a half cycle of the positive wave Th_1 must be in forward bias when also applying trigger pulses or a firing angle ψ on its gate, also diode D_4 is still connected during the period $\pi \leq wt \leq 2\pi$. This leads to make a short line between a and b points especially in the inductive load case as shown in Figure 3.5 [11].

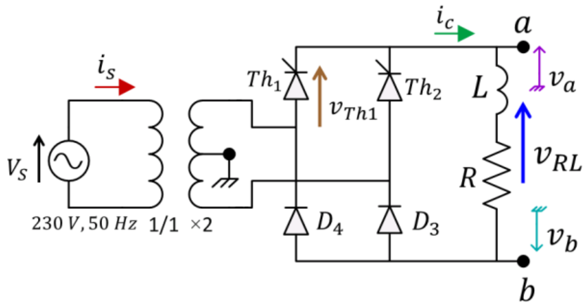


Figure 3.4 - PD2 Symmetrical Half-Controlled Bridge.

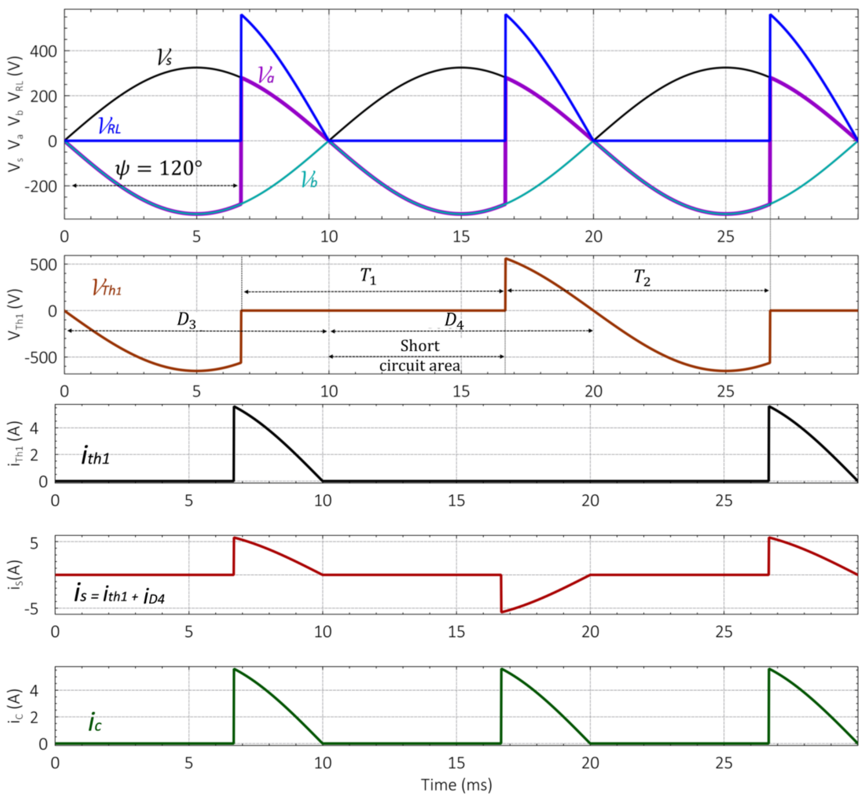


Figure 3.5 - Symmetrical Half bridge Results (Inductive load).

Consequently, during this period of time Th_1 and D_4 are working together and that leads to make the output voltage value equals to zero. The same process is also repeated between Th_2 and D_3, so in each cycle T there are two short circuit durations. The average value of the output voltage is:

$$V_c = \frac{q}{2\pi}\int_{\psi}^{\pi} V_m \sin \omega t \; d\omega t = \frac{q}{2\pi} V_m(1+\cos \psi) \qquad (3.2)$$

The peak value of output voltage happens when the firing angle $\psi = 0$, and in this case:

$$V_c = \frac{q}{\pi} V_{\text{m}} \, , I_c = \frac{V_c}{R} \quad , q = 2$$

Table 3.2 - Work mechanism for symmetrical PD2 Graetz rectifier.

The angle	Th_1	Th_2	D_3	D_4
0 → 120°	0	1	1	0
120°→ 180°	1	0	1	0
180° → 300°	1	0	0	1
300° → 360°	0	1	0	1

3.3.1.3.Half Controlled Asymmetrical Graetz Bridge Rectifier

Asymmetrical PD2 bridge means that one of the load voltage points (for example point *a*) is always connected to the common cathodes point that related to different type of semiconductor elements and the other load voltage point (point *b*) is always connected to the common anodes point which is also related with a different type of semiconductor elements, so this asymmetrical bridge means that there are always a common anodes or cathodes points which are related with different types of semiconductor elements as shown in Figure 3.6.

Work mechanism for this bridge during the positive half cycle of the wave Th_1 must be in a forward bias when applying trigger pulses or a firing angle ψ on its gate, and also the diode D_2 starts to connect at $wt = \pi$. That leads to force Th_1 to stop working, so Th_1 works just during γ period $\psi \le \omega t \le \pi$. That leads to make a short line between point *a* and *b* during $\pi \le \omega t \le 2\pi - \gamma$. Consequently, during this period of time D_2 and D_4 are working together and that leads to make the output voltage value equals to zero as shown in Figure 3.7. The same process is still repeated, so in each cycle T there are two short circuit durations.

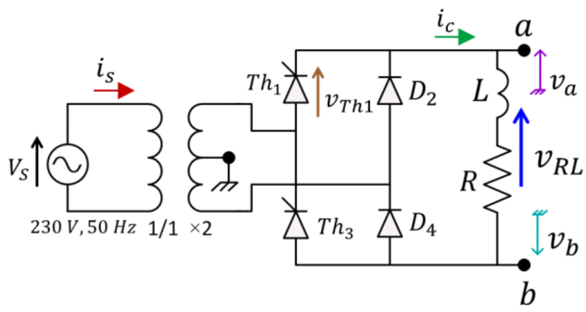


Figure 3.6 - PD3 Asymmetrical Half-Controlled Bridge.

The Average value of output voltage is:

$$V_c = \frac{q}{2\pi}\int_{\psi}^{\pi} V_m \sin\omega t \; d\omega t = \frac{q}{2\pi} V_m (1 + \cos\psi) \qquad (3.3)$$

The max value of output voltage happens when the firing angle $\psi = 0$, and in this case:

$$V_c = \frac{q}{\pi} V_m \,, \; I_c = \frac{V_c}{R} \quad , \; q = 2$$

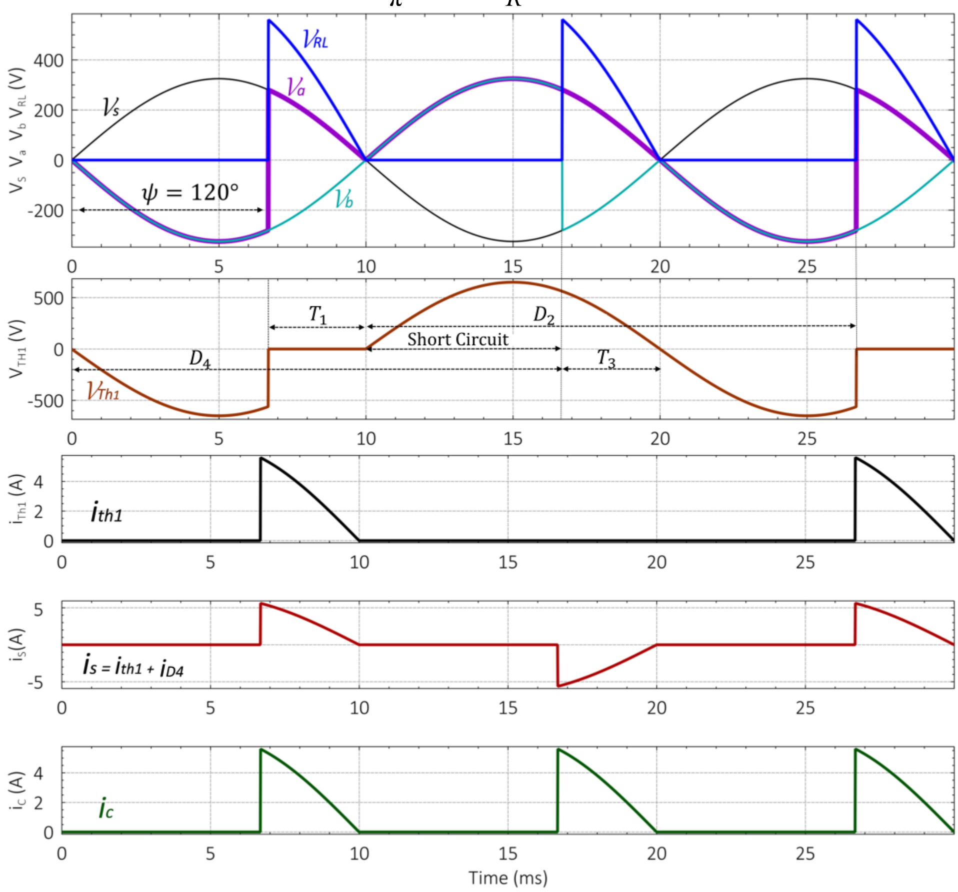


Figure 3.7 - PD2 Asymmetrical Half-Controlled Bridge Results.

Table 3.3 - Work mechanism for asymmetrical PD2 Graetz rectifier.

The angle	Th_1	D_2	Th_3	D_4
0 → 120°	0	1	0	1
120°→ 180°	1	0	0	1
180° → 300°	0	1	0	1
300° → 360°	0	1	1	0

3.3.2. Graetz Bridge (*H* Bridge) Chopper

In this case, the source is connected at DC points (D,C points) as shown in Figure 3.8, also the work mechanism has both natural and forced commutation cases.

To drive DC machine in four quadrants (both of output voltage and current could be positive or negative), it should to use full bridge chopper or *H* bridge to run this machine as a motor or a generator (braking) as shown in Figure 3.8, also the main feature of this converter that the output voltage could be totally controlled by the magnitude and the polarity.

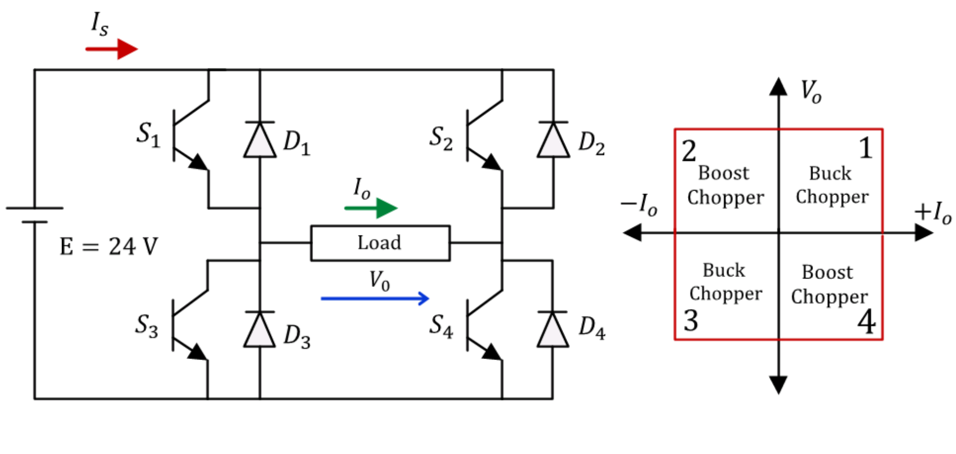


Figure 3.8 - Full bridge chopper circuit.

In case of firing the elements S_1 , S_4 during the period K_1T, the machine will work as a motor and starts to rotate in clockwise direction (First quadrant) and the bridge works as a buck converter (Step-down chopper) also the elements S_2 , S_3 still in reverse bias state. When S_1 switch is disconnected and S_4 still works, the current of machine still flows through S_4 , D_3 and the load voltage equals to zero, next if S_4 switch is disconnected, the current still flows through D_2 , D_3 and the chopper works in the fourth quadrant (Boost converter).

In case of firing the elements S_2 , S_3 during the period K_2T, the machine will work as a motor and starts to rotate in opposite clockwise direction (Third quadrant) and the bridge works as a buck converter (Step-down chopper) also the elements S_1 , S_4 still in reverse bias state. When S_2 switch is disconnected and S_3 still works, the current of machine still flows through S_3 , D_4 and voltage load equals to zero, next if S_3 switch is disconnected the current still flows through D_1 , D_4 and the chopper works in the second quadrant (Boost converter) as shown in Figure 3.9. The average output voltage can be changed by the controlling in duty cycle for each converter K_1 , K_2 but driving process for this full bridge must be integrated process, so $K_1 + K_2 = 1$.

$$V_o = \frac{1}{T}\int_0^{t_{on1}} v_o(t)\, dt + \frac{1}{T}\int_0^{t_{on2}} -v_0(t)\, dt = \frac{1}{T}\int_0^{t_{on}} E\, dt + \frac{1}{T}\int_0^{t_{on2}} -E\, dt \qquad (3.4)$$

$$\Rightarrow = \frac{t_{on1}}{T}E - \frac{t_{on2}}{T}E = K_1E - K_2E = K_1E - (1-K_1)E \Rightarrow$$

$$V_o = (2K_1 - 1)E \qquad (3.5)$$

- When $K_1 = 0 \Rightarrow K_2 = 1 \Rightarrow V_o = -E$
- When $K_1 = 1 \Rightarrow K_2 = 0 \Rightarrow V_o = +E$
- When $0.5 < K_1 < 1 \Rightarrow 0 < K_2 < 0.5 \Rightarrow V_o > 0$ and the current has a positive value (S_1 , S_4) (motor rotates in clockwise direction)or negative value (D_1 , D_4) (braking status) as shown in Figure 3.9.
- When $0 < K_1 < 0.5 \Rightarrow 0.5 < K_2 < 1 \Rightarrow V_o < 0$ and the current has a positive value(D_2 , D_3) (braking status) or negative value (S_2 , S_3) (motor rotates in opposite clockwise direction).

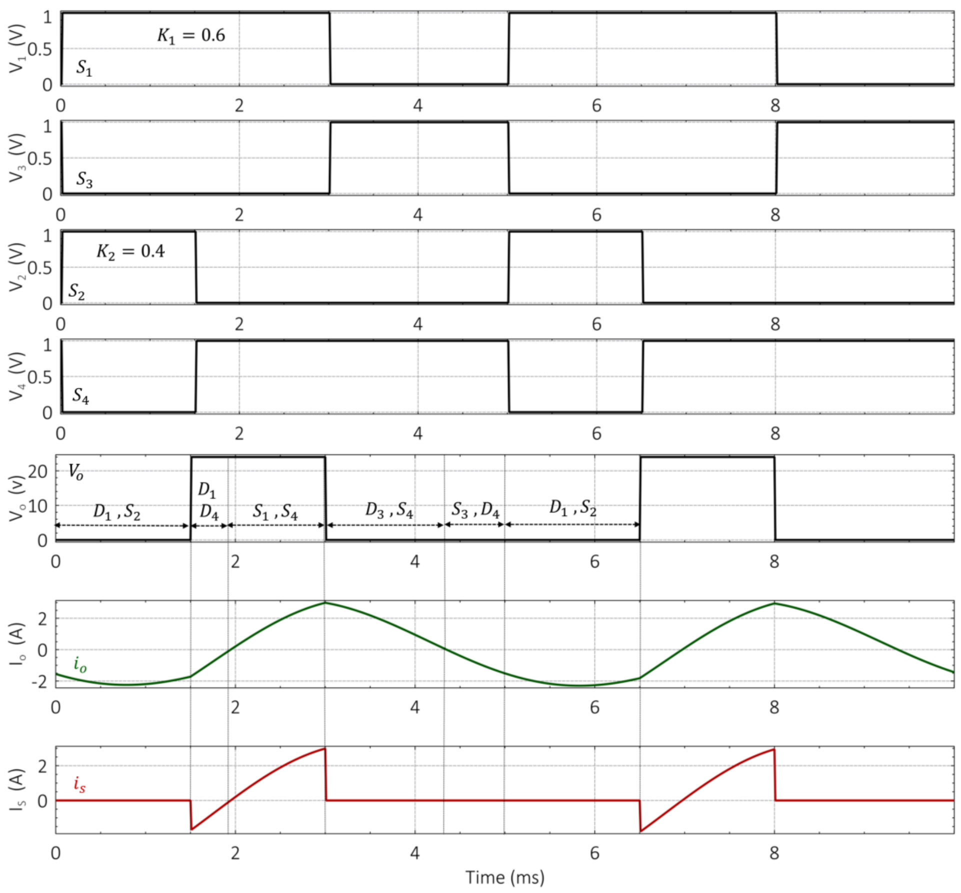


Figure 3.9 - Full bridge chopper results at K_1=0.6.

Figure 3.10 shows the work characteristic curves for full bridge chopper.

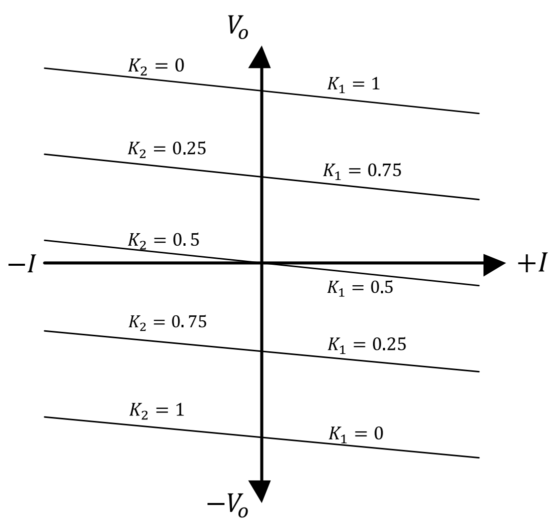


Figure 3.10 - Work characteristic curves for full bridge chopper.

3.3.3. Graetz Bridge (*H* Bridge) Inverter

This bridge consists of two groups of elements Th_1 , D_1 , $Th_1{}'$, $D_1{}'$ and Th_2 , D_2 , $Th_2{}'$, $D_2{}'$ connected with DC source E as shown in Figure 3.11. The Single phase *H* bridge inverter circuit is very similar to the full bridge chopper circuit but the driving method for semiconductor elements is completely different.

By supposing that $T = \frac{1}{f}$ is a cycle of an alternating voltage, so the angular velocity is $\omega = \frac{2\pi}{T}$. At $t = \varphi$, both of Th_1 and $Th_2{}'$ are connecting to pass positive current, then Th_1 forced to turn off and the current pass through $Th_2{}'$, $D_1{}'$. Both of $Th_1{}'$ and Th_2 are connecting at $\omega t = \pi+\varphi$ until $\omega t = \beta$, where to change the RMS and average values of output voltage, the angle β takes the values $0 \rightarrow \pi$ and it is called phase shifting angle to start firing the elements as shown in Figure 3.12.

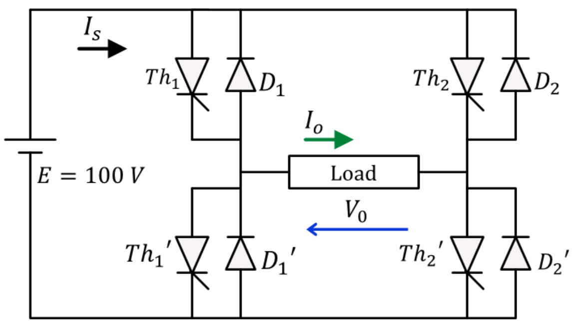


Figure 3.11 - Single phase *H* bridge Inverter circuit.

Table 3.4 - Work mechanism for single phase *H* bridge inverter.

