DEVELOPMENT OF CURRENT CONTROL FOR THREE PHASE MULTILEVEL INVERTER

MUHAMMAD QHUZAIFAH BIN ZOLKEPLEE

A project report submitted in partial
fulfillment of the requirement for the award of the
Degree of Master of Electrical Engineering

Faculty of Electrical and Electronic Engineering
Universiti Tun Hussein Onn Malaysia

JULY, 2014

ABSTRACT

Inverter is a device, a type of electronic converter in which purpose is to convert a DC signal to AC signal. This project aims to develop a current control method for a multilevel inverter. The purpose of adding a controller is so that the output from the said device, can be controlled and maintained. The simulations of the project are done by using MATLAB Simulink. Results obtained are from the open loop test and closed loop test. Two stages cascaded H bridge are created in which it uses 12 PWM signals for the switching scheme. PWM signals are generated by comparing a sine wave and triangular wave. Switching frequency for this project is chosen to be at audible range of 20kHz. PI controller is used for this project, in which it is set to control current at value of 0.5A and 0.8A. Current sensor is used for detection, in which it will output current value in terms of voltage. The sensitivity is around 40mV/A and with starting value of 2.5V at 0A. It is used for the measurement of the output current, in which it is processed inside microprocessor board, TI C2000 TMS320F28335 for controlling process. Multilevel system created is tested with RLC load in order to verify the validity of the methods used. The results obtained are very much satisfactory in both test. Multilevel inverter produce twice the voltage supplied, as how it should works theoretically. The waveform shapes obtained are of a staircase, 3 level output. Voltage is supplied at 10V and giving the total output of 20V. Current output comparison shows that the closed loop with control element yield better waveforms than the open loop test.

ABSTRAK

Penyongsang adalah alatan, sejenis pengubah electronic di mana kegunaan utama adalah untuk menukar signal DC kepada AC. Projek ini bertujuan untuk menghasilkan cara mengawal arus untuk kegunaan penyongsang berperingkat. Tujuan sistem kawalan dipasang adalah supaya arus keluar dapat dikawal dan dikekalkan. Simulasi telah dijalankan untuk projek ini di dalam MATLAB Simulink. Hasil yang telah didapati adalah daripada ujian buka gelung dan ujian tutup gelung. Dua peringkat timbunan jejambat H telah dibina di mana ia menggunakan 12 signal PWM untuk mengawal suis. Signal PWM telah dijana dengan membandingkan signal sine dengan signal segitiga. Frekuensi suis telah dipilih dengan nilai yang sesuai iaitu 20kHz. Pengawal PI telah digunakan untuk projek ini, di mana ianya telah digunakan untuk mengawal arus di nilai 0.5A dan 0.8A. Pengesan arus digunakan untuk mengesan, di mana ia akan menukarkan arus keluar kepada nilai voltan. Kepekaannya adalah di nilai 40mV/A dengan nilai permulaan adalah 2.5V di 0A. Ia digunakan untuk mengukur arus, di mana ia seterusnya akan diproses di dalam TI C2000 TMS320F28335 microprosessor. Penyongsang berperingkat telah diuji dengan beban RLC untuk menguji kesahihan cara yang telah digunakan. Hasil yang telah didapati daripada projek ini amat memuaskan di dalam kedua – dua ujian. Penyongsang berperingkat telah berjaya menghasilkan voltan output dua kali ganda daripada voltan pembekal, seperti mana ia patut berfungsi mengikut teori. Bentuk gelombang yang didapati adalah berbentuk tangga, 3 peringkat. Voltan pembekal adalah 10V yang mana ia akan memberi 20V keluar. Perbandingan arus keluar menunjukkan yang ujian tutup gelung dengan sistem kawalan memberi gelombang yang lebih bagus daripada ujian buka gelung.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

V	-	Voltage
A	-	Ampere
P	-	Power
Ω	-	Ohms
PWM	-	Pulse Width Modulation
ADC	-	Analog to Digital Converter
DAC	-	Digital to Analog Converter
P	-	Proportional
PI	-	Proportional Integral
PID	-	Proportional Integral Derivative
UTHM	-	University Tun Hussein Onn Malaysia

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

Grid instability, voltage outages and power quality are amongst the problems that appeared time to time as the needs for energy consumption is increasing. To balance this out, a way to generate power through renewable energy sources such as Photovoltaic (PV), biomass and wind are introduced. These method are said to be cleaner, environment – friendly and most importantly pollution free. Because of how most power generation system generates a Direct Current (DC) power, inverter is always used as an approach in converting said power to Alternating Current (AC). To create a stable system, it is always important that the power delivered is smooth, without as much loss as possible and with good efficiency. Because of this, design of better technology and control systems are always of a priority amongst power electrical engineering.