Statues		Th_1	D_1	$Th_1{}'$	$D_1{}'$	$Th_2{}'$	$D_2{}'$	Th_2	D_2
$0 \longrightarrow \pi$	$P > 0$	1				1			
	$P < 0$		1				1		
	$P = 0$		1					1	
$\pi \longrightarrow 2\pi$	$P > 0$			1				1	
	$P < 0$				1				1
	$P = 0$				1	1			

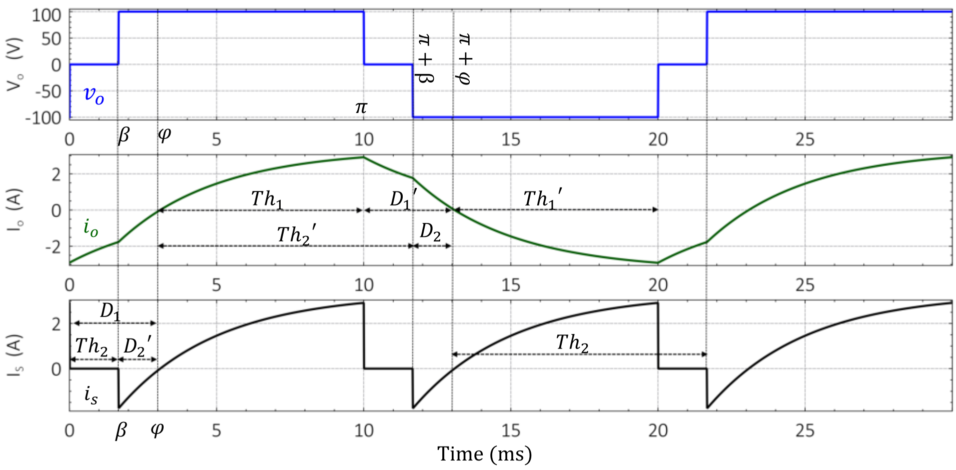


Figure 3.12 - Single phase *H* bridge Inverter results.

Load current must stay continuous and it has three work cases. Therefore, the first case happens when the current passes through a closed loop like Th_2', D_1' (i_s equals to zero). The second case happens when the current passes from the source $\longrightarrow$ load (i_s is positive). The third case happens when the current passes from the load $\rightarrow$ source (i_s is negative).

3.4. Three Phase PD3 Dualconverter

Full controlled converter can work as a rectifier ($0 \le \psi \le 90°$) or as an inverter ($90° \le \psi \le 180°$), but in both cases the power is transferring from AC $\rightarrow$ DC and the direction of power P could be changed because the full controlled converter can produce a reversible direct output voltage (with two direction of voltage) but still produces one direction output current, so this dualconverter can work in four quadrants as shown in Figure 3.14 instead of use one bridge with an inverse breaker and it can be used to drive DC machines to work as a motor or a generator.

If two bridges are connected to each other and working together to feed the load with two power directions as shown in Figure 3.13, in this case, it is possible to make a controlling in power flow with two directions depending on which bridge works as a rectifier and the other bridge certainly works as an inverter or in stopping mode. Therefore, There are two types of work mechanism for this dualconverter:

1- Working without circulation current between bridges:

   Always one bridge works and the other one stopping (floating mode).

   Circulation current: the current passes through two bridges and it is not related to the load current. This current has a big value in normal cases.

2- Working with circulation current between bridges:

Always one of the bridges works mainly and the other one works also to receive or send the power. Consequently, these two bridges must work by an integral work system which means the summing of the firing angles for the two bridges is always 180°, for example if the first bridge is working at a firing angle ψ_A= 60° (rectifier mode), the second bridge must work at a firing angle ψ_B= 120° (inverting power mode) [12].

Figure 3.14 shows the relation between the firing angle and the average output voltage value. Figure 3.15 shows the results when bridge *A* works as a rectifier and bridge *B* works as an inverter, also the basic task of an inductor *L* is to attenuate the instantaneous differences of voltage values between two bridges. The circulation current i_{L2} has a value when the voltage of inductor v_L is not equals to zero.

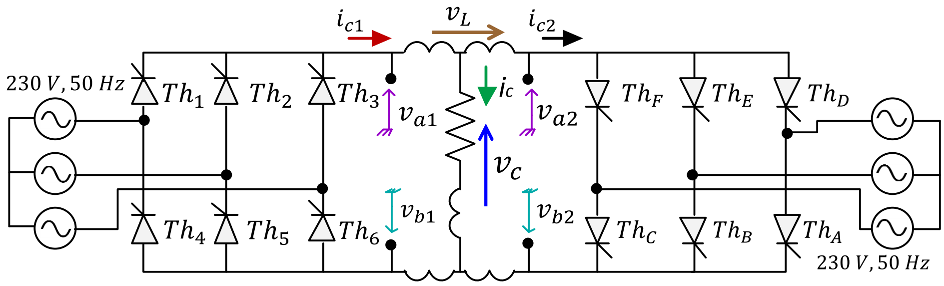


Figure 3.13 - PD3 dualConverter.

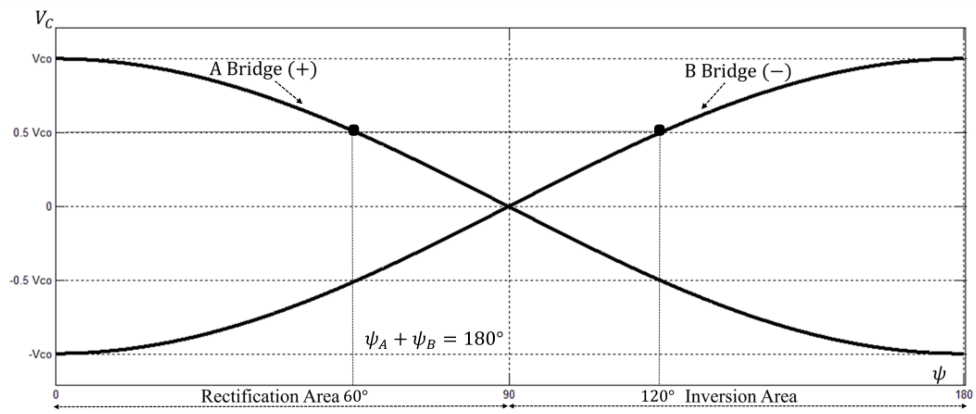


Figure 3.14 - Relation between firing angles and average output voltage value in dualconverter.

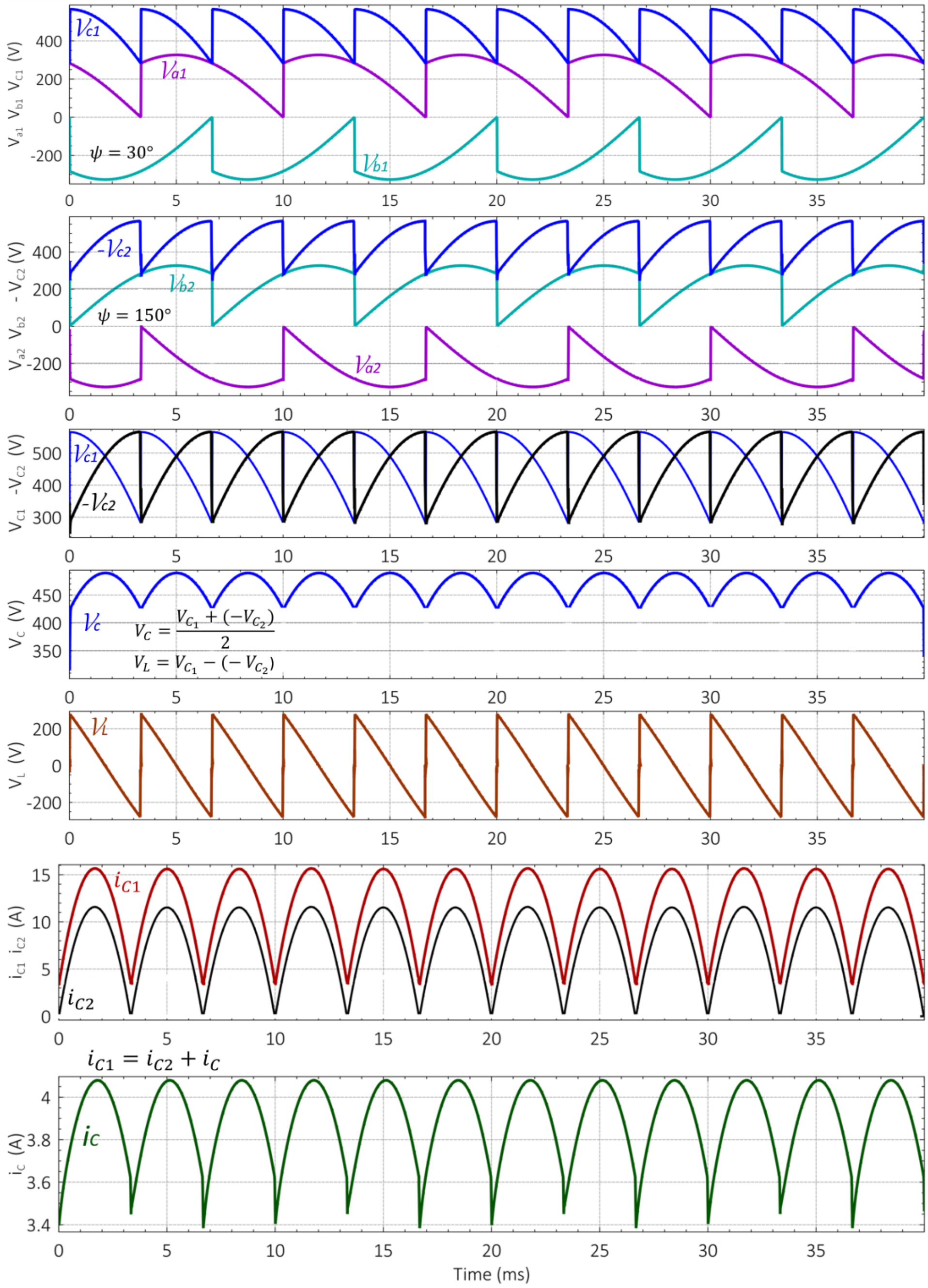


Figure 3.15 - PD3 dualconverter results ψ_A= 30°, ψ_B=150°.

3.5. Three Phase PD3 Cycloconverter (Frequency Converter)

It is already known that the dualconverter is capable of passing the load current in any direction after making a control in firing angle for semiconductor elements and also can work in the four quadrants.

The integral equation of firing angles values in dualconverter also possible to apply in cycloconverter (frequency converter) but by making an attention which the firing angle here does not have constant value during all the cycle, so ψ_A+ψ_B=180°

during specific periods of the cycle as shown in Figure 3.16 [13] and to achieve that it is done often by using PWM (Pulse Width Modulation) control method.

It is expected that by making a change in the firing angle control process for SCRs to have an alternating load voltage instead of a DC load voltage. That is the main purpose of this cycloconverter (frequency converter) which is also a naturally commutated and forced commutated converter. In addition, cycloconverter has a special feature, that can feed loads with different power factors, then the active power P is completely free to pass in anyway.

Step down cycloconverter means that the output frequency is less than the input frequency $f_{in} > f_{out}$ and it is very common to use in industrial applications more than Step up cycloconverter [14].

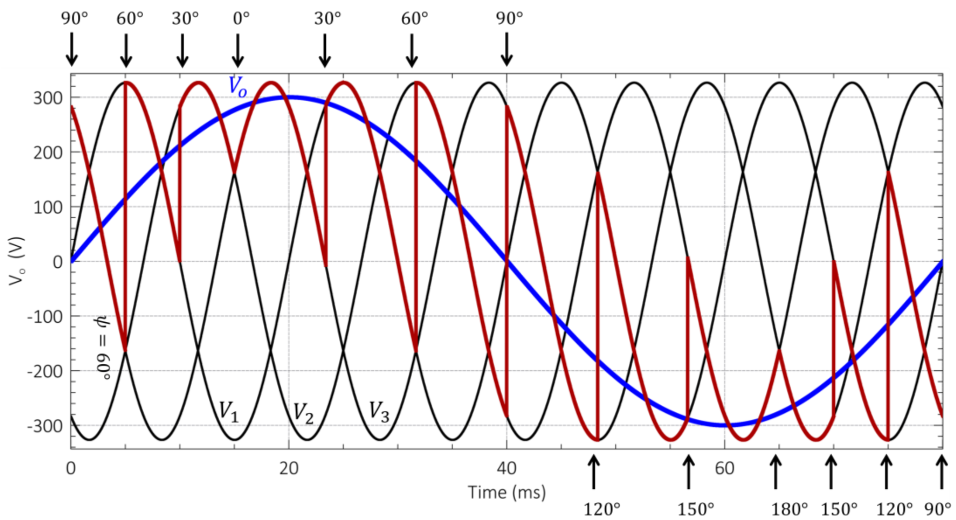


Figure 3.16 - Driving mechanism for simple half wave step down cycloconverter.

Circuit diagram of three-phase to single-phase cycloconverter is shown in Figure 3.13. This cycloconverter has also two work cases according to presence of the circulation current. It is usually used for a three-phase, high power, low speed synchronous motor drives.

Figure 3.17 shows the results of three-phase source to single-phase load cycloconverter before and after making a filtering for the output voltage and with an output frequency $f_2 = 20$ Hz.

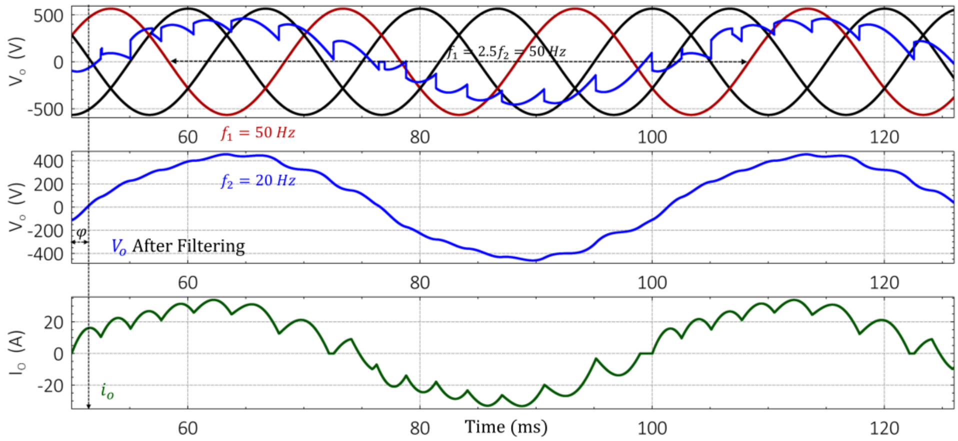


Figure 3.17 – Three-phase to single-phase cycloconverter results.

3.6. Conclusion

The main objective of this chapter was to present the Educational Power Electronics document that was prepared under the scope of this Master thesis. This document was prepared with the objective of being a motivational way to learn Power Electronics, as much far away as possible from boring documents which almost only present mathematical equations and little more. This way, it was considered that the learner of Power Electronics should understand the concepts, with the help of figures and tables, and perform work mechanisms for all the circuits through simulations.

In the end, an interesting presentation way for the Educational Power Electronics document was identified, in the best possible way that helps the student to gather new ideas in the shortest time possible.

CHAPTER 4

Simulation of Power Electronic Circuits

4.1. Introduction

The model for any economic problem or administrative, scientific or military is only a simplified model of this problem, which mostly takes the form of equations and mathematical functions represent the variables that can be quantified for different factors, so the model is a simplified representation or description of a real situation or phenomena. After building the model of any problem, it is possible to simulate the system, where the simulation is a tool to make the real system equivalent to the virtual one, which should act in a similar way to the real system, giving the same or minimizing results in the case of having the same real system inputs [15].

The modeling process for any problem must consider these two points:

1- System conception, which includes full understanding and knowledge of the real system, taking into consideration system pre-dimension and the feasibility of the model in case of needing any changes in the future.

2- System optimization, which includes reduction in the system costs (design and implementation costs) and improvement in the system efficiency by using intelligent system control [16].

These points must be taken into consideration before simulating any PE system, which means understand and determine the inputs, outputs, variables values and constant values of the system, after that the optimization process should start to decrease unnecessary points.

4.2. Modeling and Simulation Type

Normally, there are three main types of models which sorted as the following:

1- Mathematical models which can be divided into two types:

a- Analytic model: it has a solution of equations used to describe system changes that can be expressed as a mathematical analytic function.

For example, the wind turbine output power equation is:

$$P = \frac{1}{2} \rho A V^3 \qquad (4.1)$$

ρ: Air density, V: wind speed, A: rotor swept area.

b- Numeric model: it uses some sort of numerical stepping-time to procedure and obtain system behavior over time. The mathematical solution is represented by a generated table and/or graph.

2- Computer aided models: programming commands which equal to mathematical equations that can describe real system and its work mechanism. Sometimes, it is called algorithm, for example, simulation programs on computer.

3- Physical models: it is a minimizing system of the physical real system which can give the same results (in minimizing values). Sometimes it is called laboratory models [17].

Usually, the first and second kind are used together to simulate PE circuits.

The simulation types are normally divided into two main parts and both of them could be used to simulate PE circuits. The first one is an off-line simulation (fixed time-step simulation) to design and test by using *MATLAB*, *PSPICE*, *C++*, *JAVA*, *PSIM*, and this type of simulation has been used in this project. The second one is a real time simulation (system validation before implementation) by using *RT-LAB* tools in *MATLAB* program, where this simulator is used with special *Simulink* modeling tools called *ARTEMIS* and RT-Events which give the possibility to do real time simulation with step of 10 μs as shown in Figure 4.1 [18].

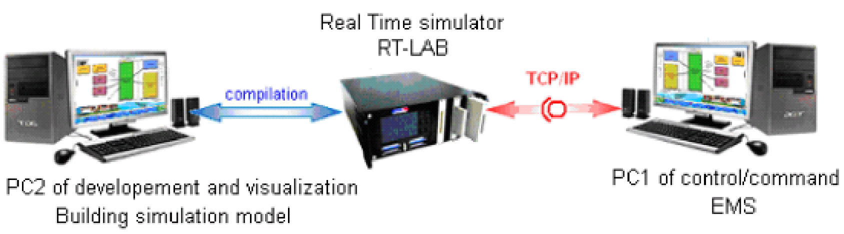


Figure 4.1 - Real time simulator in *MATLAB* [19].

4.3. Simulation Feasibilities and Limits

Usually, simulation processes can be more feasible in the following cases:

1- When the real system is very well known ⟹ The model is also designed very well.

2- When this model gives the possibility to change system components and parameters to observe its work mechanism after any changes.

3- When this model gives the possibility to know the system response when one of the inputs is changed (knowing the system sensitivity for one of the inputs).

4- When this model gives the possibility to do a virtual maintenance for the system to observing the new results.
5- When it allows to training new users for the real system.

Some reasons which limit using of simulation and modeling:

1- When it is not possible to find an equation or a relation between system inputs and system outputs, like neural networks.
2- When doing the tests for the implemented system is easier than modeling this system.
3- When the real system is a very complex system ⇒ needed a powerful simulation program which cost lots of money and the model takes lots of time to do [20].

4.4. Power Electronics Simulation Programs

There are lots of PE simulation programs. Some of them are specified for huge systems simulation, and others are more specific for control systems simulation. Therefore, in this work, two simulation programs have been used: *MATLAB* and *PSIM*.

4.4.1. *MATLAB* Program

MATLAB is a one of the simulation programs which gives the ability to work in high level programming environment. Therefore, many new libraries inside the program recently have been developed.

MATLAB is an abbreviation of ***mat***rix-***lab***oratory which is using for scientific and engineering calculations. This program is a very huge program comparing to *PSIM* and it has many benefits like modeling, simulation and prototyping for lots of engineering problems.

The program in *MATLAB* normally consists of one or two files, the first file is an important one and Irreplaceable which calls the *Model* file and contains the simulation and modeling for the problem. The second file is not necessary for simulation process but it could organize and facilitate the simulation which calls the *Editor* file and contains the simulation variables and some of *C* programming code. The program mainly has four user interfaces:

1- Command window: it is one of the most important user interfaces, which can be used for enter data and to display results.

2- Work space: this user interface is necessary to use in huge projects because it helps to manage the work by allowing the user to see and change the values of contents.

3- Command history: this user interface shows the history and changing levels of the project.

4- Current directory: it is a user interface to find *M* file (*Model* file), so any model you want to run must be in the current directory interface.

To simulate electrical and PE circuits using *MATLAB* there are two libraries that can be used. The first library is a *Simulink* library, which is the main library in *MATLAB*, and it is used to simulate different cases, but the problem of using this library is that we should know about the mathematical equations of the model, otherwise it is not possible to simulate by using this library.

The second library is a *Simpowersystem* library, which is used for simulating PE circuits, and that is easy to use, because it is not necessary to know any mathematical equation. In some models it is possible to use both libraries together.

4.4.1.1. Using *Simulink* Library for Simulation

Creating a model file in *MATLAB* allows for us to use all *MATLAB* libraries, so the first step is to create a *Model* file. *Simulink* library is the hugest library in *MATLAB* and it contains many of sub-libraries inside the main library like *Sources* sub- library for input units, *Sinks* for output units and *Math operation* sub-library.

As a simple example for using this library, RLC circuit as shown in Figure 4.2 is simulated by using both *Model* and *Editor* files. In the end, we will notice that it is not simple to use this library for a complex circuits or systems.

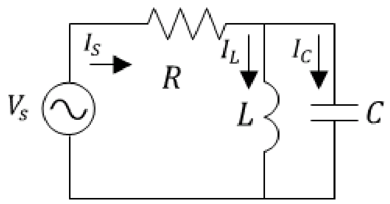


Figure 4.2 - RLC Power Circuit.

In this example, the following elements will be used:

- *Integrator* element to make an integration process (*Continuous* sub-library).
- *Gain* and *Sum* elements (*Math* sub-library).
- *Mux* element to make mixing between many signals (*Signal and System* sub-library).
- *Sine wave* source and *clock timer* elements (*Sources* sub-library).
- *Scope* element to monitoring the results and *Workspace* element to organize the results in a matrix (*sinks* sub-library).

The previous elements are linked together according to the differential equation for the circuit, so in the end we obtain the final mathematical model to do the simulation.

$$v_S = v_C + i_S\, R$$

$$i_S = i_L + i_C \ ,\ i_L = \frac{1}{L}\int v_C\, dt$$

$$v_C = L\,\frac{di_L}{dt} = \frac{1}{C}\int i_C\, dt = \frac{1}{C}\int (i_s\text{-}i_L)\, dt$$

$$\Rightarrow \quad v_C = \frac{1}{C}\int \left(\frac{v_S - v_C}{R} - i_L\right) dt \qquad (4.2)$$

The final equation is a differential equation for the circuit which is using to build the mathematical model for the system as shown in Figure 4.3.

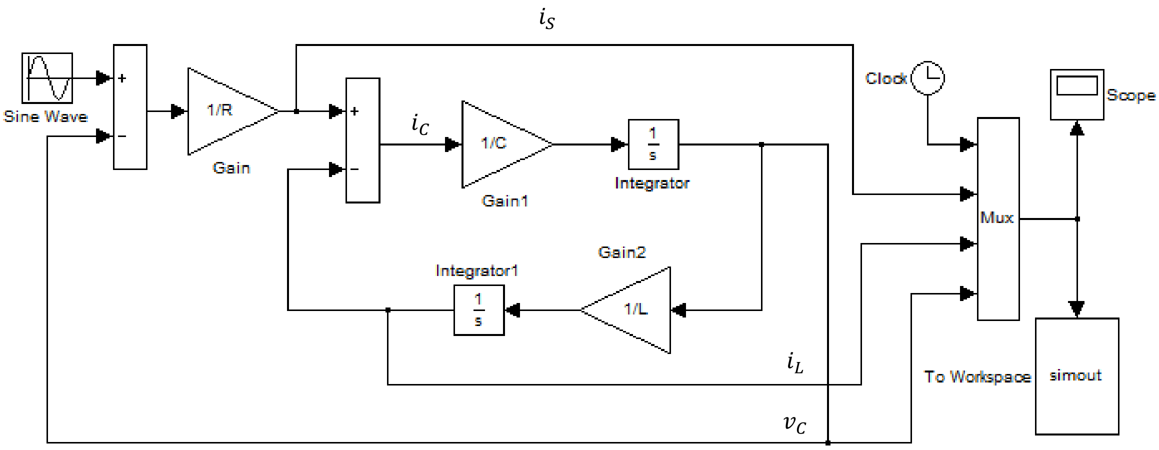


Figure 4.3 - The mathematical model for RLC power circuit.

After making the *Model* (first file) to simulate the circuit, we have to create the *Editor* file (second file) to write the values of variables and printing the results by using *Workspace* element which store the results in the matrix form. It is also possible to do the simulation without using the *Editor* file but in this case the values of variables must be written inside the elements and the *Scope* element will be used to see the results in Figure 4.4.

The *Editor* file will contain the following codes:

```
R=50;
L=0.1;
C=1000e-6;
tdelay=0.05;
vCo=0;
```

```
iLo=0;
tstop=0.5;
disp('run simulation,type ''return'' when ready')
keyboard
subplot(3,1,1)
plot(simout(:,1),simout(:,2),'r')
title('source current')
ylabel('iS in A')
subplot(3,1,2)
plot(simout (:,1), simout (:,4),'b')
title('capacitor voltage')
ylabel('vC in V')
subplot(3,1,3)
plot(simout (:,1), simout (:,3),'k')
title('inductor current')
xlabel('time in sec')
ylabel('iL in A')
```

It is not easy to use this library to simulate PE circuits, because most of these circuits have complex mathematical equations. Therefore, it is preferable to use *Simpowersystem* library to simulate complex PE circuits.

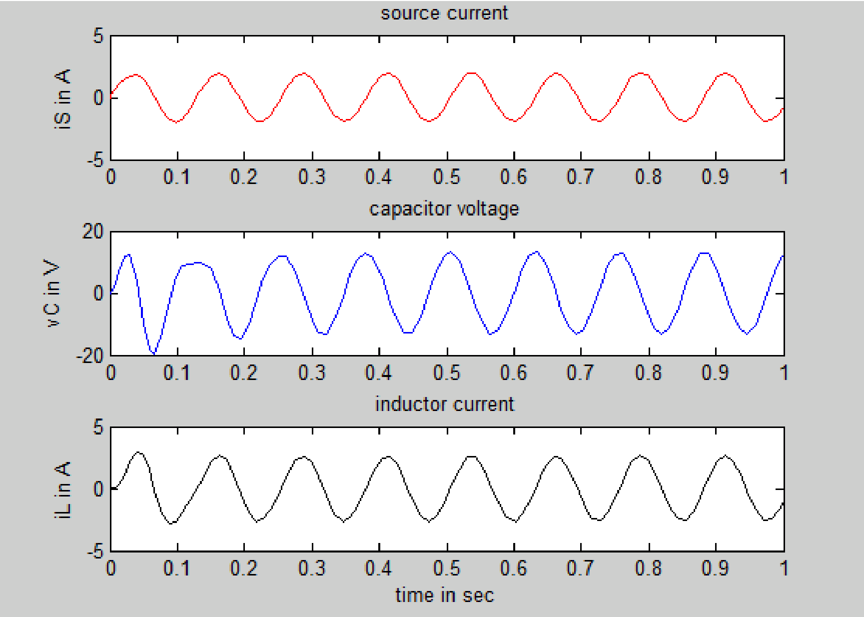


Figure 4.4 - Simulation results for a RLC power circuit.

4.4.1.2. Using *Simpowersystem* Library for Simulation

Simpowersystem library is a simulation environment for electrical power systems. This library already contains the models of semiconductor PE elements, like SCR, Diode, GTO (Gate Turn-Off Thyristor), etc. So, it is possible to simulate PE circuits without needing to find the mathematical model for the circuits. The library has already many sub-libraries like *power electrical sources, electrical elements, control blocks, measurements, three-phase machines, power electronics* and *renewable energy system.*

To show how we can use this library in *MATLAB*, a three-phase controlled rectifier bridge, as a simple example, with 30° delay angle, is simulated by using *Simpowersystem* library as shown in Figure 4.7, that presents the results in Figure 4.6. After that, the same circuit, with the same variables values, was simulated by *PSIM* program, in order to compare the results of both programs. The three-phase rectifier bridge is shown in Figure 4.5 with the values:

$$V_{eff} = 230\text{ V} , f = 50\text{ Hz} , R = 120\ \Omega$$

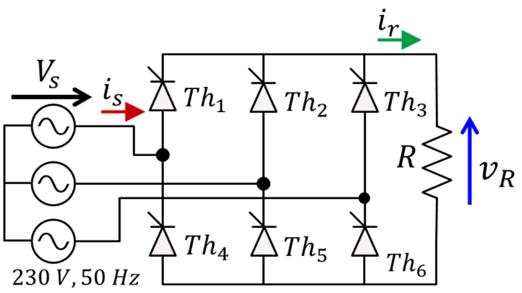


Figure 4.5 – Three-phase rectifier bridge.

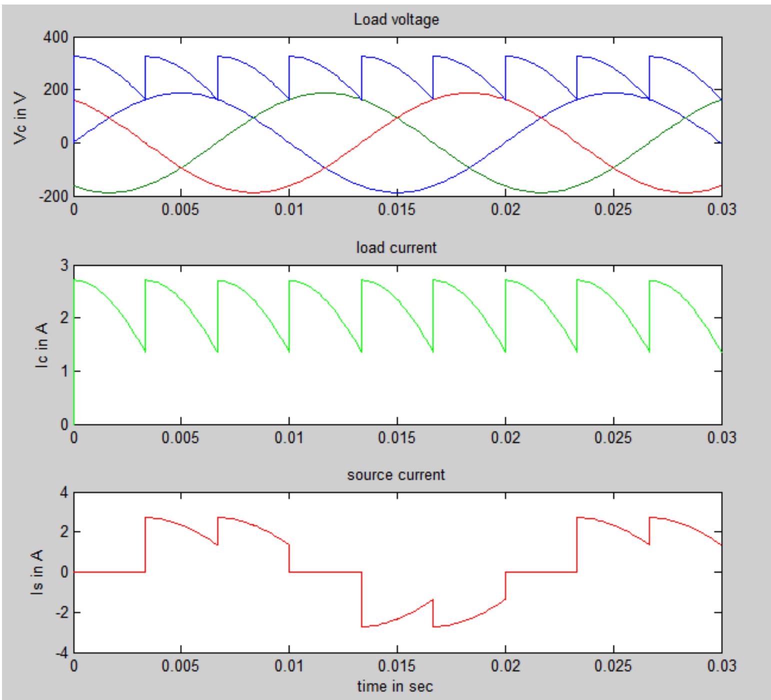


Figure 4.6 – Three-phase rectifier bridge results by using *Simpowersystem* library.

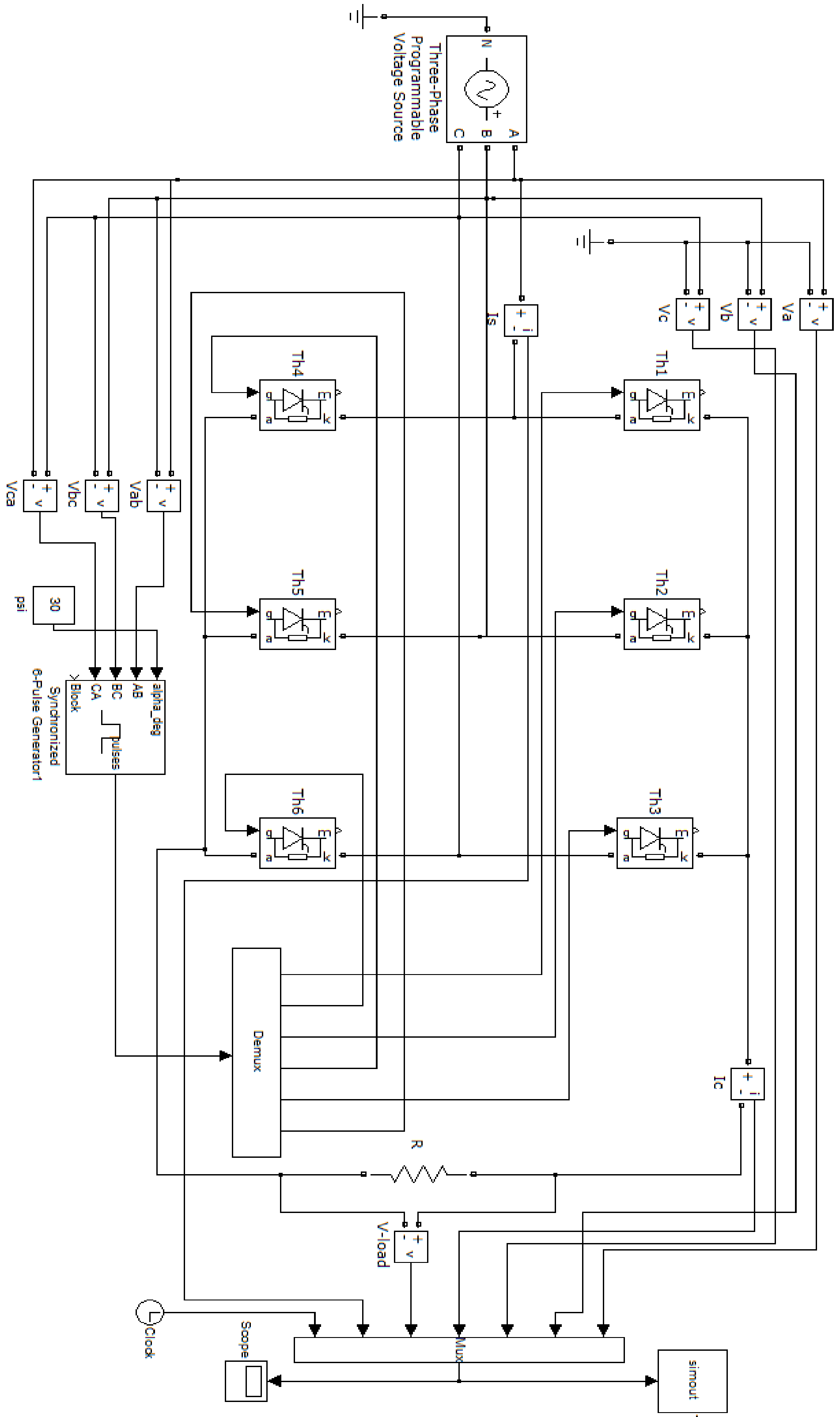


Figure 4.7 – Three-phase controlled rectifier bridge model using *Simpowersystem* library.

4.4.2. Powersim Program (*PSIM*)

PSIM is a simulation program which is designed for PE circuits and dynamic system simulation. This program is using a compact and strong algorithm about electrical circuits, so the simulation period is very short and the results have very acceptable accuracy.

PSIM has a comfortable user interface and quick simulation process. Therefore, *PSIM* provides powerful results. Any circuit can be created and changed in a very easy way, also every circuit has a help available for each component.

To handle with a huge electrical system, *PSIM* provides the sub-circuit function to be parts of the whole system.

The features of using *PSIM* for simulation are [21]:

1- *PSIM* user interface is a powerful, easy to use and that leads to work in more productivity way.
2- *PSIM* has a running on virtual test which allows to you change the values of components during simulation.
3- *PSIM* is capable to simulate complex and large power systems in very short period, so it is one of the fastest simulator program for PE circuits.
4- The most important advantage in *PSIM* that this program has a *C+* compiler which allows to compiling any *C+* code directly without using any other programs. That makes the program very easy to use to implement your control method.
5- *PSIM* has a large number of examples which have already done like DC power supplies, PWM, active filter control loops.
6- *PSIM* has the ability to move from the design stage to simulation and implementation stage in the shortest time possible as shown in Figure 4.8.

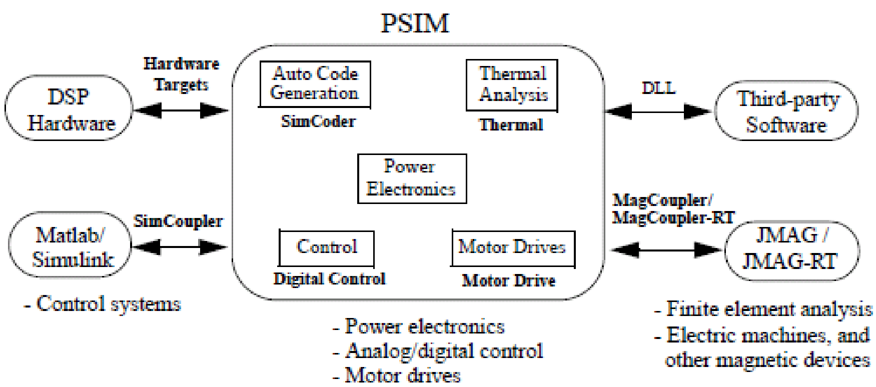


Figure 4.8 - PSIM environment [22].

As a part of PE simulation, the most important section is to know about how to simulate the driving for PE switchers, and to do that, *PSIM* provides four methods as shown in Figure 4.9 by using:

1- Switch gating block: determines the pulse frequency and the duty cycle for pulses. It contains number of interruption points during one cycle which at least must to be 2 points, also it has a number of switching points which must to be equal to the number of interruption points. Switching points normally take a values between $0 \rightarrow 360°$. This controller is available to control in SCR, MOSFET, GTO, etc.
2- Alpha controller: it is used for delay angle control to drive SCR or TRIAC (forced-commutated switches in the switch mode). It has three inputs, enable input which turn on or turn off the controller, alpha angle input which gives the delay angle value in degree and sync input which normally make a synchronization with voltage signal by using voltage sensor and comparator. The main feature of alpha controller is that the delay angle in degree can be directly controlled. Normally SCR bridge can be controlled by an alpha controller. It is also able to dive GTO transistor by using this controller (GTO transistor is a symmetrical device with both forward-blocking and reverse-blocking capabilities).
3- On-off controller: the on-off switch controller interfaces between the control circuit and the power circuit and it is using for self-commutated switches like MOSFET and BJT (Bipolar Junction Transistor). The MOSFET's n channel and npn BJT transistors are turned on when the gate signal is high and the switch is in positive bias(Collector-Emitter V_{CE} or Drain-Source voltage V_{DS} is positive) and turned off in case of the gating signal is low. For p channel MOSFET and pnp BJT transistors are turned on when the gating signal is low and the switch is in negative bias. The input must to be a logic signal coming from control circuit. The signal level of 1 is for switch on and 0 for switch off. This controller is a kind of PWM controller but does not give the value of delay angle directly, so the user must calculate the value of this angle.
4- PWM controller: the PWM controller has four inputs, enable input which turn on or turn off the controller, sync input which normally make a synchronization with voltage signal by using voltage sensor and comparator, delay angle input which gives the value in degree and M input (modulation index) which selected the PWM pattern. Normally voltage/current source inverter can be controlled by a PWM controller [23].

In *PSIM* program, the BJT transistor is simulated as a voltage signal controlled transistor instead of current controlled one to facilitate driving process for BJT which gives the opposite behavior for the BJT in practical life [23].

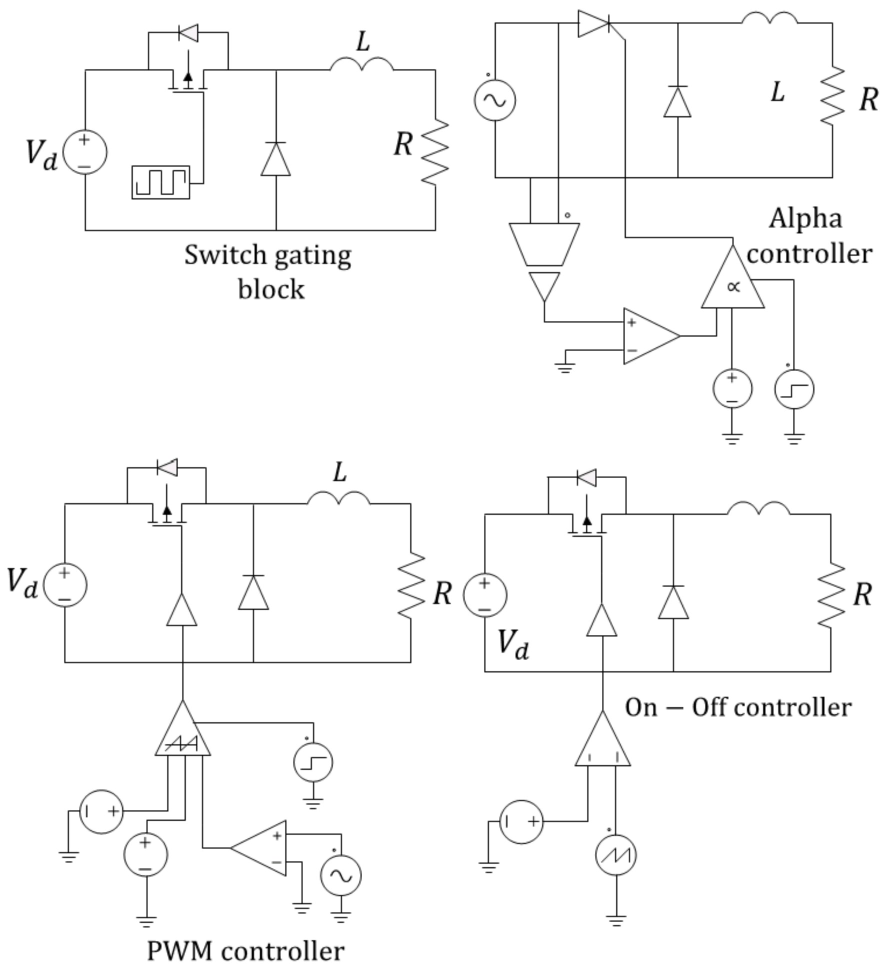


Figure 4.9 - *PSIM* controllers for driving power electronics switches.