As the system of the grid is in three phase, three phase inverter is used in converting the power. The single stage inverter has advantage such as low cost, high efficiency, robust performance, high reliability and simple structure [1]. On the other hand, multilevel inverter are suitable for higher voltage application for their ability to synthesize waveforms with better harmonic spectrum. Multilevel inverter is created by cascading a number of single stage inverter. There is a few topology associated with this inverter such as cascaded inverter with different DC sources, Neutral Point Clamped (NPC) and Diode clamped multilevel inverter topology [2].

To control the inverter, control switching scheme is needed to turn ON and OFF the period of the inverter. Pulse Width Modulation (PWM) control is often used as the switching scheme. There are a lot of methods in generating PWM signal such as Sinusoidal Pulse Width Modulation (SPWM), Space Vector Pulse Width Modulation (SVPWM) and many more. PWM is important as selective parameters such as switching frequency, switching devices and duty cycle will gives out certain advantages and disadvantages.

Control strategies is one of the most important aspect in any grid connection or higher voltage application. This is because, with higher power, it is more open to harmonic distortion and instability of power delivery. Current control strategy should fulfill certain basic requirements, such as providing low harmonic distortion, high dynamic response, regulation of the dc-link voltage, and providing a bidirectional power flow.

1.2 PROBLEM STATEMENT

Power distribution from grid is important as it takes care of our everyday electricity usage and such, grid’s ability to produce and deliver quality electricity needs to be ensured. Problem such as low power quality, voltage sagging, non – constant voltage is always happening because of incompetent design of inverter, the one that is converting electricity from generator and supplying the grid. Inverter is normally used to control the power flow of the electricity, and problem inside of the inverter means the same for the distribution system. One of the problem is to make sure that the inverter will deliver a constant voltage output and for this, control method needs to be utilized fully. This is important to ensure stability. From the grid, distribution and load, the electricity will experience power lost. Inverter system needs to be able to inject amounts of current or voltage to mitigate the situation. The design of the inverter should be always in 1 – way operation in which the power will travel from the inverter to grid.

Inverter converts a DC source to AC source. While it is good at what it does, constructing for a higher voltage application inverter will attract numbers of problem such as power quality and switching losses. For this, concept of multilevel inverter is used in which it utilized a multiple small voltage level inverter for higher power conversion. Advantages in this is including good power factor, good electromagnetic compatibility and low switching losses.

Mainly, the problems that lies in the inverter to grid system revolves around the power flow, delivering of constant output voltage and electricity quality problems that will be harmful and wasting resources. Different inverter design and control strategy are often proposed to counter this situation. Electrical engineer are always struggling in getting the most out of the design of the system.

1.3 AIM AND OBJECTIVES

The aim of this project is to develop a working inverter that will be connected to grid and to develop a control method in which will assist the operation of the inverter. Issues like efficiency and stability will be analyzed. In order to achieve this aim and objectives are formulated as below:

i) To generate a PWM signal using Texas Instrumental (TI) board.
ii) To develop and create a three phase inverter.
iii) To develop and create a control method by using PI controller for the system.
iv) To analyze the output of the system.

1.4 SCOPES OF STUDY

Scope is important as it makes our objectives more specific in order for the project to be completed in time. Below are the scopes of the project:

i) PWM signal will be generated based on TI C2000 TMS320F28335 board.
ii) To build a multilevel inverter that is able to withstand based on a 1kW operation.
iii) To design a current control method by using MATLAB for the system.
iv) The inverter's power flow created is in one – direction operation that is from the inverter to the grid only.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter is a review of the PWM, inverter and control methods. This review is based on past thesis, journals, proceeding papers, books, and the internet. This information helps generate an idea and widen the scope.

2.2 POWER DISTRIBUTION GRID

Electric power is supplied through a system called power distribution grid which consists of generation, transmission and distribution systems. Electrical power is generated at a power plant, which consists of a large generator which uses coal, oil, natural gas, nuclear energy, wind or water as energy sources [3-4]. As of how electrical demand is growing over the years, a more friendly approach in generating electrical such as by using solar energy is researched more. The power created in generation is connected to the transmission system. Here at the transmission system, electric power is being stepped up to extremely high voltages for long distance transmission by using a large transformers. It is carried to the distribution system through wires over power tower which will includes protection system. At distribution system, power is being stepped down by using transformer so that it could be delivered to the consumers. Among the elements in distribution substation is that it has a bus to split distribution power in multiple directions. For protection and maintenance purpose, circuit breakers and switches are often installed so that the substation and the power flow can be disconnected or separated at any time. Figure 2.1 shows the power distribution grid system. Complexity of the whole distribution system contributes in what is known as loss. There are many type of losses in the distribution line such as the corona losses, leakage current losses, dielectric losses and many more. Among the factors that contribute to these losses is the length of distribution lines, sizing of conductors, low power factor and even transformer sizing and selection [5-6]. Efficiencies needs to be take care of properly in delivery of power electrical system so that stability can be ensured.