Simulating a three-phase rectifier bridge circuit with 30° delay angle by using *PSIM* must give the same results which have already obtained by using *Simpowersystem* library in *MATLAB*, as shown in Figure 4.11. Since the bridge uses SCR elements, the controller must be an alpha controller, as shown in Figure 4.10. The black lines refer to power lines and the red ones refer to control lines.

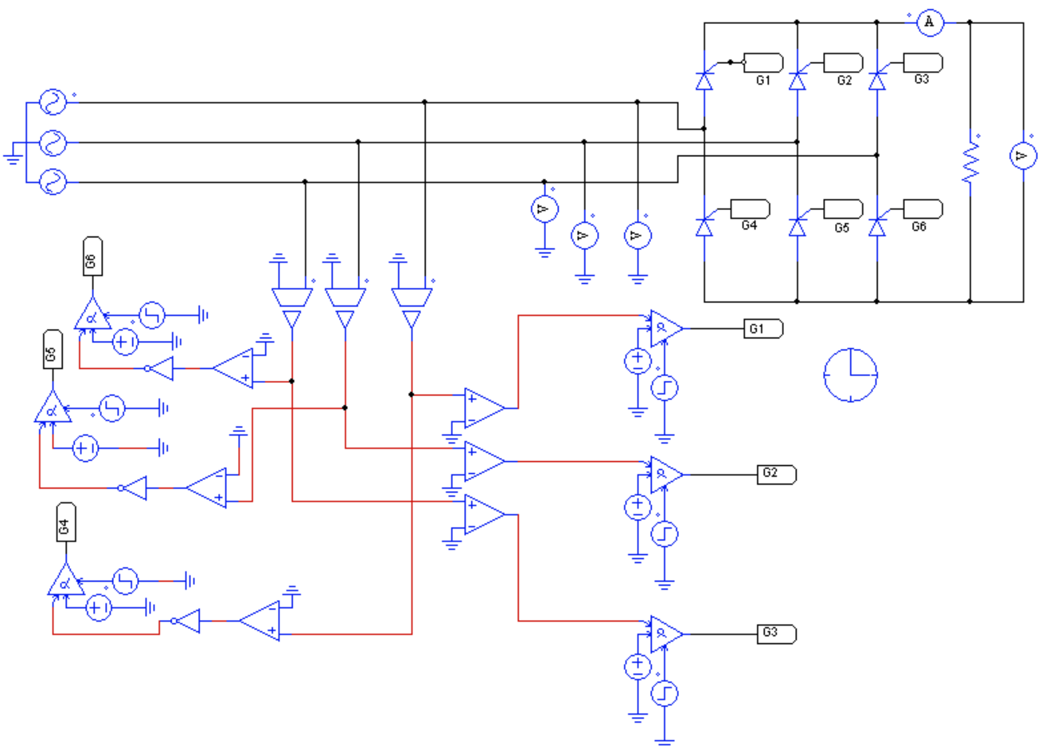


Figure 4.10 – Three-phase controlled rectifier bridge model by using *PSIM*.

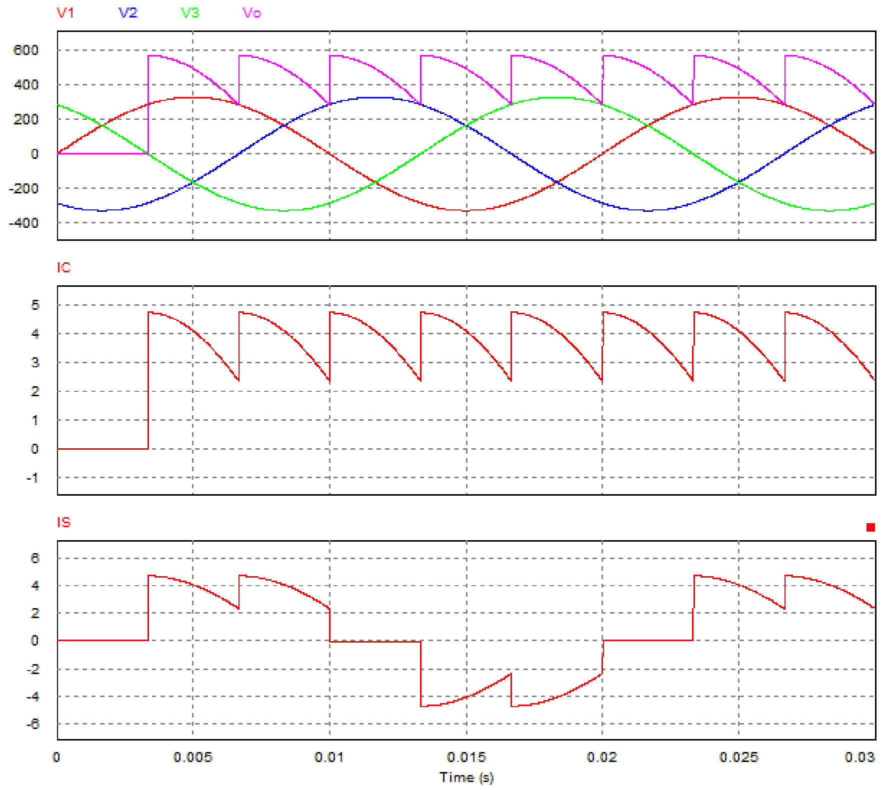


Figure 4.11 – Three-phase controlled rectifier bridge results by using *PSIM*.

4.5. Conclusion

Type of Simulation and modeling are presented in this chapter to know the differences between modeling and simulation. Also, the steps which must to be known before simulating any problem were presented in order to make an optimum simulation process (verifying simulation feasibility and limits). The main objective of this chapter was to present some ideas about PE simulation programs, like *PSIM* and *MATLAB*, which include some sub-libraries. To verify that both PE simulation programs give the same final result, a three-phase full controlled bridge rectifier was simulated by using both programs, *MATLAB* and *PSIM*. We could conclude that building the model by using *MATLAB* is more complex than using *PSIM*, because of *MATLAB* has a spacious simulation environment to simulate all problems but in the same time both of programs have their strength and weaknesses when they are using for educational or research purposes like: for educational purposes, *PSIM* has a simple user interface and has the simplest model to build circuits and extract the results than *Simulink* library in *MATLAB.* For research purposes, *MATLAB* has more simulation capability where *Simulink* environment gives the possibility to do detailed study on circuit's behavior during transient state [24].

CHAPTER 5

Development and Simulation Results of the MPPT System with SEPIC Converter

5.1. Introduction

This chapter describes the development and present the simulation results of a MPPT (Maximum Power Point Tracker) system for a micro wind power turbine, with a 450 W permanent magnet synchronous generator. The MPPT uses a SEPIC converter, which is applied in charging of batteries.

To simulate the variation of wind speed, it was necessary to use a system with variable speed drive, where an induction motor controlled by a frequency variator. This an important device to perform all initial laboratory tests, which allowed a better generator control as well as to demonstrate the functioning of the system developed.

The generator produces three-phase voltages that need to be rectified, so a three-phase full wave uncontrolled rectifier PD3 with DC-DC converter (SEPIC converter) is used here to increase or decrease the value of DC voltage. In addition, the rectifier is followed by a capacitor filter (condenser) to attenuate the ripples of DC voltage as much as possible. The control incorporates a MPPT for ideal use of the wind resources and this control depends on the measured values of input current and voltage to calculate the instantaneous power value and compare this value with the old value of power to stay work in the optimal power point as much as possible.

The general diagram for all system was explained in the Figure 1.3.

5.2. Wind Power Generator

Normally, wind turbine is controlled to work inside limited wind speed domain which specified between $v_{cut\text{-}in}$ and $v_{cut\text{-}out}$ speeds. The turbine must work inside the domain and beyond of this domain limits, the turbine must stop to prevent it from being driven by the generator. Figure 5.1 shows the ideal curve of the wind turbine power which divided to the three sectors according to the wind speed value [25].

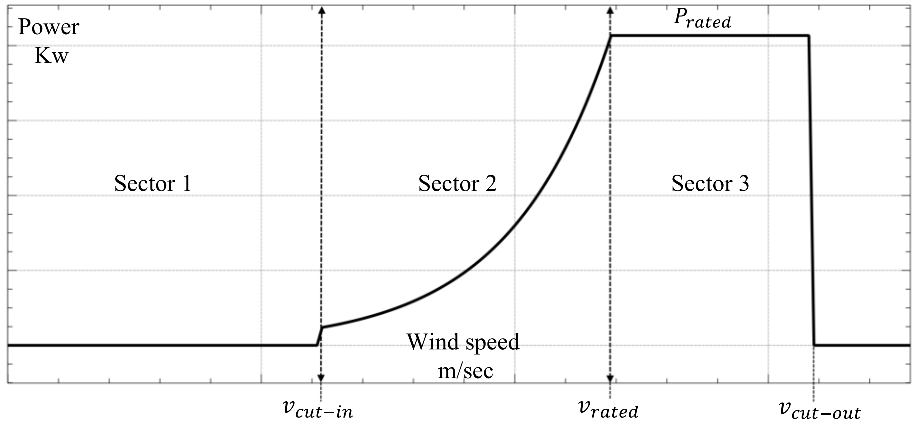


Figure 5.1 - The ideal power curve of wind turbine [25].

The first is a low speed sector which is not allowed because it located outside of the natural domain limits. The second is the streamline power curve sector which varies between $v_{cut\text{-}in}$ and the rated speed value v_{rated} where at this speed, the turbine gives its rated power and normally it is controlled at this point to obtain the available power as much as possible.

The third is limited power sector where any increasing in the wind speed does not lead to increase the output power of turbine so the turbine and generator are not over loaded [25], so the wind turbine should turned off after $v_{cut\text{-}out}$ point to protect it from structural overload. The MPPT control is defined in the second sector (streamline power curve sector).

In variable speed wind turbines there is a ratio between the tip speed of blades and the wind speed called tip speed ratio (*TSR*) where the turbine must designed at the optimal TSR to get the maximum output power from the wind [26].

$$TSR = \frac{\text{Tip speed of blades}}{\text{Wind speed}} = \frac{r\,\omega_b}{V} \qquad (5.1)$$

Where r is the radius of turbine blades and ω_b is the angular speed.

If the rotor of the wind turbine spins slowly, most of the wind will pass through the gap between turbine blades and in this case the extracted energy is too small. On the opposite, if the wind turbine spins too fast, the turbine blades penetrate the air as much as possible and the extracted energy is too high [25].

Because of the wind speed is changing instantaneously, the speed of blades must be varies to maintain the optimal *TSR* ratio in any time but physically it is impossible to achieve that and instead of changing the speed of blades, it is possible to simulate that by changing the duty cycle of the DC-DC converter (increase or decrease the load of wind turbine) which already included inside the micro wind energy system.

There are three main equations to describe the wind turbine system which are the mechanical power, the mechanical torque and the tip speed ratio equation [26].

$$P = \frac{1}{2} A\, C_p(TSR, \beta)\, V^3 \tag{5.2}$$

$$T_m = P \frac{r}{G\ TSR\ V} \tag{5.3}$$

Where the C_p is a power coefficient.

β : is a Pitch angle of power turbine blades, G is a gear ratio between the turbine shaft and the generator rotor shaft.

The governing equation for the wind turbine $C_p = f(TSR, \beta)$ is the main equation which describe the power coefficient as a function with tip speed ratio and the pitch angle for the blade β and given as:

By supposing the pitch angle equal to zero $\Rightarrow \beta = 0$

$$C_p(TSR, \beta) = C_1 \left(\frac{C_2}{(TSR)_i} - C_3\right) e^{-\left(\frac{C_4}{(TSR)_i}\right)} + (TSR\ C_5)$$

$$(TSR)_i = \frac{TSR}{1 - (0.035\ TSR)} \tag{5.4}$$

$$C_1 \approx 0.5\ ,\ C_2 = 116\ ,\ C_3 = 5\ ,\ C_4 = 21\ ,\ C_5 = 0.0068$$

By giving different values of *TSR*, the governing equation simulation results as in the Figure 5.2 [26].

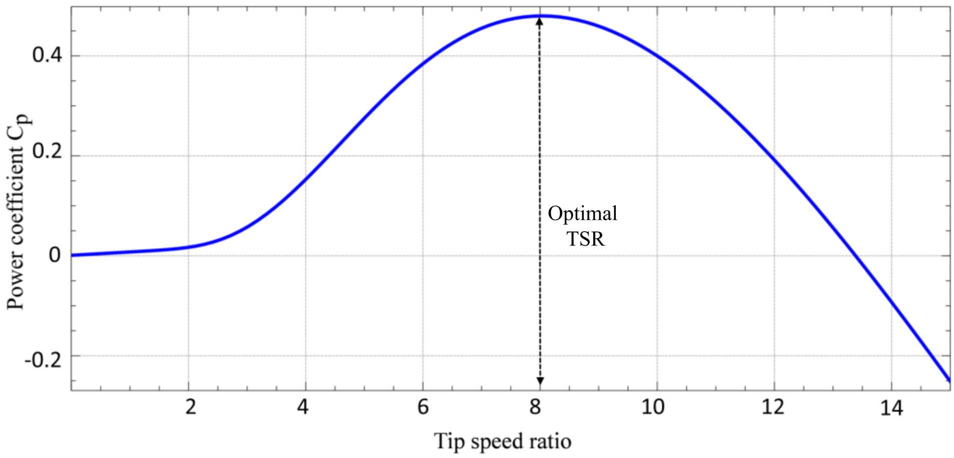


Figure 5.2 - Power coefficient curve as a function with *TSR* ($\beta = 0$).

The micro wind power must work at optimal power curve which is the maximum point of every mechanical power – speed characteristics (with fixed pitch angle). These curves change according to linear speed value as shown in Figure 5.3 [26].

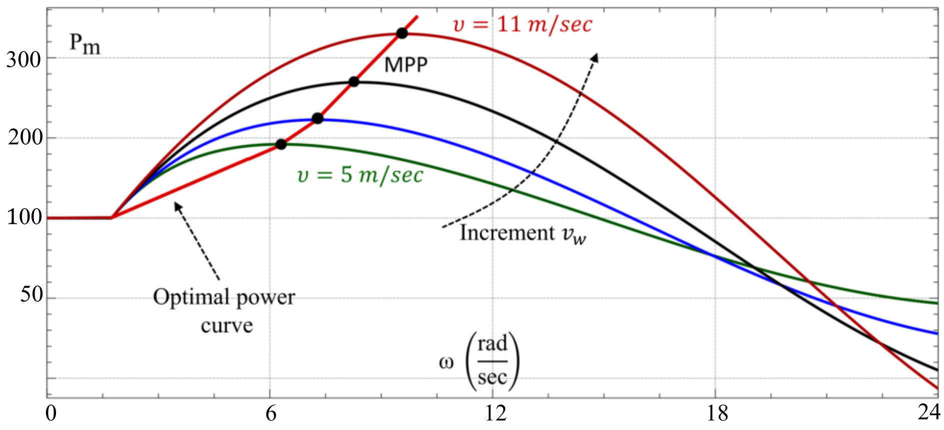


Figure 5.3 - Mechanical power – speed characteristics.

To convert the wind energy into mechanical energy and then to obtain electrical energy, a micro wind generator (*SilentWind*) is used as shown in Figure 5.4. This generator has small dimensions and ready to use in small applications such as boats, caravans, recreational vehicles, telecommunications, etc. This synchronous permanent magnet generator in Figure 5.5 has a maximum power 450 W and rated voltage 24 V. This wind turbine has the following characteristics to determine the work limits and the range of wind speed as shown in the Table 5.1 (electrical specifications) and Table 5.2 (mechanical specifications).

Figure 5.4 - SilentWind micro wind turbine [27].

Figure 5.5 - Permanent magnet synchronous generator.

Electrical Specifications:

Table 5.1 - Electrical characteristics for micro wind “SilentWind” [27].

Generator type	Permanent magnet generator, 3 phase
Rated voltage	24 V-DC
Rated power output	450 W
Rated wind speed	14.5 m/s
Start-up wind speed	2.2 m/s
Start-up charging	2.5 m/s
Charging indicator	LED-blue, at generator body
Number of poles 2P	12 poles

Mechanical Specifications:

Table 5.2 - Mechanical characteristics for micro wind “SilentWind” [27].

Security check in the wind tunnel	122 km/h without any complaints
Rotor diameter	1.15 m
Quantity of blades	3
Weight of blade	150 g/blade - low centrifugal load
Rotor blade material	CFK – hand-laminated
Rotation speed, range of charging	550 - 1600 rpm
Weight generator	6.8 kg (Generator)

Packing dimensions	780 x 400 x 210 mm (packing weight: 10 kg)
color	white RAL 9010, powder coated
Warranty	36 month

The micro wind turbine power "*Silentwind*" characteristics are shown in the Figure 5.6, as mentioned in its datasheet, but the manufacturer does not give any additional information about the conditions in which it was obtained, so this curve is not taken into consideration in the control parameters. The true values were obtained experimentally in no load case, as shown in the Table 5.3.

Values of generated frequency from synchronous generator can be obtained from the equation (5.5), which describes the relation between the rpm (Revolutions Per Minute), frequency and number of poles $2P$:

$$n = \frac{120\ f}{2P} \qquad (5.5)$$

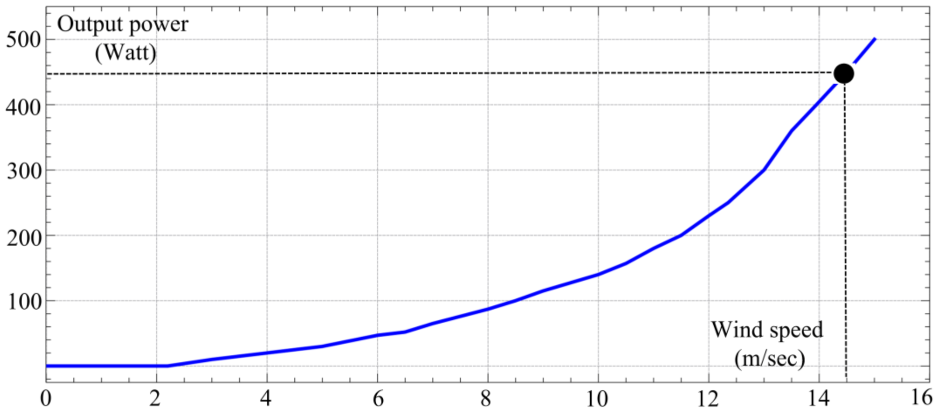


Figure 5.6 - SilentWind turbine power curve characteristics [27].

Table 5.3 - Obtained test results in no – load case.

Velocity (rpm)	RMS voltage value (V)	$V_{DC} = 1.6541\ \text{RMS}\ \sqrt{2}$ (V)	Frequency (Hz)
120	2.2	5.14	12
169	3.15	7.33	16.9
219	4	9.32	21.9
268	5	11.65	26.8
317	5.97	13.91	31.7
366	6.9	16	36.6
415	7.85	18.3	41.5

464	8.8	20.5	46.4
549	10.3	24	54.9
600	11.36	26.46	60
850	16.5	38.44	85
1000	19	44.2	100

5.3. Uncontrolled Three-Phase Rectifier Bridge with Condenser

The output voltage wave consists of the tops of the three-phase AC voltage waves so this voltage will be with a small oscillation and it is possible to solve this problem by using a capacitive condenser to get a DC voltage as much as possible. According to the (5.6) equation, the max value of output DC voltage will be more than the max value of AC input voltage by 1.6541 factor (without using the condenser).

$$V_{DC} = \frac{2q}{\pi} V_m \sin\frac{\pi}{q} \quad (5.6)$$

$$V_{DC} = 1.6541\ V_{AC\text{-}Max} \quad (5.7)$$

Practically, it is possible to get uncontrolled three-phase rectifier bridge by using two single phase bridges. The single-phase bridge that will using here is a GBPC5010 with a condenser 1400 μF. Figure 5.7 shows how to use two single-phase rectifier bridges to obtain one three-phase rectifier bridge. Figure 5.8 shows the condenser that will be used to have DC wave as much as possible.

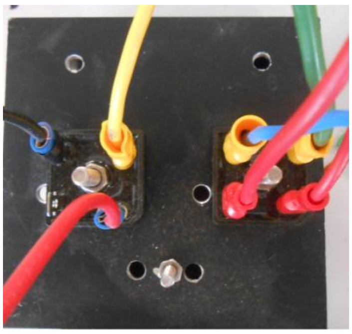


Figure 5.7 - Using two single-phase rectifiers to obtain three-phase rectifier bridge.

Figure 5.8 - 1400 μF Condenser.

5.4. SEPIC Converter Design

Single Ended Primary Inductance Converter (SEPIC) is very common to use in PV panels and wind turbines circuits as a voltage regulator because it is capable to work as a step-up or step-down converter (like Buck-Boost converter) but with more efficiency and less circuit size.

In this project, coupled inductor SEPIC converter is used here to get more efficiency and other features. It consists of two coils wound onto one core and has 1:1 turn ratio, which leads to generate mutual electromagnetic flux $\varnothing_m$ between the inductors, thus decrease the volume of coils and other active elements. Input voltage of SEPIC converter is connected with series inductor and the output voltage is connected with parallel capacitor as shown in Figure 5.9, so SEPIC converter equevalent circuit has a current source charactaristic at the input side, also it has a voltage source charactaristic at the output side.

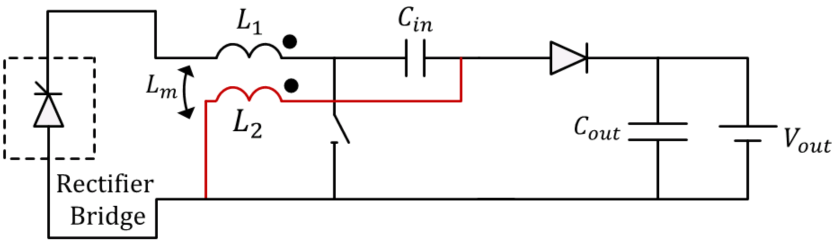


Figure 5.9 - SEPIC converter equivalent circuit.

Work mechanism for this converter is very similar to isolated coils one and the main equation which gives the average output voltage is:

$$V_{out} = V_{in} \frac{K}{1 - K} \qquad (5.8)$$

Average output voltage for this converter could be higher or fewer than the input voltage depinding on K duty cycle value, but it does not invert output voltage polarity.

If $0 < K < 0.5 \Rightarrow$ output voltage is lower than input voltage.

If $0.5 < K < 1 \Rightarrow$ output voltage is higher than input voltage.

The benefits of using one coupled inductor instead of using two separated ones are [28]:

1- The most Important feature is to generate mutual electromagnetic flux $\Rightarrow$ leads to decrease the inductors values $\Rightarrow$ DC resistances for inductors can be reduced $\Rightarrow$ heating losses will decrease $\Rightarrow$ increase the efficiency of the SEPIC.

2- Decrease the inductors values $\Rightarrow$ leads to decrease the volume of device $\Rightarrow$ low costs.

3- Because of mutual inductance, the input ripple current will divide between two inductors $\Rightarrow$ input ripple current will decrease $\Rightarrow$ using smaller capacitors values.

For sure, next calculations will suppose continuous work mode of SEPIC to avoid many problems to appear.

5.4.1. Duty Cycle Values

The duty cycle of SIPEC is given by the next equations:

$$K_{max} = \frac{V_{out} + V_D}{V_{in(min)} + V_{out} + V_D} \qquad (5.9)$$

$$K_{min} = \frac{V_{out} + V_D}{V_{in(max)} + V_{out} + V_D} \qquad (5.10)$$

Where V_D is a diode voltage dropping.

It is not possible to work with wide duty cycle domain to have a stabilize output voltage. Therefore, the duty cycle domain must be limited between two values and according to our application, the output voltage must always be constant with a value more than battery's voltage value to activate charging process. The voltage of battery equals to 12 V so the output voltage for SEPIC is assumed 13 V. The minimum value of input voltage is 6 V and the maximum value of input voltage is 20 V. Consequently, the values of K_{min} and K_{max} are:

$$K_{max} = 0.68 \quad , \quad K_{min} = 0.4$$

5.4.2. Inductors Values

The first step of designing PWM switching regulator is to detect the inductor ripple current ΔI_L to make EMI (Electromagnetic Interference) between the inductors, where too little value may cause to have unstable PWM operation. The main rule is to use a factor (m) between $20 \longrightarrow 40\%$ of input current with pay attention that it is not possible to work in the discontinued region [29].

$$\Delta I_L = \frac{m}{\eta}\ I_{in} = \frac{m}{\eta}\ \ I_{out}\ \frac{V_{out}}{V_{in(min)}} \qquad (5.11)$$

η : The worst-case efficiency for the SEPIC.

The charging current for the battery is not constant and it depends on the kind of battery, for example some batteries have recommended maximum charging current limit about 2 A and other batteries have other values of charging current about 7 A. Therefore, the domain of output current will be taken as:

$$I_{out(max)} = 8\text{ A} \ \Rightarrow\ P_{max} = 105\text{ W}\ ,\quad I_{out(min)} = 2\text{ A} \ \Rightarrow\ P_{min} = 26\text{ W}$$

$$\Delta I_{L(max)} = \frac{0.3}{0.9} \times 8 \times \frac{13}{20} = 1.75\text{ A}$$

$$\Delta I_{L(min)} = \frac{0.3}{0.9} \times 2 \times \frac{13}{6} = 1.43\text{ A}$$

$$\Delta I_L = \Delta I_{L(max)} - \Delta I_{L(min)} = 0.32\text{ A}$$

In the coupled coils SEPIC converter, if the coupled coils have the same number of windings and homogeneous coil, the mutual inductance will force the ripple current to be divided equally between two coupled inductors, but in real coupled inductor the inductors do not have exactly the same value so the ripple current will not divided equally but regardless to that, the values of coupled inductors here are assumed to be half of separate inductors values [29].

$$L_1 = L_2 = \frac{1}{2}\ \frac{V_{in(min)}\ K_{max}}{\Delta I_L\ f_{min}} \qquad (5.12)$$

$$L_1 = L_2 = \frac{6 \times 0.68}{2 \times 0.32 \times 110\,000} \approx 58\ \mu\text{H}$$

It is not available to get an accurate value of inductance as a calculated value so the real value of coupled inductor equals to 53 μH.

The peak value of input side inductor current should be more than the peak value of output side inductor current as shown in next equations [29].

$$I_{L1(peak)} = \left(\frac{I_{in}}{\eta} + \frac{\Delta I_L}{2}\right) > I_{L2(peak)} \qquad (5.13)$$

$$I_{L1(peak)} = \frac{I_{out(min)}\ V_{out}}{V_{in(min)}\ \eta} + \frac{\Delta I_L}{2} = \frac{2 \times 13}{6 \times 0.9} + \frac{0.32}{2} \approx 5\text{ A}$$

To determine the value of mutual inductance L_m firstly, one of both inductors measured by special device to determine individual characteristics of inductor, after that both of inductors connected on series (case of polarity addition or subtraction) so the equivalent inductance in case of addition will be:

$$L_{eq} = L_1 + L_2 + 2\, L_m$$

In case of polarity subtraction:

$$L_{eq} = L_1 + L_2 - 2\, L_m$$

At the frequency of $f = 124$ kHz the results for both measures are shown in Table 5.4.

Table 5.4 - Coupled inductor characteristics at 124 kHz frequency.

Characteristics	One inductor (individual characteristics)	Connected in series (Additive polarity)
L_{eq}	53 µH	210 µH
R_{eq}	452 mΩ	1.9 Ω
C_{eq}	46 µF	11.5 µF
Z_{eq}	34.5 Ω	137 Ω

From the previous table, it is very clear that the value of mutual inductance almost equals to L_1 and L_2.

Figure 5.10 shows coupled inductor SEPIC converter which will be used in SEPIC converter.

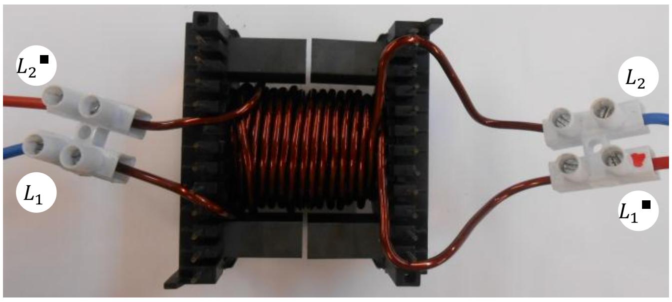


Figure 5.10 - Coupled inductor with mutual inductance.

5.4.3. Capacitors Values

The output capacitor must have a big capacitance with low equivalent series resistor to stabilize output voltage value, so the value of C_{out} (with too low equivalent series resistor) is [29]:

$$C_{out} \geq \frac{I_{out(min)}\ K_{max}}{\Delta V_{out}\ f_{min}} \tag{5.14}$$

The difference between the output voltage of SEPIC and battery's voltage should be less than 1 V so the value of ΔV_{out} supposed as 0.3 V.

$$C_{out} \geq \frac{2 \times 0.68}{0.3 \times 110\,000} \approx 42\ \mu\text{F}$$

The real value of C_{out} equals to 44 μF.

This capacitor must have an RMS current rating more than the RMS load current value as the next equation [29]:

$$I_{C(out)RMS} = I_{out} \sqrt{\frac{K_{max}}{1 - K_{max}}} \tag{5.15}$$

The input capacitor current must be calculated after adding the losses to its value (dividing on the efficiency η) [29].

$$I_{C(in)RMS} = \frac{I_{in}}{\eta} \sqrt{\frac{1 - K_{max}}{K_{max}}} = \frac{I_{out(min)}\ V_{out}}{V_{in(min)}\ \eta} \sqrt{\frac{1 - K_{max}}{K_{max}}} \tag{5.16}$$

The ripple voltage across C_{in} is:

$$\Delta V_{C(in)} = \frac{I_{out}\ K_{max}}{C_{in}\ f_{min}} \tag{5.17}$$

By supposing $\Delta V_{C(in)} = 0.5 \Rightarrow C_{in} \approx 22\ \mu\text{F}$

5.4.4. Selection of Active Components

The current rating for the MOSFET I_Q must selected carefully because this value will determine the maximum output current for the SEPIC [29].

$$I_{Q(peak)} = I_{L1(peak)} + I_{L2(peak)} = \frac{I_{in}}{\eta} + I_{out} + \Delta I_L \tag{5.18}$$

At the moderate temperature, MOSFET losses is given by the next equation [29]:

$$P_{Q(losses)} = \left(I_{Q(RMS)}\right)^2\ R_{DS(on)}\ K_{max} + \left[I_{Q(Peak)}\ \left(V_{in(min)} + V_{out} + V_D\right)\right]\ \frac{t_r + t_f}{2}\ f_s \tag{5.19}$$

Where $R_{DS(on)}$ is the resistor of Drain-Source junction in turn-on case.

Where the RMS MOSFET current value is [29]:

$$I_{Q(RMS)} = \frac{I_{in}}{\eta\ \sqrt{K_{max}}} \tag{5.20}$$

The diode must carry same value of MOSFET current so:

$$I_{D(peak)} = I_{Q(Peak)}$$

STTH30R06W power diode will be used here with average forward current equals to 30 A.

IRFB4110PbF power MOSFET will be used here also.

Figure 5.11 shows the implemented circuit of coupled inductor SEPIC converter.

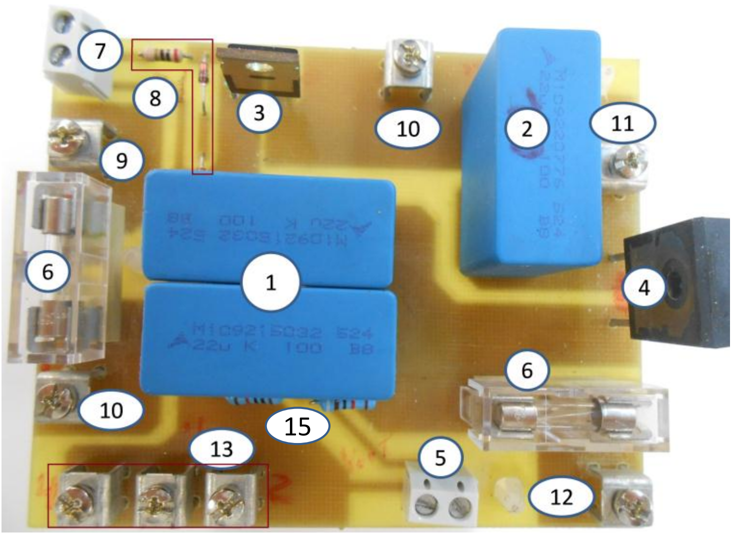


Figure 5.11 - Implemented circuit of SEPIC converter.

1- Output capacitor C_{out} = 44 μF.

2- Input capacitor C_{in} = 22 μF.

3- IRFB4110PbF power MOSFET.

4- STTH30R06W power diode.

5- Output voltage divider pins.

6- Protection fuses.

7- Gate – ground MOSFET pins.

8- MOSFET protecting and driving circuit.

9- Input source pin.

10- L_1 polar pin.

11- L_2 normal pin.

12- Load pin.

13- Ground pins.

14- Output voltage divider.

5.5. Control Process

To drive the SEPIC, PWM pulses must applied on the MOSFET's gate with varies duty cycle according to the input voltage of the SEPIC (the output of rectifier).

The microcontroller (*ATMEGA UNO* 328*P*) tasks are:

1- Generate PWM pulses with the possibility of change duty cycle value.
2- Read the input voltage value and change the duty cycle magnitude according to this value.
3- Applying the MPPT control process of all system.

ATMEGA UNO 328*P* microcontroller will be used in this project from *Atmel* manufacturer, where the *ATMEGA* family characterized by simple programming and the possibility of programming in several languages like *C+* and *Assembly*.

The microcontroller board is shown in the Figure 5.12.

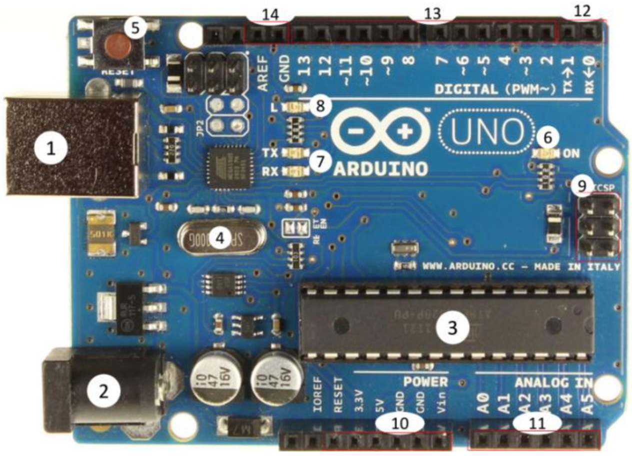


Figure 5.12 - ATMEGA UNO 328P board [30].

1- External USB plug.
2- External power supply.
3- *ATMEGA* 328*P* microcontroller ship.
4- Microcontroller crystal which gives the clock frequency 16 000 kHz.
5- Reset button.
6- Power on detector.
7- Serial in and serial out detectors.
8- Processor detector.
9- In-circuit serial programmer (ICSP).
10- 5 V and 3.3 V Power supplies pins with grounded pins.
11- Analog pins for analog to digital converter (ADC).
12- Serial in or receive information detector (RX) and serial out or sending information detector (TX).
13- Digital input/output pins (some of pins have PWM output).
14- Ground pin and analog reference pin (normally 5 V) for ADC.

5.5.1. Generation of PWM Pulses with the Possibility of Changing the Duty Cycle

Pulse Width Modulation (PWM) is a technique mainly used in power electronics switchers to control the amount of power given to the electrical device. Therefore, by varying the duty cycle more or less, we can easily change power flowing for the output side of converter. *ATMEGA* is provided with three timers/counters to use PWM technique and other application where two of them (counter 0 and 2) are 8 bit counters so the max top value (2^8 - 1 = 255) and the counter 1 is 16 bit one with more accuracy and the max top value (2^{16} - 1 = 65 535). *ATMEGA* 328*P* provided with 6 PWM pins and three types of PWM signals (every timer has 2 PWM channels) as follows:

1- Phase correct PWM.
2- Phase and frequency correct PWM.

The datasheet says there are no differences between them if the top register (OCRnA) is in the same location where the top value determines our PWM frequency as shown in Figure 5.13. The timer register here counts from bottom to top (up counter) then decrease its value from top to bottom (down counter). Both modes are suitable to use in motor controller because as we change the bottom register value (OCRnB-PWM duty cycle) the phase between each duty cycle stay the same. The main differences between both methods that in phase and frequency correct PWM the output compare register (OCRnA and OCRnB) are changed by the buffer when the timer counter register (TCNTn) reaches at the bottom instead of the top as in phase correct PWM mode, also phase and frequency correct PWM method is just available to use on timer/counter 1 (16 bit) because this way needs more prescaler.

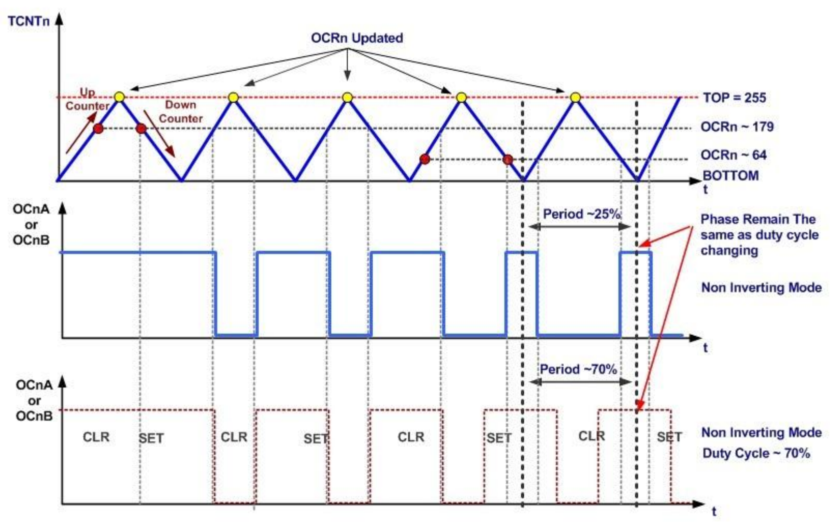


Figure 5.13 - Phase correct PWM / Phase and frequency correct PWM modes [31].

3- Fast PWM mode.

This way could generate the highest PWM frequency comparing with the other PWM methods as shown in Figure 5.14 and because of the MOSFET needs high work frequency, so this PWM type is suitable for our application and possible to use with timer/counter 1 (16 bit) and timer/counter 0 or timer/counter 2 (8 bit). The timer/counter register here will just count from bottom to top (up counter).

According to our application and before start programming, the following points must be considered [32]:

1- The PWM operation mode.
2- The timer/counter which is necessary to use (number of bits).
3- Prescaler value.