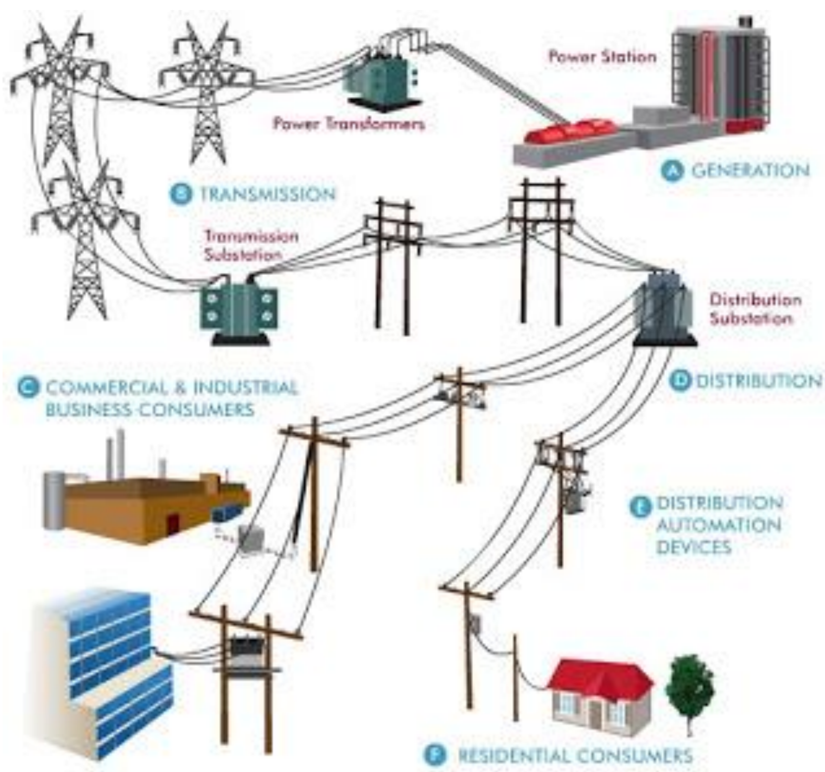


Figure 2.1: Power distribution grid [1].

2.2.1 Distributed Generation (DG)

Distributed Generation (DG) is an approach that use a small scale technology for power generation at the point of consumption. DG system allows customers to produce some or all the electricity that they needs. DG technologies usually consist of modular and renewable energy generators such as wind turbine, solar photovoltaic, gas turbine and many more. Generally, DG systems can produce power for the building in which the systems are connected to. By using renewable sources, it is able to provide power with minimal impact to the environment. There is several reasons as to use DG for example for standby or emergency means, increasing reliability, green power source (renewable) and many more. DG system allows the customers to generate their own electricity, rather than depending on the traditional power plant [29]. With this, the customers are able to compensate for load reduction on the grid through the net metering system. What DG offer is mainly in form of flexibility, in which a customer can have a choice of generating amount of electricity they needs and at time they choose.

Although that renewable energy can be very good to the environment, most renewable DG systems only produce power when their energy source (sun, wind) is available. Renewable sources, especially solar, has become a popular DG option. There are several challenges associated with DG system. First is that there are no national interconnection standards addressing safety, power quality and the overall reliability for small DG system. Interconnection of the DG may involve communication with several different organization, which will result in complexity.

2.2.2 Photovoltaic system

Photovoltaic also called solar cells, are electronic devices that convert sunlight directly into electricity. As of today, PV is one of the fastest growing renewable energy technologies and is expected to play a major role in the future global electricity generation mix. In order to use solar as a source, solar cells are together to form what is called PV module. The whole PV system will consists of batteries for electricity storage, the power converters and control components. Finally, the solar system includes products for example household appliances like radio or TV set that use solar as it source of operation [30]. Nowadays, there are a wide range of PV cell technologies on market, using a different types of materials and expected to be growing in the future. Benefit of using solar power is that it is a renewable resource, meaning that it is available everywhere in the world. Solar PV technologies are small in size and can be used almost anywhere, unlike others power generation technologies. In contrast with conventional power plants using coal, nuclear, oil and gas, solar PV will have no fuel costs which mean a relatively low operation cost and maintenance. Figure 2.2 shows the solar PV arrays.

Figure 2.2: Solar PV arrays [2].

2.2.3 Wind energy

Another alternative of renewable energy is by using wind. Wind energy is one of the most cost effective among all types of renewable energy. Like solar energy, it does not create pollution, brings harm to the environment and also did not used faster than what is produced. It is also the least expensive of the renewable energy sources and becoming more affordable as new technologies are being invented [27]. Aside that, remote areas that are not connected to the grid network, can take advantage of the wind turbine and produce their own supply. The goal of the conversion is to find the right combination of size, shape, materials and location that will produce the most electricity for the least cost [28].

The mechanism of the conversion is called wind turbine, which convert mechanical energy obtained from wind into usable electrical energy. For this, it requires work of physics alongside mechanical knowledge. Wind turbine main component is basically a very large fan, which captures the wind and produces electricity. The challenge lies in the design of wind turbine, because the fan is very large, it is often require complicated works. The fan usually have three blades and always have a horizontal axis shaft. Modern wind turbines range from about 40 – 80m in height, 50 – 85m in span and producing power of 850kW to 4.5MW. Disadvantages of the wind turbine includes of the inconsistency of the electricity produced that is because the strength of the wind is not constant and varies from time to time. Wind turbines also will produce some kind of noise and in manufacturing process of the generator, it does produce some kind of pollution. Figure 2.3 shows the typical wind turbine generator.

Figure 2.3: Wind turbine generator [3].

2.3 Power electronic converters

Power electronics refers to the electronics in which the control and the conversion of the electrical power are applied by using the semiconductor - based electronic switches. The power electronics works by supplying the voltages and currents depend on what suits the user loads. The range of power scale for power electronics goes from a few watts to several Megawatts (MW). Nowadays, power electronics field has been greatly developed in which results in various type of converters introduced. The challenges in power electronics now are regarding to the issues like distortion, losses, speed of response and efficiency. For that, different power level, switching devices and topology are often tested to improve the quality and utilization of electric power [7].

The four main forms conversion are classified as rectification, DC to AC conversion, DC to DC conversion and AC to AC conversion. Power converters refer to the power electronic circuit that is responsible for the conversions of voltage and current from one form to another. The type of characteristic that is shared between each power electronics circuits is that the switches are operated in either fully ON or fully OFF states. It is usually comprised of primary electronic elements like semiconductor devices, resistors, capacitors, inductors and transformers. Table 2.1 shows the difference between each power converters.

Table 2.1: Different types of power converter

NAME OF CONVERTER	CONVERSION FUNCTION
Rectifier	Converts AC voltage to a DC voltage
Inverter	Converts DC voltage to an AC voltage
Chopper	Converts a DC voltage to another level of DC voltage.
Cycloconverter	Converts an AC voltage to another level of AC voltage.

2.3.1 Inverter

Because of how electricity is always supplied in AC from the grid, many applications are designed to only accept AC voltages from the input. Inverter is basically a type of power converter that the primary function is to converts DC power to AC power at a desired output voltage or current and frequency. In the power industry, the term power inverter is used to avoid confusion between the digital electronics' inverter (used for a circuit that switches the logic level of a signal). The output voltage of an inverter has a periodic waveform that is not sinusoidal but can be made to closely approximate to the desired waveform. There are many types of inverter, which are classified according to number of phases, use of power semiconductor devices, commutation principles, and output waveform. The quality of the inverter is determined by the type of output waveform it produces [8]. The three types of output waveform is as follows:

i. Square wave
ii. Modified Sine wave
iii. Sine wave

Inverter that produces a square wave output is basically the one that are really cheap and simple. Figure 2.4 shows the square wave output of the inverter. A square wave inverter can only run simple things and is not really recommended. Unlike sine wave inverter, where the waveform goes smoothly from negative maximum to positive maximum, square wave inverter's output repeatedly produce a positive maximum for a half cycle and negative maximum for half cycle. The peak voltage of the square wave output is lower than the other types and causes problems with certain equipment, hence is not advisable to be use.

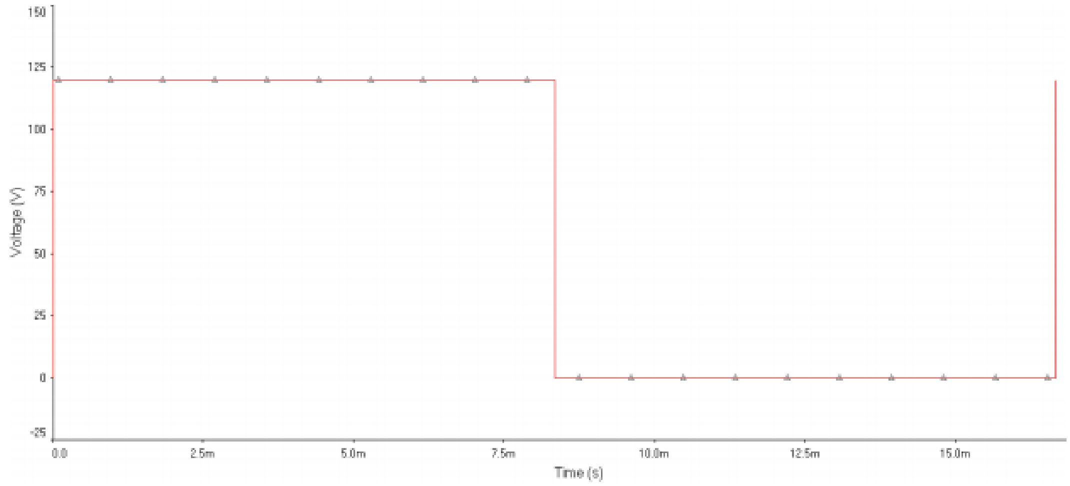


Figure 2.4: Square wave output [4].