Because of our application here requires high work frequency, so the PWM operation mode should be fast PWM mode and it is possible to achieve that by using any timer/counter. The timer/counter 2 will be used here with varies top register values. The prescaler factor *N* here takes one of these values (1, 8, 64, 256, or 1024) and closely linked with the PWM frequency value, clock frequency and decimal value of top register (OCR2A) which equals to ($2^8 = 256$). PWM frequency equation is given by:

$$f_{OCnxPWM} = \frac{f_{clk\text{-}I/O}}{256\,N} \qquad (5.21)$$

The value of prescaler factor *N* here is defined as 1 to obtain the highest frequency and that achieved by activate (CS20) register, In this case the highest PWM frequency will be:

$$f_{OCnxPWM} = \frac{16\,000 \text{ kHz}}{1 \times 256} = 62.5 \text{ kHz}$$

In case of more PWM frequency is required, the decimal value of top register must be less than 256. It should be clear now that to generate a PWM frequency more than 62.5 kHz we should sacrifice the duty cycle resolution and to achieve that, the value of the register (OCR2A) which define the top value must be less than 256 according to the required PWM frequency value. This choice can be achieved by activate the bits (WGM20) and (WGM21) on (TCCR2A) register and activate the bit (WGM22) on (TCCR2B) register as shown in Table 5.5.

Table 5.5 - Choosing fast PWM mode.

Mode	WGM22	WGM21	WGM20	Timer/counter mode operation	Top	Update of OCR2 at	TOV flag set on
7	1	1	1	Fast PWM	OCR2A	Bottom	Top

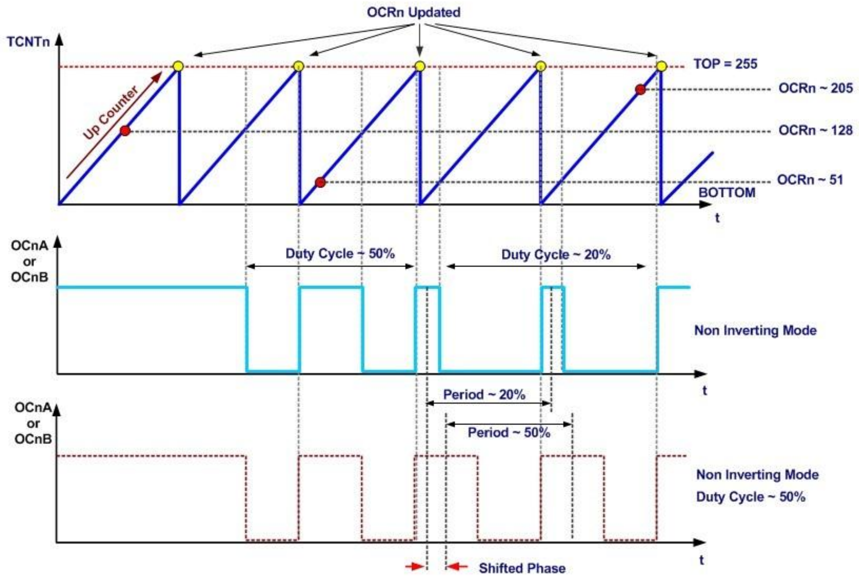


Figure 5.14 - Fast PWM mode using ATMEGA UNO 328P [31].

The value of the register OCR2B determines the duty cycle value.

$$\text{Duty cycle} = \frac{\text{OCR2B}}{\text{OCR2A}} \qquad (5.22)$$

The MOSFET performance changes according to the values of both duty cycle and PWM pulses frequency.

Normally the MOSFET has a delay time to connect and disconnect, so the PWM pulses is not identically the same with the drain-source voltage V_{DS}. Usually the turn-off time of MOSFET is more than the turn-on time and there are lots of methods to solve this problem (it does not consider in this project), for example the turn on time of power MOSFET is related with the amount of injected power into its gate [33].

Next chapter will contain practical results about this issue to see MOSFET performance V_{DS} at 70% of duty cycle and PWM frequency 62.5, 124 kHz.

Normally, MOSFET has problems at high PWM frequencies because the duty cycle error increases at high frequency values especially the turn-off time.

5.5.2. Read the Input Voltage / Current Values (ADC)

ADC (Analog to Digital Converter) gives us the possibility to convert analog voltage to digital one and read voltage values from sensors like temperature, humidity and pressure sensors for many applications.

ATMEGA family are provided with analog to digital converter which ready to use with maximum 10 bits resolution (2^{10} = 1024) and that means the input ADC voltage (analog voltage) will be converted to a decimal value between 0 and 1023. In addition, *ATMEGA* 328*P* is provided with 6 ADC input pins (PORT *C* pins) but the microcontroller can only do one ADC conversion in the same time, so between ADC conversion process, there is an analogic multiplexer which allow for us to select the ADC pin that we want to read. In the other words, it is possible to read one ADC value from all 6 ADC pins at the same time.

The analog input pins can read the input analog voltage from 0 ⟶ 5 V so the 5 V value equals to 1023 numeric if the AREF (pin 21) is connected with 5 V source pin and in this case the resolution will be 5 V/1023 = 4.88 mV for each value.

$$\mathrm{ADC} = \frac{1024\ V_{in}}{V_{ref}} \qquad (5.23)$$

The internal ADC can also be used in 8 bits but that leads to decrease the ADC resolution and reducing the time which need to complete the conversion process. The 8 bits ADC is useful to use in case of using more than 3 ADC channels.

In our project, two 10 bits ADC channels for voltage and current with 5 V reference was used.

Also, one of ADC characteristics is an ADC frequency where any increasing in this value leads to decrease ADC prescaler (as in PWM process).

Because of this project depends on change MOSFET's duty cycle according to SEPIC input voltage, the ADC reader and value must have high prescaler as much as possible, so high ADC prescaler value was used here (equals to 128) with 10 bits ADC resolution. Consequently, The ADC frequency will be:

$$f_{ADC} = \frac{f_{clk\text{-}I/O}}{\text{ADC prescaler}} = \frac{16\ 000\ \text{kHz}}{128} = 125\ \text{kHz} \qquad (5.24)$$

The ADC prescaler is defined from the (ADCSRA) register and the bits (ADSP0, ADSP1, ADSP2).

5.6. MOSFET Driving Circuit

The pulses which are applied on MOSFET's gate should be provided with high power density. Therefore, this circuit contains many elements to provide the PWM signals in high efficiency as much as possible. These elements are voltage isolation elements and gate drive optocoupler to achieve an optical isolation between the microcontroller and MOSFET's gate as shown in Figure 5.16.

To ensure safe operation range for MOSFET, two Zener diodes are using to limit the voltage level between gate pin and source pin, so from MOSFET's datasheet, the absolute maximum rating of gate to source voltage equal to 40 V in repetitively case, so the voltage must not be more than 40 V otherwise the MOSFET will damage.

By using two Zener, the voltage will be 30 V as shown in Figure 5.15.

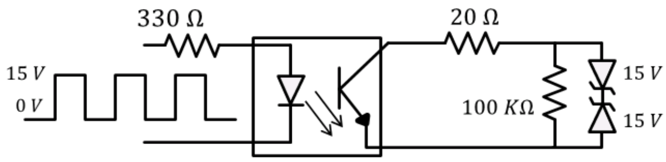


Figure 5.15 - Optical isolation between microcontroller and gate to ground circuit.

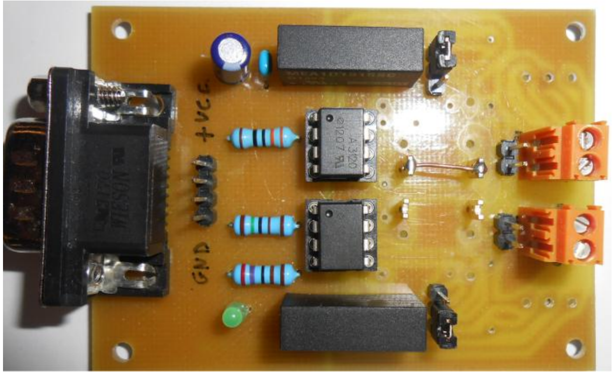


Figure 5.16 - MOSFET driving circuit.

5.7. MPPT Control Algorithm

The using of a Maximum Power Point Tracker (MPPT) means that the charging system always work in the maximum power point, and to achieve that, the wind turbine speed must be determined at specific speed but the wind speed is always changing instantaneously, so it is almost impossible to make a controlling in wind turbine speed.

Because of changing wind turbine speed is very hard to define the MPPT, the duty cycle of DC-DC converter (SEPIC converter) must varies according to the wind turbine speed until reaching for the maximum power point regardless of the load value. by other words, this way depends on changing the equivalent load value for whole system (SEPIC duty cycle) regardless of wind speed value.

In general, there are two different ways to do MPPT control. The first one is an optimal torque control (OTC) which founded to be the best MPPT control method [25].

The second method which is used here is a perturbation and observation (P&O) method that is a very simple mathematical technique to implement but with less efficiency comparing with OTC method [25].

The main task for this method is to search about optimal point of power curve by create a control variable ΔK in a small step size to increment or decrement the power according to the location of operating point. If the operating point is located on the left of the optimal power point, the control variable should make a shifting for operating point in right direction and vice versa as shown in Figure 5.17.

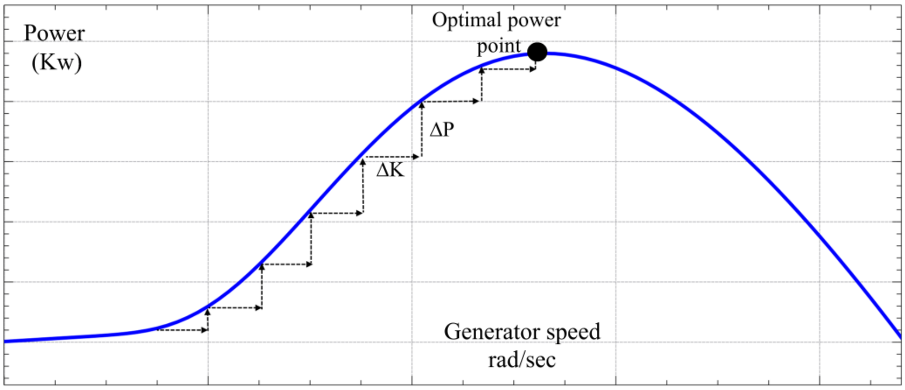


Figure 5.17 - MPPT perturbation and observation control method [25].

The step size of the control variable should not be large to get the optimal power point and get more efficiency as much as possible. Otherwise, the operating point will oscillate around the optimal power point with faster response and the system will not work at MPPT point (unstable work) [34].

The main feature for P&O method that it could be implemented without knowing any information about wind characteristics curve. However, this method is not suitable for rapid wind variation system because it does not give the optimal power point at rapid wind variation.

The MPPT (P&O method) flowchart is as shown in the Figure 5.18 where K is a duty cycle value, P_{ins} is an instantaneous power value, P_{av} is an average power value and P_{av-1} is a previous average power value.

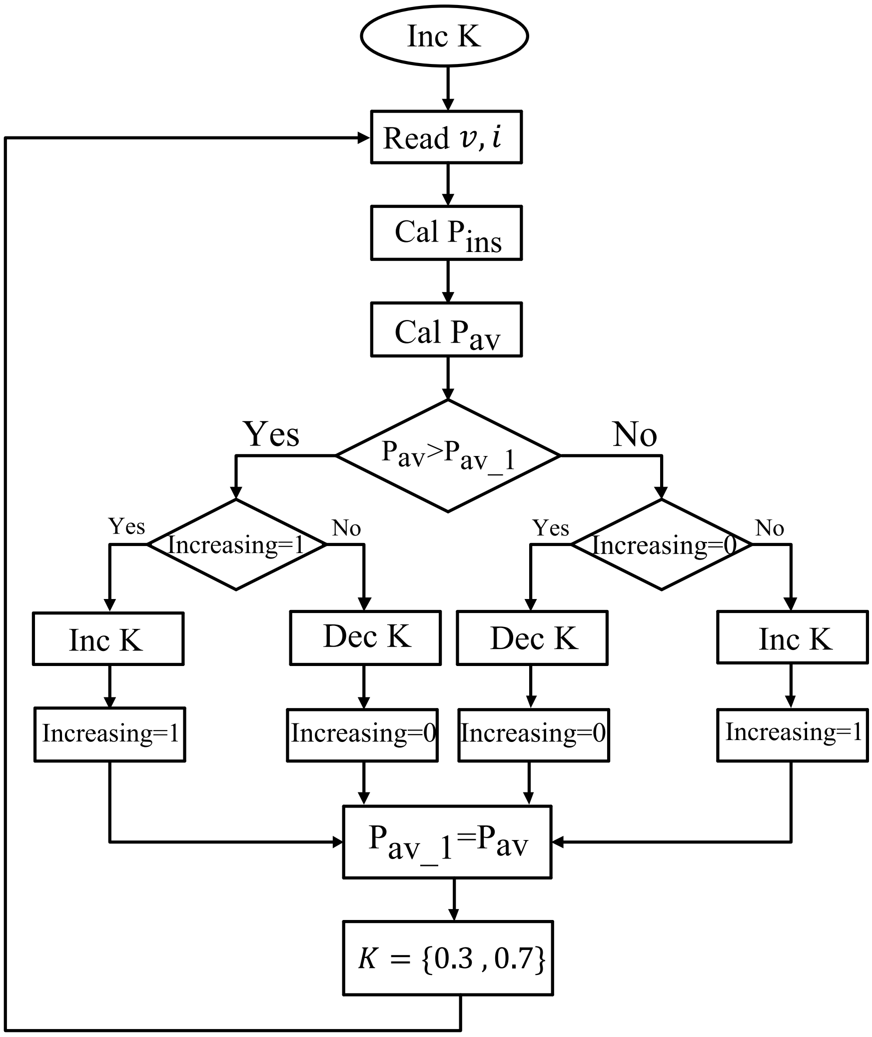


Figure 5.18 - MPPT perturbation and observation flowchart [35].

The first step is to read the values of input current and voltage by using voltage divider (to read the voltage value) and rheostat or current hall sensor (to read the current value) with pay an attention for the reading values must not be more than 5 V, otherwise the *ATMEGA* will damage.

After reading the values of current and voltage, the instantaneous value of power should calculate to make a comparison between current value and previous power value. On this basis, the duty cycle will decrement or increment after make a checking and browsing to know where the present location of the working point is.

If this work point is located on the left side (increasing=1) so increment the duty cycle and make the increasing variable value equals to 1 again (increasing=1) to ensure that the next perturbation will be in the same direction (incrementing again the duty cycle) or if it is located on the right side (increasing=0) decrement the duty cycle and make the increasing variable value equals to 0 again (increasing=0) to ensure that the next perturbation will be in the same direction (decrementing again the duty cycle).

After that the old value of power will be updated as a new value to make a comparison again. The duty cycle of PWM must be determined within a domain to ensure the stability work for the MOSFET. In this project the duty cycle limited between 30% and 70%.

During this process, there is a block to calculate the average value of power because using this value in programming is more accurate than using the instantaneous value and the final signal has more stability.

5.8. Simulation Results Using *PSIM*

Now as a primary simulation model by using *PSIM* program, we will use a variable DC source instead of using wind turbine with permanent magnet synchronous generator and three-phase rectifier bridge, as shown in the Figure 5.20, to detect that MPPT control if it is working well. To know that the work point is corresponding with the maximum power point, we must use a maximum power transfer theory which says that we can obtain the maximum output power if the equivalent load resistance is identical to the internal source resistance.

Figure 5.19 contains two resistors, the resistance R_1 is a rheostat and the resistance R_2 includes the equivalent resistance of SEPIC and the load.

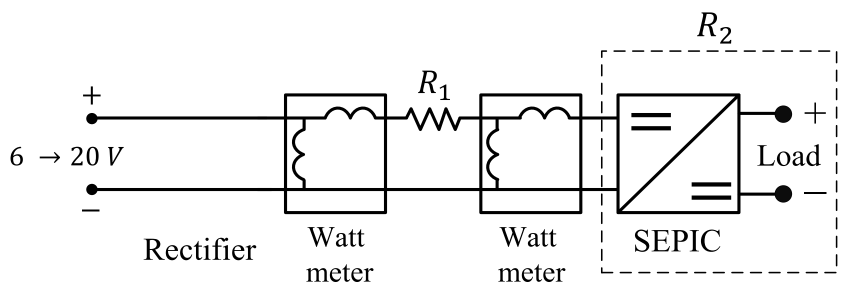


Figure 5.19 - Equivalent circuit of maximum power transfer theory.

According to the maximum power transfer theory, we obtain the maximum power when output voltage value (input voltage of SEPIC V_{R2}) is equal to the half value of source voltage (rectified voltage V_{Rec}) as the following equations:

$$V_{R2} = V_{Rec}\ \frac{R_2}{R_1 + R_2} \tag{5.25}$$

$$R_1 = R_2 \quad \Rightarrow \quad V_{R2} \approx \frac{V_{Rec}}{2} \tag{5.26}$$

$$R_1 = R_2 \quad \Rightarrow \quad P_2 \approx \frac{P_1}{2} \tag{5.27}$$

By applying variable DC voltage $6 \rightarrow 20$ V as a rectified voltage and gives the value of $R_1 = 12.7\ \Omega$, $R_{Load} = 200\ \Omega$, In this case the system will work almost at optimal power point and the extracted power from the source is almost a maximum.

MPPT work mechanism does not related to SEPIC's load value. Therefore, changing the value of this load does not change the final result of MPPT.

Simulation results for primary simulation model that shown in Figure 5.20 are shown in the Figure 5.21 where the equations (5.26) and (5.27) are applied here by choosing the increment step value equals to 2.

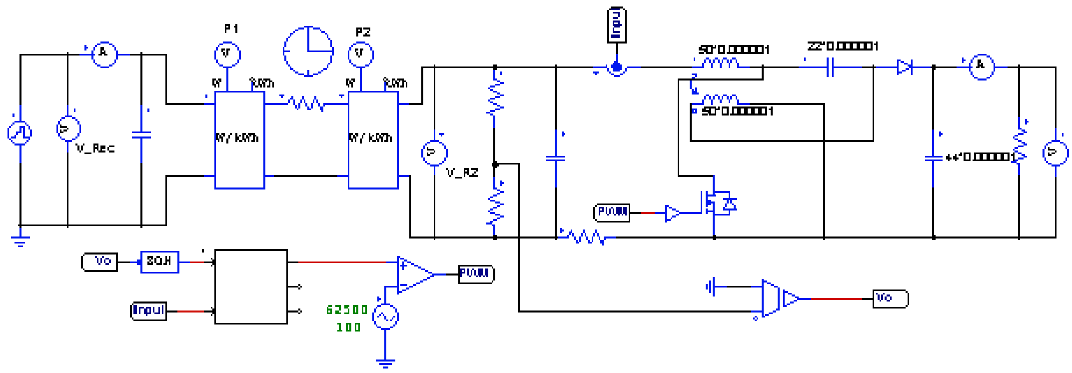


Figure 5.20 - Primary simulation model to test MPPT control.

Now after make a confirmation about MPPT control method in case of passive load, a micro wind turbine with permanent magnet synchronous generator and uncontrolled three-phase rectifier bridge will be added for the primary simulation model in Figure 5.20. The rectifier bridge will followed by a condenser 1400 μF to decrease the ripples as much as possible and the input resistance will be removed. New simulation model will contain also all previous components and 12 V battery in the output to test charging process.

The micro wind turbine and permanent magnet synchronous generator characteristics in *PSIM* were considered as shown in the Table 5.6.