The next type of the inverter is the modified sine wave inverter which is as shown in Figure 2.5. This is the most used inverters out there because it works fine on most equipment although that the efficiency is lower than sine wave inverter. Although the name is modified sine wave, the output wave looks more like a square wave except that it rests at zero volts for a while before switching back to maximum or minimum voltage. The purpose of that is to thin out the square wave so that the peak voltage is closer than that of a sine wave. Modified sine wave is used on lower to middle range of power supplies and the cost is cheap too.

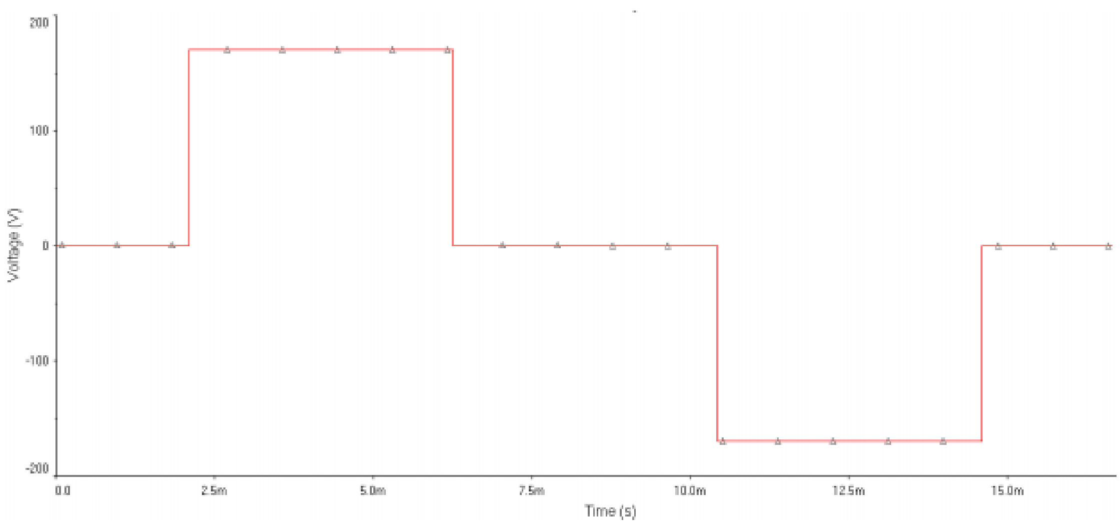


Figure 2.5: Modified sine wave output [5].

The best type of the inverter is the sine wave inverter. The output waveform shape is similar to the AC electrical signal from our wall socket. The biggest advantage for using this type of inverter is that the equipment is guaranteed to work to its full specifications. Some equipment like digital clock, light dimmers and battery chargers require a sine wave inverter to works. The output of the true sine wave inverter goes smoothly from negative minimum to positive maximum like a sine waveform. Sine wave inverter is the most expensive out of the three types in exchange for its best quality. Figure 2.6 shows the sine wave output of the inverter.

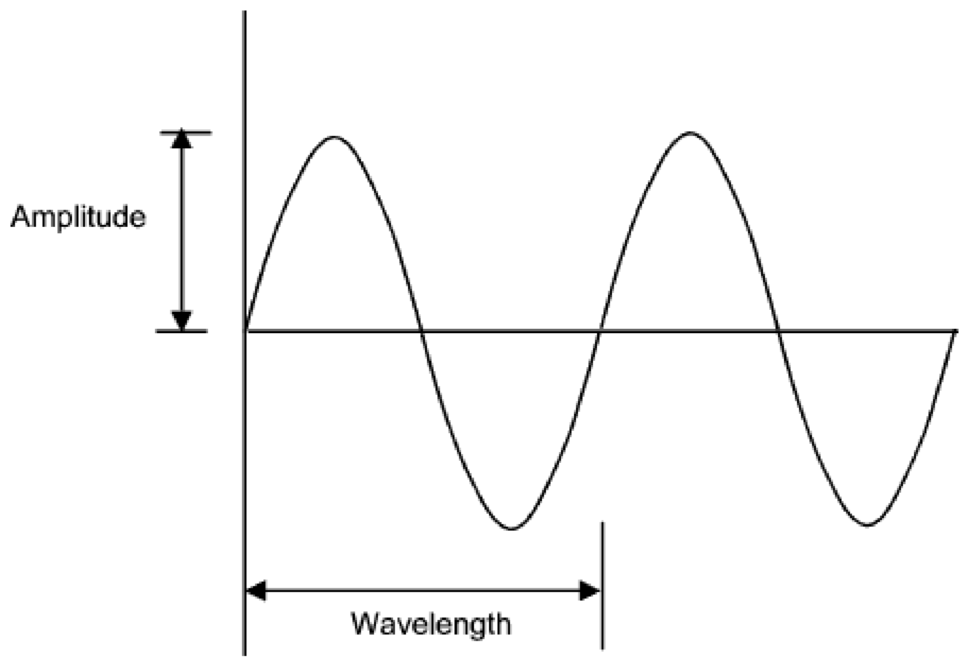


Figure 2.6: Sine wave output [6].

2.3.2 Three phase inverter

A three phase inverters are classified into Voltage Source Inverter (VSI) or Current Source Inverter (CSI) depending on the type of the supply source and the topology. The single phase inverter is used low – range power applications while the 3 phase inverter is used for high power applications. VSI design has been widely used as it has proven to be more efficient, more reliable, saves more cost and faster dynamic response. The main purpose of the VSI is to provide a three phase voltage source with the means to control the amplitude, phase, frequency and the voltages. The three phase inverter is mainly being used in motor drives, active filters, uninterrupted power supplies and much more. The DC input of the inverter is usually obtained from AC voltage that goes through a rectifier or from a battery source. The PWM technique can be applied in the three phase inverter, in which the modulation index value can be varied to control the voltage output value [9].

In theory, three phase equipment is far better than the single phase. One of the advantages is that three phase system reduces vibrations and other motor corruptions, which are made happen because it carries three wires that carry the same current which gives a constant balanced load and the power transfer is always constant. Another reason is because three phase power makes the equipment run much smoother, with better efficiency and cost effective. For this inverter, a pulse width modulator is used to feed the inverter which gives a steady output voltage. Figure 2.7 shows the three phase half bridge inverter which use 2 transistors to control the switching.

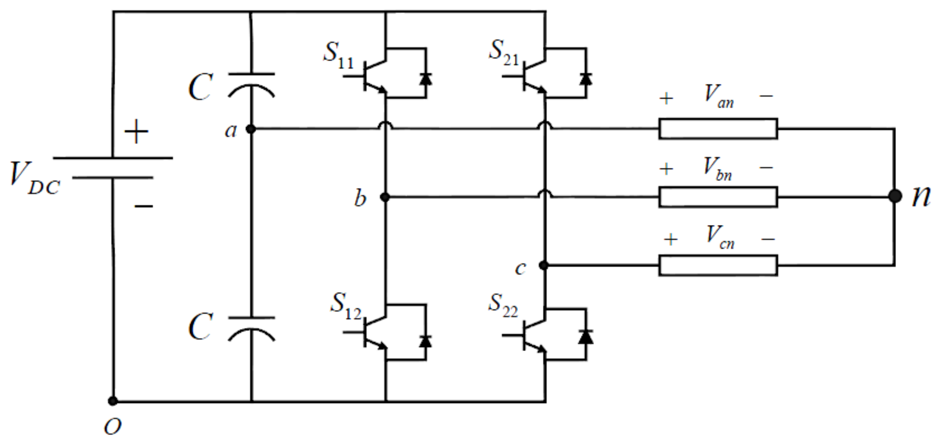


Figure 2.7: Three - phase half bridge inverter [7].

For three - phase full bridge inverter has eight switch states depends on which switch get turned ON. Figure 2.8 below shows the full bridge inverter. In order to satisfy the Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL), no switches in the same leg can be turned on, as it would violate the KVL. Table 2.2 shows all the switching states in the three - phase inverter. Equation 1 shows number of switches to be turned ON.

$$S_{11} + S_{12} = 1$$
$$S_{21} + S_{22} = 1$$
$$S_{31} + S_{32} = 1 \quad (2.1)$$

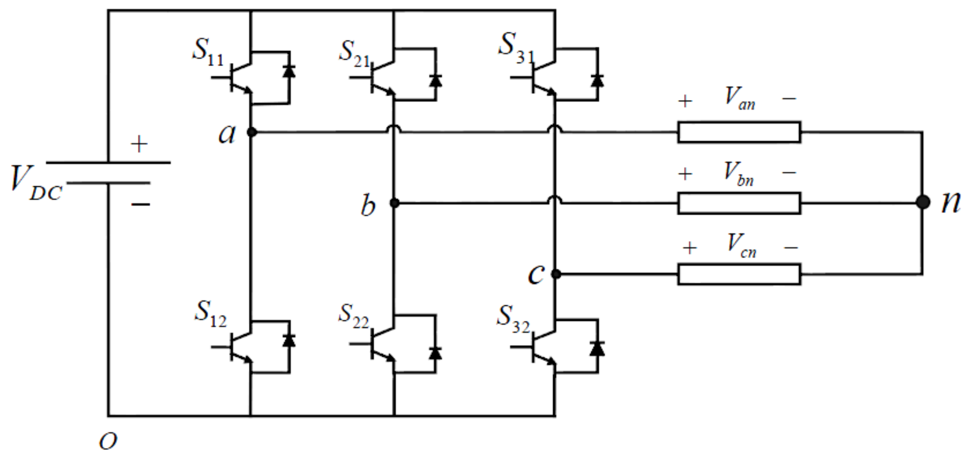


Figure 2.8: Three - phase full bridge inverter [8].

Table 2.2: Switching states.