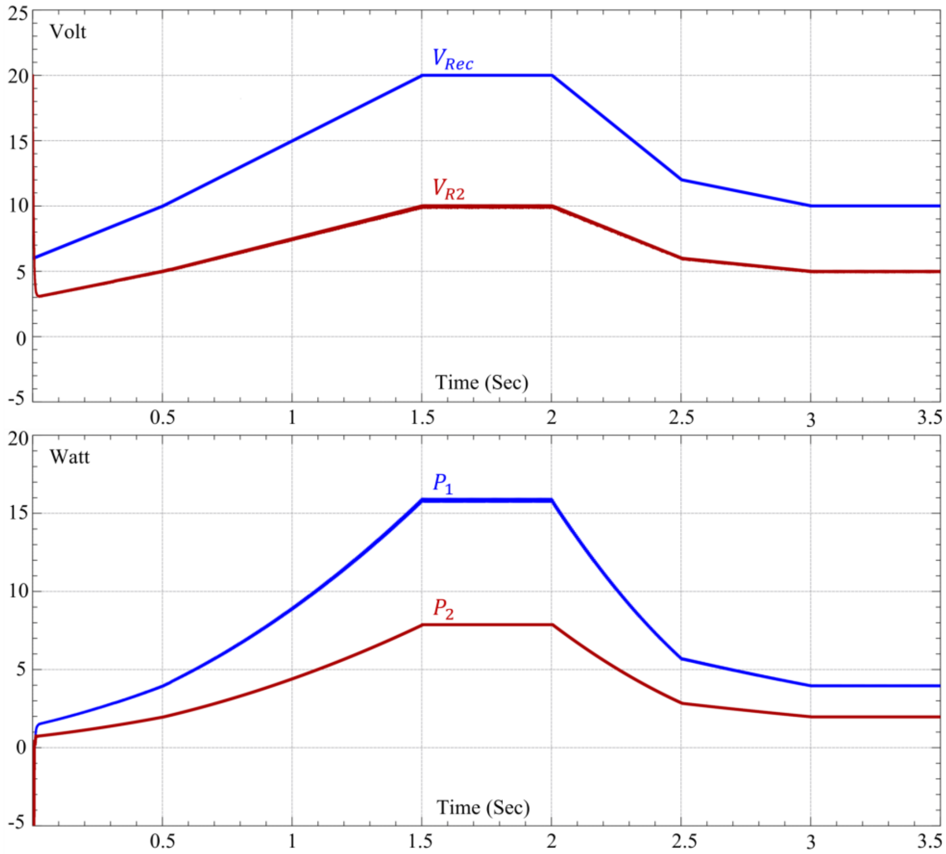


Figure 5.21 - MPPT simulation results in case of $R_1 = 12.7\ \Omega$, $R_{Load} = 200\ \Omega$, $V_{Rec} = 6 \rightarrow 20$ V.

Table 5.6 - Wind turbine and synchronous generator characteristics in *PSIM*

Micro Wind Turbine		**Permanent Magnet Synchronous Generator**	
Nominal Output Power	450 W	R_s Stator Resistor	1
Base Wind Speed	14.5 m/sec	d_axis Inductance	1.51 mH
Base Rotational Speed	1600 rpm	q_axis Inductance	1.17 mH
Initial Rotational Speed	Variable	$\frac{V_{PK}}{\text{Krpm}}$	46.7
Moment of Inertia	Very high	Number of Poles	12
		Moment of Inertia	Very low

If the Initial Rotational Speed value equals to 530 rpm, the peak value of line voltage is almost 21 V and the rectified voltage will have the same peak value of line voltage as shown in Figure 5.22.

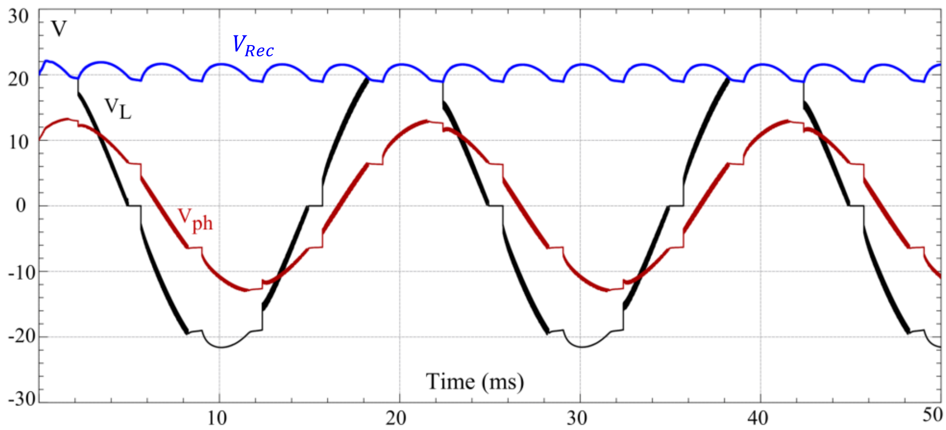


Figure 5.22 – Line and phase voltages of synchronous generator – Rectified voltage.

In case of replacing passive load by an active load (12 V battery) to see the final results, the resistance R_1 must be removed.

Figure 5.23 shows the results of P_1 , P_o , V_{Rec} and V_o where:

P_1 is an input power for all system, P_o is an output power of SEPIC, V_{Rec} is an output voltage of rectifier and V_o is an output voltage of SEPIC.

Both curves of input and output power P_1, P_o are almost similar and it is noticed that there is a little differences between them because of power losses in SEPIC's components and power losses in current-voltage measuring resistors, also both of curves have some ripples because of the DC voltage V_{Rec} has also some ripples and that leads to make the MPPT control always trying to work at the maximum power point. To detect that our MPPT control work well, it is very clear that the load consumes the highest power from the source as much as possible after take into consideration the power losses in SEPIC elements and external resistors.

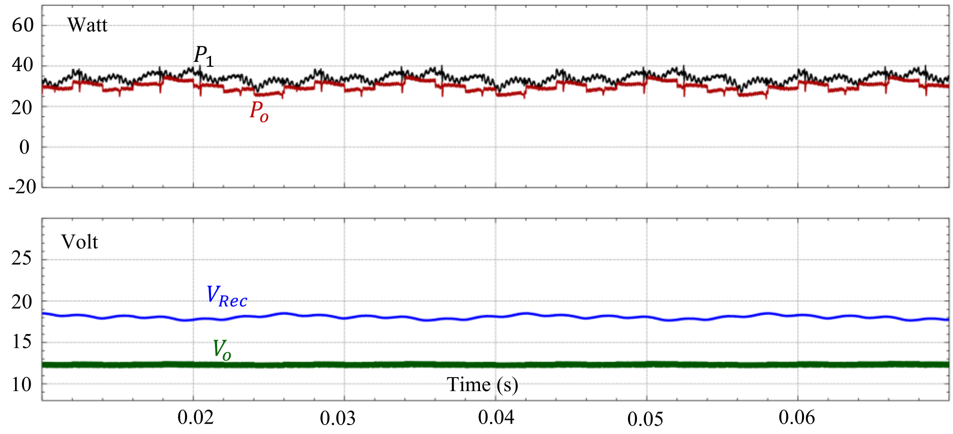


Figure 5.23 - MPPT simulation results in case of 12 V active load.

For sure, the value of output power is less than P_1 because of the SEPIC's components consume some power as losses power, so:

$$(P_o = V_o\, I_o)_{\text{average}} = (12\text{ V} \times I_o) < P_1$$

Figure 5.24 shows charging current result for the battery I_o where normally this value varies between 2→ 6 A according to the type of battery. The current wave has lots of ripples because of L_2 inductance and variable P_o wave. The average value of this current here equals to 1.4 A at speed 500 rpm.

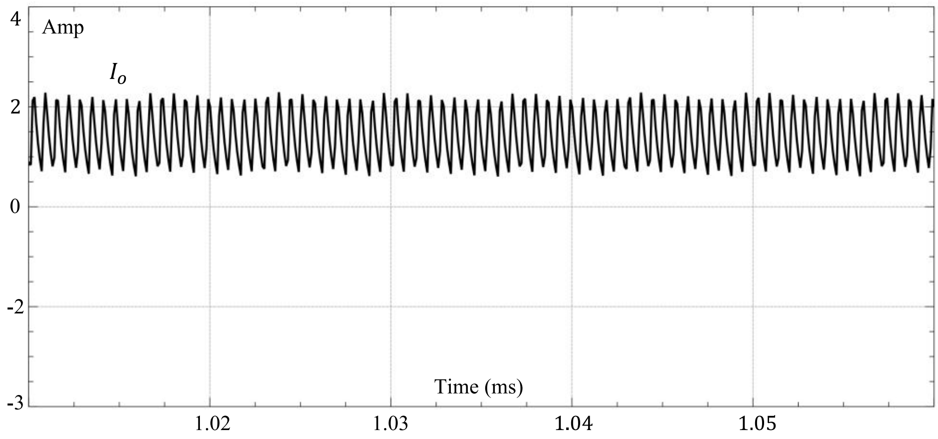


Figure 5.24 - Charging current of battery I_o result.

5.9. Conclusion

This chapter described the developed battery charging system design using MPPT algorithm, which includes a micro wind turbine, permanent magnet synchronous generator, three-phase rectifier bridge with a capacitor in the DC side, DC-DC coupled inductor SEPIC converter (chopper), driving circuit of the MOSFET and MPPT control algorithm with digital controller. Also some theoretical information about micro wind turbine characteristics, like *TSR* (Tip Speed Ratio) and ideal curve of wind turbine were explained.

The design calculations for SEPIC converter and other components are described in this chapter and applied on *PSIM* simulation model. In addition, the MPPT control flowchart (perturbation and observation MPPT) using *ATMEGA UNO* 328*P* was described with ADC and PWM processes.

Finally, simulation results showed the MPPT control results, where the maximum power transfer theory was achieved to work in optimal power point and obtain the maximum power as much as possible in case of passive load (resistor). In addition, it was noticed that in case of active load (battery) the maximum power transfer theory and MPPT control were achieved and both curves of P_1, P_o are almost similar if the power losses in SEPIC's components and current-voltage measuring resistors are taken into consideration.

CHAPTER 6

Experimental Results of the MPPT System with SEPIC Converter

6.1. Introduction

This chapter presents the experimental results of the MPPT system for micro wind power using coupled inductor SEPIC converter in case of passive (resistive) and active load (battery), which have already presented in chapter 5 as simulation results.

Normally in engineering field, simulation results are different from and nearby implementation ones for many reasons, like changing in MOSFET response at different PWM work frequencies, inaccurate simulation parameters values and measurement errors. Therefore, this chapter will describe these differences and their causes.

Most of the simulation parameters that were introduced in the Chapter 5(SEPIC parameters, PWM signal properties, MPPT control flowchart) will be taken into account in this chapter without any changes.

6.2. MOSFET Switching Response

The switching power losses of MOSFET becomes a major factor in the total power losses of PE components especially when the PWM frequency being increased to decrease the total volume of passive equipment. In reality, power MOSFET switching frequency is limited by reverse recovery losses of body diode more than turn-on / turn-off time speed, where both of those effects give a poor performance of power MOSFET and lead to decrease the conversion efficiency [36].

Poor performance of power MOSFET is related with high PWM frequency, low PWM amplitude and duty cycle value. Therefore, the value of PWM switching frequency is closely related with the value of duty cycle and turn-on / turn-off time speed where these times must be less than the half cycle of PWM signal to give the ability for power MOSFET to switch from on-state to off-state and vice versa. Consequently, duty cycle value of power MOSFET in this project was bounded between 30% and 70%.

For previous purposes, MOSFET driving circuit was used in this project to get high PWM amplitude (about 15 V) and makes isolation between microcontroller board and MOSFET's gate circuit.

Normally, power MOSFET and body diode losses are [37]:

1- Conduction losses which related with the drain-source resistor in on state.
2- Switching losses which related with turn-on delay time, turn-off delay time, rise time, fall time and reverse recovery time of body diode.

All of implementation results waveforms were visualized in *YOKOGAWA* digital oscilloscope as shown in Figure 6.1.

Figure 6.1 - YOKOGAWA digital oscilloscope.

The following results in Figure 6.2 shows MOSFET's response at different PWM frequencies 62.5 kHz, 123 kHz , 70% of duty cycle and 15 V PWM amplitude.

It is clear that at the frequency 123 kHz, the cycle period *T* is less than in case 62.5 kHz and that leads to decrease MOSFET's capability to change its work situation (on-off), so to work at high frequency, fast switching MOSFET with small turn-on / turn-off time speed must be used. Therefore, the frequency of 62.5 kHz was adopted in this project because it is more preferable to use and gives spacious domain of reliability.

Also, some distortions are founded in drain to source voltage signal V_{DS} when switching frequency equals to 123 kHz as shown in the Figure 6.2.

It is very difficult and complex to simulate MOSFET's response state in simulation programs because of non-linear equations and characteristics of MOSFET. Therefore, these results did not presented in chapter 5 as simulation results [38].

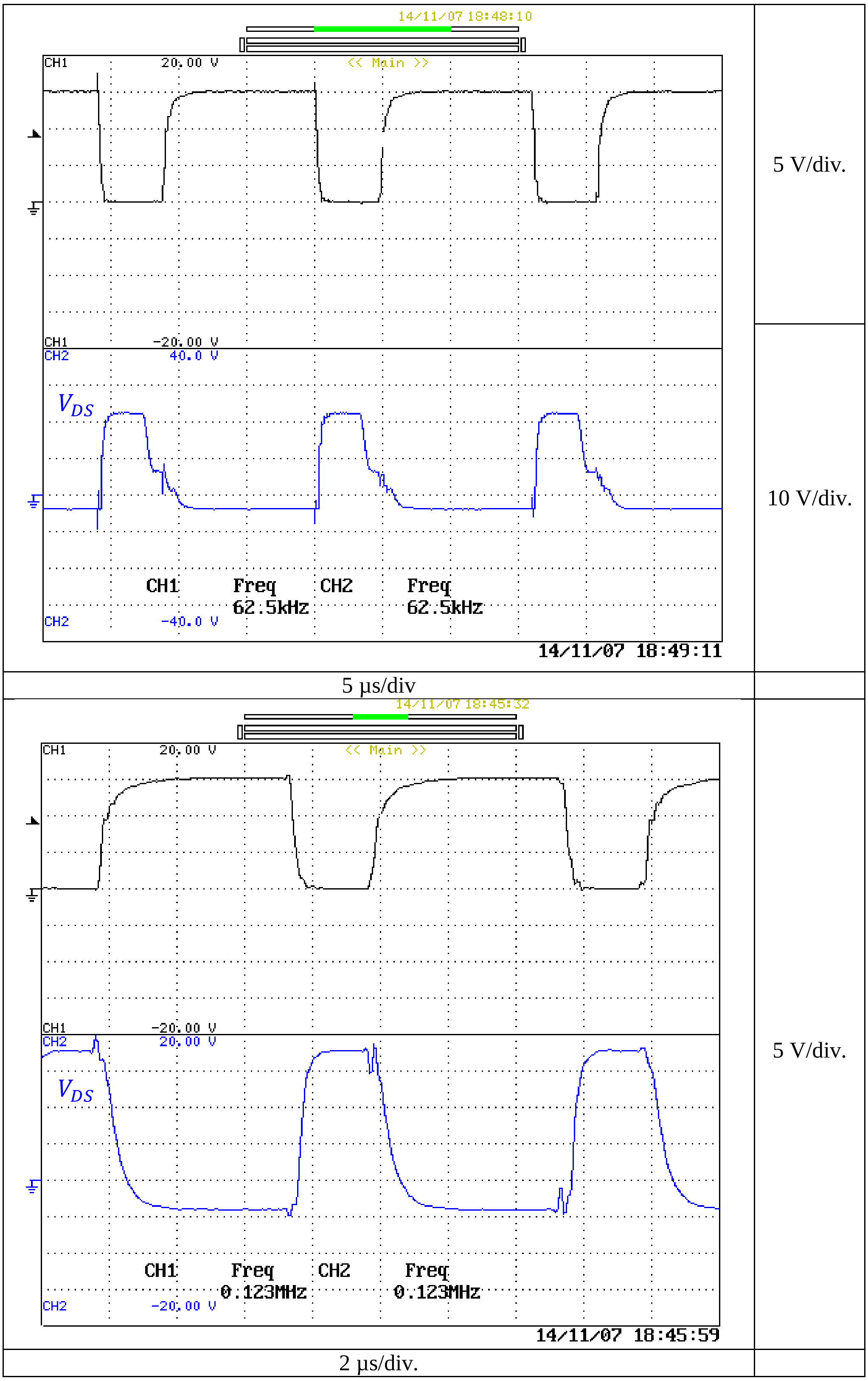


Figure 6.2 - MOSFET's response at different PWM frequencies.

6.3. MPPT Experimental Results

Perturbation and observation MPPT control flowchart that is shown in the Figure 5.18 has been implemented here by using *ATMEGA UNO* 328*P* microcontroller with the same C^{+} codes that have written in *C Block PSIM* program.

At first, confirmation process for primary simulation model that illustrated in the Figure 5.20 to test MPPT control in passive load case (resistive load) by using constant DC voltage as a rectified voltage, then the final results will be taken by using wind turbine (induction motor controlled by a frequency variator), permanent magnet synchronous generator, three-phase rectifier bridge and active load (battery).

6.3.1. MPPT Experimental Results by Using Passive Load

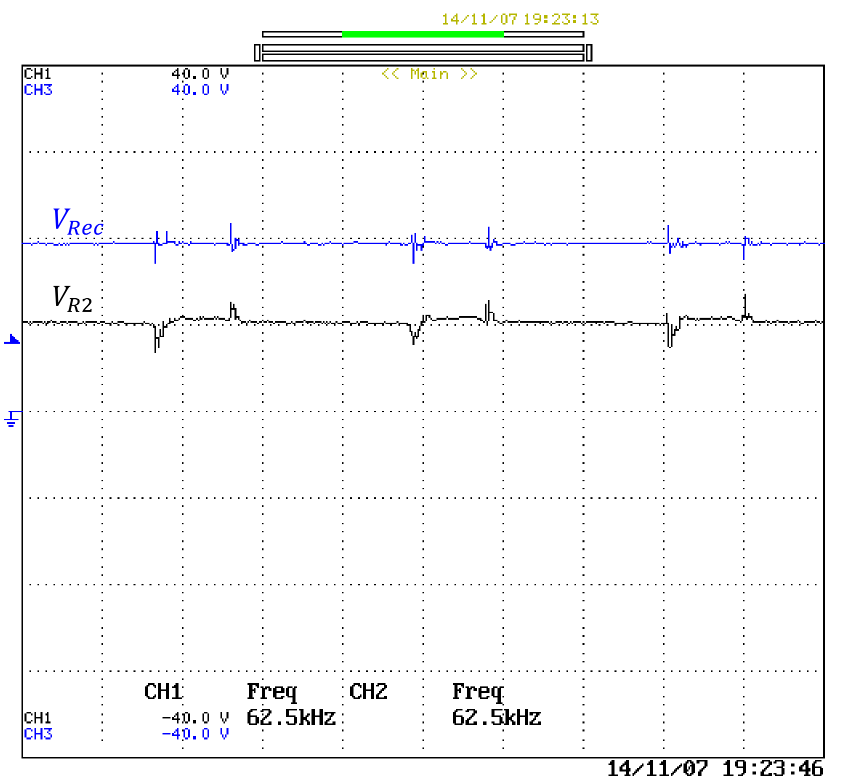
Primary simulation model that is shown in the Figure 5.20 is implemented here but by using constant DC voltage source equals to 20 V as a rectified voltage. The values of other components are still the same $R_1 = 12.7\ \Omega$, $R_{Load} = 200\ \Omega$. we should remember that, the results of MPPT control did not related with the load value insofar as related with the increment step value.

In *PSIM* model, the increment step value was 2 and the sawtooth fast PWM wave peak value was 100. However, in C^+ codes of *ATMEGA UNO* the sawtooth fast PWM wave peak value equals to 255 (8 bit - timer 2) and the increment step value equals to 8.

As in simulation parameters, the increment step value in implementation must be equals to 5.1 to equivalent this value in simulation which equals to 2, but it was noticed that to get a good implementation results as shown in the Figure 6.3, the increment step value must be around 8 where a very low value leads to not reaching to optimal power point (see the Figure 5.17), also a very high increment step value makes the system unstable and oscillate around the optimal power point.

If the output power value equals to the half value of the input one, the maximum power transfer theory will be applied and the extracted power from the source is a maximum.

We must pay attention that the SEPIC must not work without applying load otherwise, MOSFET’s temperature will increase and damage the MOSFET.



10 V/div.

5 μs/div.

Figure 6.3 - MPPT implementation results by using passive load.

Using *ATMEGA UNO* 328*P* to do MPPT control is not very recommended because it is not a powerful microcontroller comparing with other microcontroller types like *Texas Instrument* family, also it has a slow performance and some weaknesses like:

1- In the previous calculations, the increment step value in implementation was equal to 5.1 but in reality the value should be integer one, otherwise the MPPT control will take a long time to be applied.
2- In *C Block PSIM* model, SEPIC input power average value was calculated by doing 100 calculation steps, but in reality it was 50 steps to compensate the slow performance of *ATMEGA.*

6.3.2. MPPT Implementation Results by Using Active Load (Battery)

The main objective of this project is to implement a battery charging system by using MPPT system for micro wind power (*Silentwind*) using SEPIC converter to get the maximum power at various wind speeds.