S_{11}	S_{21}	S_{31}	V_{ab}	V_{bc}	V_{ca}
0	0	0	0	0	0
0	0	1	0	$-V_{DC}$	V_{DC}
0	1	0	$-V_{DC}$	V_{DC}	0
0	1	1	$- V_{DC}$	0	$- V_{DC}$
1	0	0	V_{DC}	0	$- V_{DC}$
1	0	1	V_{DC}	$- V_{DC}$	0
1	1	0	0	V_{DC}	$- V_{DC}$
1	1	1	0	0	0

Based on table 2.2, two of the state produces zero AC line voltage at the output in which the AC line currents freewheel through the upper or lower components. The inverter needs to switch state from one another to generate the output voltage, which consists of discrete values of voltage, which are - V_{DC}, 0 and V_{DC}.

2.3.3 Multilevel Inverter

As of how industrial application keeps demanding for a medium and high power supply, multilevel power converter structure has been introduced. It has been introduced since 1974 [10]. General idea of multilevel is to use a series of power semiconductor switches with several lower voltage DC sources to perform the power conversion by synthesizing a staircase voltage waveform [11]. It began with the three – level converter and since then, several topologies have been developed [17]. Among the widely used topology is cascaded H – bridge inverter with separate dc sources, diode clamped and flying capacitors. Sources of this inverter can be either capacitors, batteries or renewable energy voltage sources. Advantages of multilevel inverter including a staircase waveform quality, in which low distortion has been proven and can also draw low distortion input current. It also can operate at both fundamental frequency and a high switching frequency of PWM. This will benefit in lower switching losses and higher efficiency. Multilevel converter also is having advantages in reducing the dv/dt stresses on semiconductor devices and reducing electromagnetic (EMC) concern [8-12].

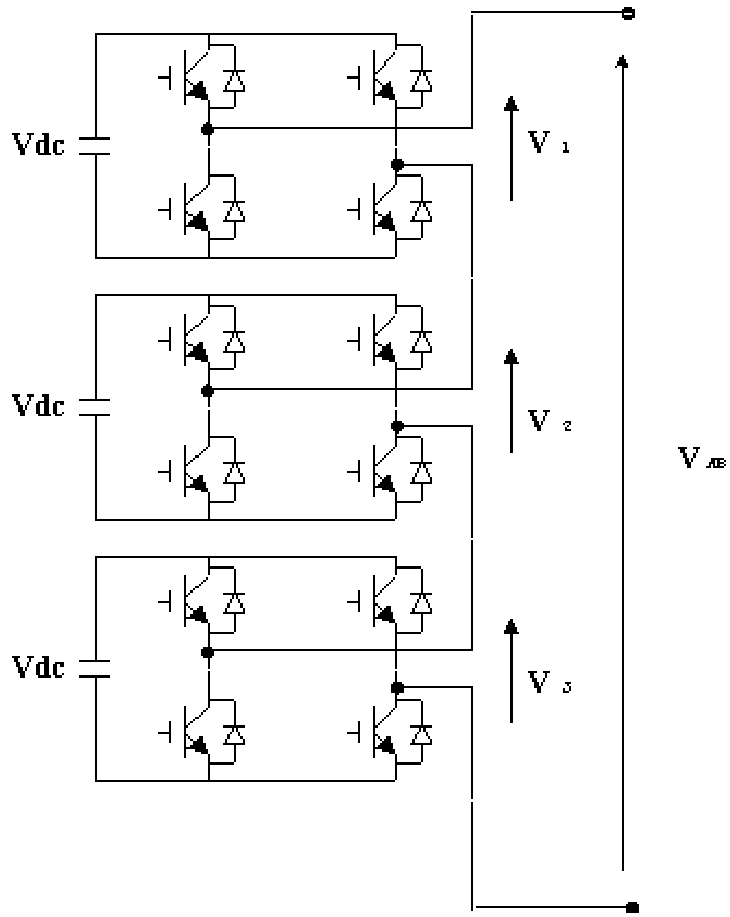


Figure 2.9: Single – phase structure of multilevel cascaded H – bridges inverter [9].

Figure 2.9 shows a single – phase structure of multilevel cascaded H – bridges inverter. It is connected with a separate DC source (SDCS). Different combination of the four switches, S_1, S_2, S_3 and S_4 will yield different AC output ($+V_{dc}$, 0 and $-V_{dc}$). The AC outputs from each of the full bridge inverter are connected in series so that the output voltage of the system is equal to the summation of each inverter outputs.

2.4 Pulse Width Modulation (PWM)

Pulse width modulation (PWM) is basically a powerful way to control the analog circuits and systems in a digital way. PWM applies a pulse train of fixed amplitude and frequency, only the width is varied proportion to an input voltage. PWM is applied almost everywhere, ranging from measurement device and communications, but the most popular one would be to control the voltage delivered to the load. In power electrical fields, the challenge to find the best, efficient, lower cost power delivery system is always on the go. By the implementation of PWM, the steady output load is gained, depending on our input, or the value in between the maximum or minimum value (0v). For example, for a system being supplied with a 12v, the output voltage is exactly like the input, that is 12v, or variable to the in between value (0 – 12v) by altering the duty cycle. Duty cycle, in simpler words, tells u the ratio when the time is on comparing when the time is off. In order to get maximum constant load, the duty cycle needs to be set to 100%. By this, the efficiency is not of a problem [8]. Figure 2.10 shows how duty cycle works. Another great advantage by using a PWM is cost. For PWM controllers, only a small potentiometer is needed to control a certain variable where in resistive controllers, expensive, high power variable resistors are needed.