At first, and before connect the battery to the system, some steps must be taken into consideration to increase system protection and avoid any dangerous cases that may cause damages for the system.

When there is a connection between the battery and SEPIC's output, high charging current value will pass through the capacitor C_2 (output of SEPIC) to charge the capacitor C_2. Therefore, high resistance value is connected in series between the battery and the capacitor to limit this current, after that a resistance is getting out from the circuit by using electrical switch to make a direct connection between the parts as shown in Figure 6.4.

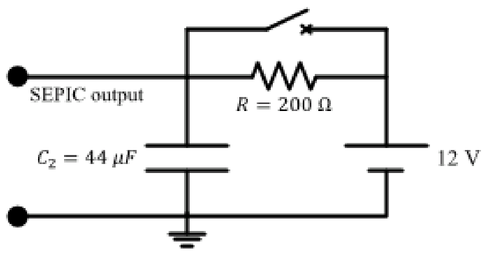


Figure 6.4 - Protection circuit from high charging current.

In this project, a *VRLA GEL* battery 12 V / 33 Ah was used here as shown in the Figure 6.5, where this kind of batteries have more advantages comparing with lead acid ones, like it could be used in any position, except upside down and have maintenance free construction (need no water additions and will not permit electrolyte spills).

Figure 6.5 - VRLA GEL battery that is used in the project.

Figure 6.6 shows the results of battery voltage V_o, input voltage of SEPIC V_i and charging current of battery I_o. We must pay attention about that the input voltage of SEPIC V_i does not equal to the output voltage of rectifier bridge V_{Rec} because of external resistor for measuring input current and this resistor has a value $1.65\ \Omega$. The voltage of battery V_o has a little changes more than 12 V (about 14 V) when charging current is not equal to zero.

This current has some ripples and unsteady value because of continuous changing in work point position of MPPT control (the instantaneous value of power that measured by the microcontroller is always changing because of unsteady value of SEPIC input current I_i which measured by external resistor as shown in Figure 6.7) and because it is resulting from a three-phase rectifier bridge PD3 which has also some ripples in output side beside to unequal connection periods (duty cycles) for SEPIC.

This problem could be limited by make an adjustment for MPPT control algorithm by applying the ADC operation during specific number of times.

The input voltage of the SEPIC V_i is almost equal to 18 V when the output voltage of a rectifier is 20 V at motor velocity equals to 500 rpm.

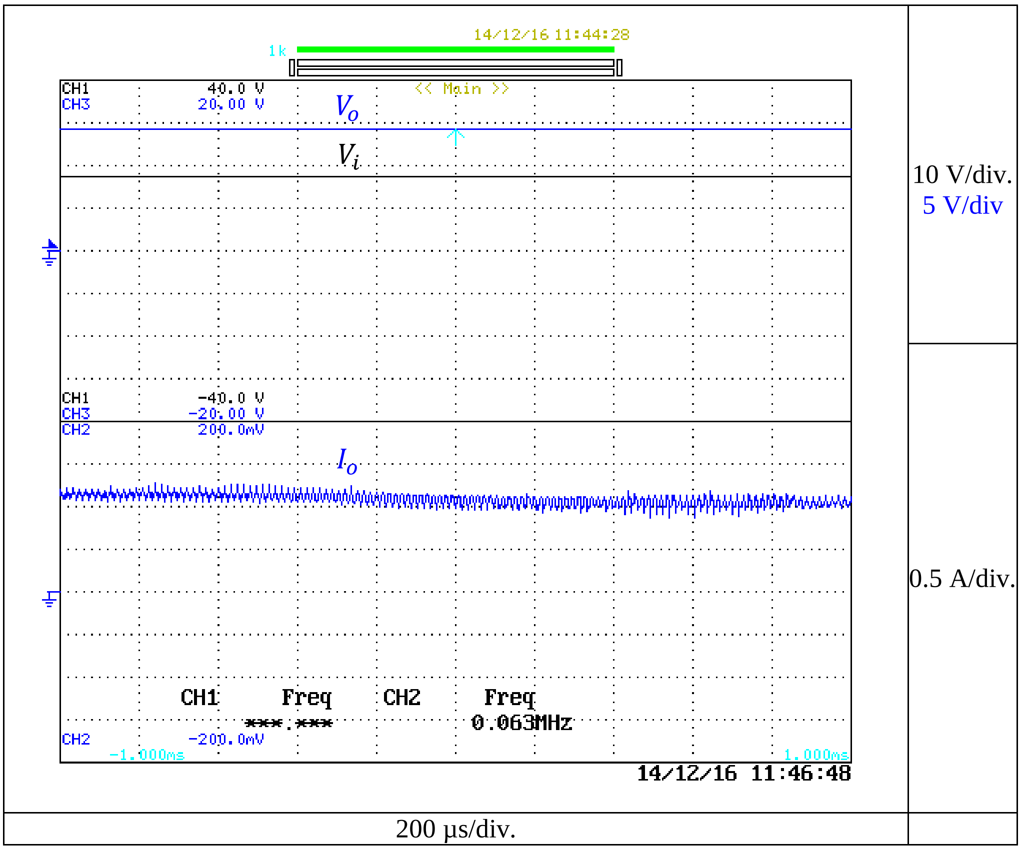


Figure 6.6 - Battery voltage V_o – Input voltage of SEPIC V_i - Charging current of battery I_o.

Figure 6.7 shows the results of SEPIC input current comparing to charging output current. It was noticed that both currents have ripples with a frequency equals to MOSFET PWM frequency. For sure, the average value of input current is higher than output one.

The values of currents were obtained by using DC clamp meter where every 100 mV is equal to 1 A.

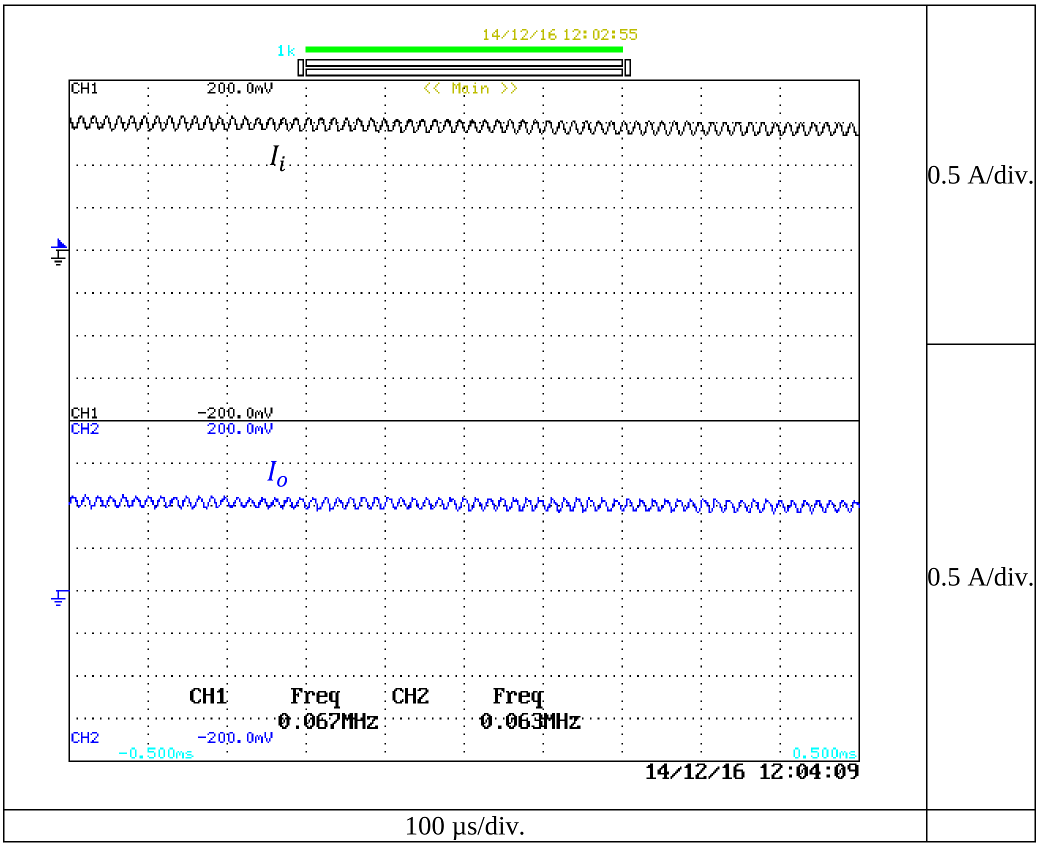


Figure 6.7 - Input current of SEPIC I_i - Charging current of battery I_o.

6.4. Comparison between Simulation and Implementation Results

The simulation and experimental results in both chapters 5 and 6 confirm that our MPPT control work properly in both cases of passive load and active load, also it was noticed that in simulation results, the battery charging current I_o has a value more than its value in experimental results because in simulation model, the resistor for measuring input current was removed and replaced by current sensor that does not consume any power. But in reality, it is not possible to remove this resistor because of its necessity for control process. Consequently, the values of input and output power P_1, P_o are not exactly the same in experimental results.

Another difference between simulation and implementation results was an increment step value in *C* code for *ATMEGA 328P* microcontroller which has already discussed in 6.3.1 paragraph.

6.5. Conclusion

In this chapter, the experimental results for the developed MPPT system using SEPIC converter were presented, and it was made a comparison between simulation and experimental results.

It was noticed that both simulation and experimental results have some variances because of several factors which are described in this chapter, such as the difference in increment step value in MPPT algorithm for both results. Also the MOSFET frequency response in reality is different from its frequency response value in simulation (the PWM frequency is the same) especially if the temperature of the MOSFET increased with the time.

Another difference that should not be ignored is the resistor 1.65 Ω for measuring input current, which was removed in the simulation model, but in reality, it should be considered, so to confirm that our MPPT control work as well in reality as in simulation, the input and output power for SEPIC must be almost the same after taking the effect of power losses in the input current measuring resistor and in the input voltage measuring resistors.

CHAPTER 7

Conclusion

7.1. Conclusions

This Master thesis work consists in two linked parts, described below.

The first part of this work is about the writing of an Educational Power Electronics document, envisaged to facilitate the work of learning PE, allowing an interesting and motivating way to study for students and non-specialists, with the offering of all simulation models of PE circuits that are included in the document. So, it is possible for the learner to change the parameters of the circuits, and then observe the new results. This part of the work was explained well through the first four chapters.

Chapter1 included an introduction about the Master thesis content in both simulation and implementation topics.

Chapter 2 discussed the present ways to learn PE and made a comparison between these methods and our Educational Power Electronics document.

Chapter 3 presented some of the PE circuits that were already simulated and explained in our Educational Power Electronics document, to show the present way of this document.

Chapter 4 discussed about simulation of PE circuits and the software used to achieve this purpose, like *MATLAB* and *PSIM.*

The second part of this work was about implementing some of PE circuits that were explained in the Educational Power Electronics document, like the mutual inductance SEPIC converter. This SEPIC converter was used to implement an MPPT system for micro wind power, employed in a batteries charging system for boats.

Chapter 5 presented all designing calculations for this project, including the SEPIC converter. The control process of this charging system is an open loop MPPT control, where the value of instantaneous input power of the SEPIC is measured and compared with its old value to increase or decrease the duty cycle of the MOSFET. This MPPT control is the heart of all the control process, so all the conclusions and suggestions for the future given next depend on development of this control.

Chapter 6 presented experimental results of the developed MPPT system and made a comparison between these results and simulated ones.

Both of results showed that in general (case of passive and active loads) the load almost consumed the maximum power from the source, where in reality, the system worked at a point slightly lower than the optimal power point, and that indicates a good control system performance. It was noticed that the battery charging current had some harmonics with a frequency equals to the PWM frequency.

The obtained results for the MPPT system are good results, but not enough for optimal using of this charging system. Therefore, some suggestions are referred to do in the future to improve this project, after describing some problems that occurred during the implementation process.

ATMEGA ARDUINO UNO 328*P* microcontroller is used to implement the MPPT control, where this kind of microcontroller is specified to use for small educational projects, but in the same time it has simple design and is easy to use, when comparing with other microcontrollers. However, it is not a powerful microcontroller, and causes some problems for the control process, like the slow performance of the control process when an increment step variable of the MPPT control has a double value instead of integer one. Also, a slow control performance was noticed by the increase of the number of array elements that were used to calculate the average power (see Figure 5.18). For example, in the simulation code this number was 100, but in the implemented solution (in reality) it was just 50 and that have led to obtain results with less stability.

In addition, the highest PWM frequency possible to obtain with an acceptable accuracy was 62.5 kHz (it is possible to have higher than this value, but by sacrificing the accuracy of the PWM pulses).

This developed system has acceptable MPPT control results, but it is possible to make it better by overcoming the previous problems. Therefore, some suggestions are referred in the following subchapter.

7.2. Suggestions for Future Works

Next are presented some suggestions for future works:

1- Develop new power electronics circuits for the Educational Power Electronics document. This document needs to be revised in order to correct eventual mistakes.

2- Make a closed loop PI (Proportional-integrator) control with our MPPT control to adjust the battery charging current and to obtain the maximum power from the wind turbine, where one of the disadvantages of the previous system was the non-controlled charging current. Therefore, the microcontroller *ATMEGA ARDUINO* 328*P* must be replaced for a more powerful one, like a DSP (Digital Signal

Processor) or any chip from *Texas Instruments* family. Also, it is recommended to change the way of measuring the SEPIC input current, by replacing the resistor by another technical way.

3- Develop the controller by using a MPPT control with variable increment step, because the fixed step MPPT control cannot follow the maximum power point when weather conditions change rapidly, and that leads to decrease the accuracy and the system performance quality.

References

[1] Jerry Bergman. (2009) Institute Creation Research. [Online]. http://www.icr.org/article/sir-ambrose-fleming-father-modern-electronics/

[2] European Space Agency. (2014, May) ESA. [Online]. http://www.esa.int/Our_Activities/Space_Engineering_Technology/Power_Laboratories

[3] N. VALLS. (2009, July) Nilium. [Online]. http://www.nilium.com/compact-muon-solenoid-up-close-and-personal

[4] Nottingham university. (2007) The university of Nottingham. [Online]. http://www.nottingham.ac.uk/elan/getting_started/benefits

[5] Allan Gyorke, "Faculty Guide to Teaching through Video conferencing," The Pennsylvania State University, Pennsylvania, 2006.

[6] Precisionvc. [Online]. http://www.precisionvc.com/Bridging.html

[7] ALSTOM. (2010, September) [Online]. http://www.alstom.com/Global/Group/Resources/Documents/Investors%20document/Investor%20events/Analysts%20presentation/Analyst%20Day%20-%20HVDC%20technology.pdf

[8] ABB. (2009, December) [Online]. http://www05.abb.com/global/scot/scot260.nsf/veritydisplay/0f2ae3c88ed9ab1b852577ec007ddb61/$file/1SXU301208B0201.pdf

[9] IEEE. (2014, January) [Online]. http://ieeexplore.ieee.org/xpl/virtualJournals.jsp

[10] International Journal of Advancements in Power Electronics & Digital Devices. (2014) IRED. [Online]. http://journals.theired.org/ijpedd.html

[11] Jose Rodrıguez and Alejandro Weinstein, "Single-Phase Controlled Rectifiers," in *Power Electronics Handbook.* University of West Florida, 2001, ch. 11, p. 171.

[12] Juan Dixon,. Santiago, CHILE., Pontificia Universidad Católica de Chile, 2010, ch. 12.

[13] BIMAL K. BOSE, *Modern Power Electronics and AC drive*., pp. 158-159.

[14] Bimal.K.Bose, *Modern Power Electronics and AC Drives.* USA, 2002, ch. 4, p. 159.

[15] Anu Maria, "INTRODUCTION TO MODELING AND SIMULATION," State University of New York at Binghamton, New York, USA, 1997.

[16] Christopher A. Chung, "Cost-Related Resource Policies," in *Simulation Modeling Handbook*. Washington, USA, 2003, ch. 2, p. 19.

[17] V.P.Singh, *System modeling and simulation.* New Delhi, India, 2009.

[18] Simon Abourida, Jean Belanger Christian Dufour, "Hardware-In-the-Loop Simulation of Power Drives with RT-LAB," Opal-RT Technologies, Montreal, IEEE 2005.

[19] (2009, May) CAE net. [Online]. http://product.caenet.cn/ShowProductNewsDetail.aspx?ProductID=248&ID=1122

[20] Christopher A. Chung, "Simulation Cannot Provide Easy Answers to Complex Problems," in *Simulation Modeling Handbook*. Washington, USA, 2003, p. 15.

[21] PSIM-Europe. [Online]. http://www.psim-europe.com/psim_keyfeatures.php

[22] PSIM-Europe. [Online]. http://www.psim-europe.com/psim.php

[23] Powersim Technologies Inc., "PSIM User Manual," Richmond-Canada, 1999.

[24] Alan Hadad and Akram A. Abu-aisheh Sameer Khader, "THE APPLICATION OF PSIM & MATLAB/ SIMULINK IN POWER ELECTRONICS COURSES," University of Hartford,

Palestine Polytechnic University, Hartofrd, CT, USA, IEEE 2011.

[25] Yatim A.H.M.a, Tan C.W.a, Saidur R. b Abdullah M.A.a, "A review of maximum power point tracking algorithms for wind energy systems," *Renewable and Sustainable Energy Reviews*, no. IEEE, p. 1, January 2012.

[26] Alireza Bakhshai Joanne Hui, "A New Adaptive Control Algorithm for MPPT Wind Energy Conversion System," Queen's University, Kingston, Canada, Phd report-IEEE 2008.

[27] Silent Wind. [Online]. http://www.silentwindgenerator.com/en/windgenerator-silentwind/windgenerator-24v

[28] ZHANG Bo, DU GuiPing, HU ZongBo DENG WeiHua, "Coupled Inductor design with small voltage spike of SEPIC converter.," University of technology - China, IEEE 2005.

[29] Jeff Falin, "Designing DC/DC converters based on SEPIC Topology," Texas Instruments Incorporated, Dallas, Texas, IEEE 2008.

[30] [Online]. http://4.bp.blogspot.com/-UwY3X19nXe8/UET1ZgU_xGI/AAAAAAAAAzA/1VJSxKnypSU/s1600/ArduinoUno_R3_Front Scheme.jpg

[31] (2010, April) Ermico. [Online]. http://www.ermicro.com/blog/?p=1971

[32] Adrian TULBURE, Mihail ABRUDEAN Bogdan CROITORU, "Microcontroller-based multiple-platform PWM Signals generation Procedures for Industrial use," Technical University of Cluj-Napoca , University of Alba Iulia, Romania, IEEE 2014.

[33] Laurenţiu Creoşteanu, Gheorghe Brezeanu Răzvan Puşcaşu, "A METHOD FOR REDUCING MOSFET HIGH SIDE POWER SWITCH TURN-ON TIME," University "POLITEHNICA", Bucharest, Romania, IEEE 2013.

[34] Mohammed Ouassaid, Mohamed Maaroufi, Sarah Abdourraziq Mohamed Amine Abdourraziq, "Modified P&O MPPT Technique for Photovoltaic System," Department of Industrial Engineering, ENSA, Cadi Ayyad University, Safi, Morocco, Rabat, IEEE 2013.

[35] Alexandre Manuel Mota José António Barros Vieira1, "Maximum Power Point Tracker Applied in Batteries Charging With PV Panels," Escola Superior de Tecnologia de Castelo Branco, Castelo Branco, IEEE 2008.

[36] Alex Q. Huang Suxuan Guo, "Control and Analysis of the High Efficiency Split Phase PWM Inverter," North Carolina State University, IEEE 2014.

[37] Bo Wang, and Rengang Chen David Jauregui, "Power Loss Calculation With Common Source Inductance Consideration for Synchronous Buck Converters," Texas Instrument, Dallas, 2011.

[38] Yali Xiong, Xu Cheng, Yue Fu, and Pavan Kumar Z. John Shen, "Power MOSFET Switching Loss Analysis A New Insight," University of Central Florida, Orlando, IEEE 2006.