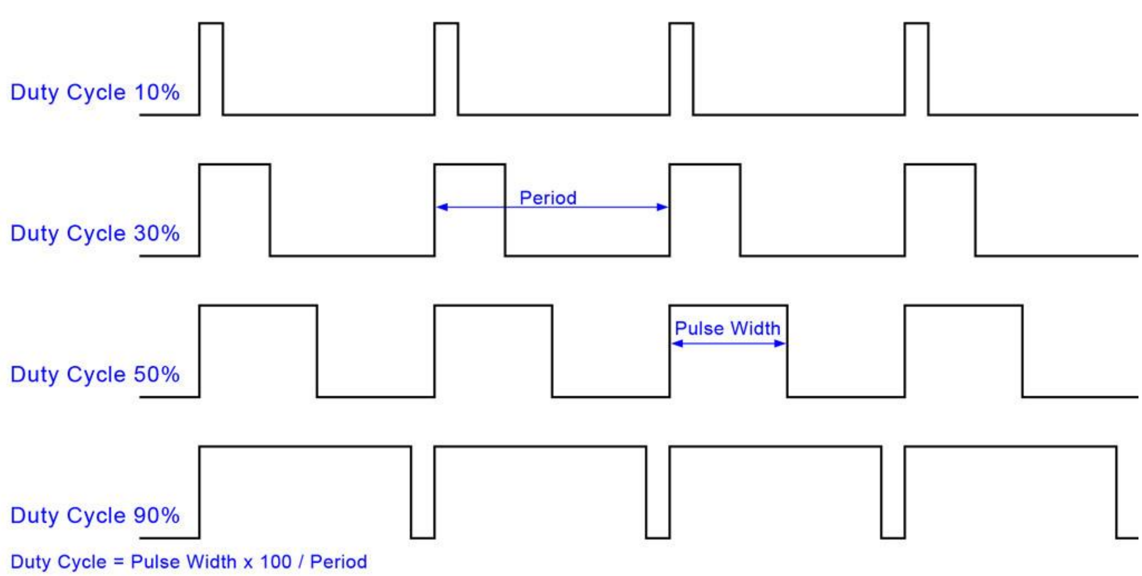
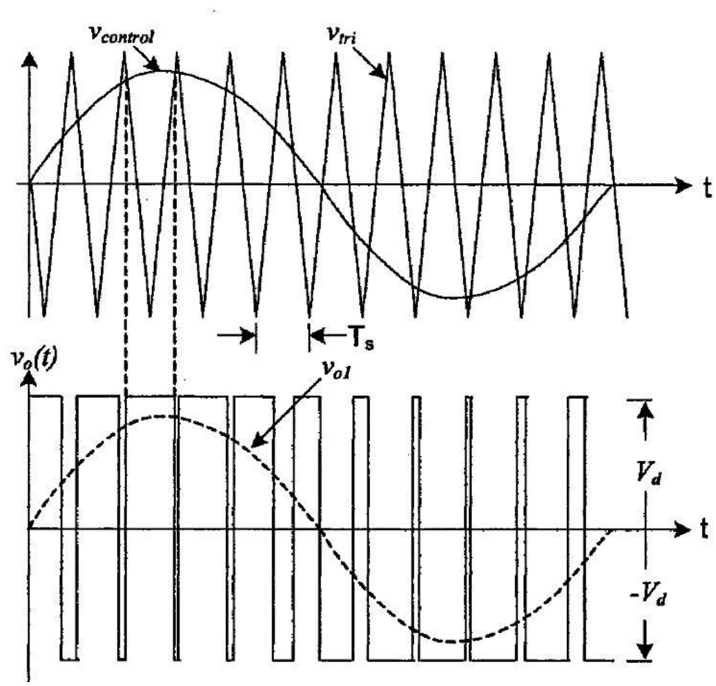


Figure 2.10: Duty cycle waveform at 10%, 30%, 50% and 90% [10].

2.4.1 Sinusoidal Pulse Width Modulation (SPWM)

SPWM is one of method in generating PWM signal. It is generated by comparing a desired reference waveform with a high frequency triangular carrier wave (several kHz) as shown in Figure 2.11. SPWM techniques are characterized by constant amplitude pulses with different duty cycles for each period. The width of the pulse depends on the intersection between the carrier frequency and the reference frequency [18]. The width of these pulses are modulated to obtain inverter output voltage control and to reduce its harmonic content. The comparator gives out a pulse when sine voltage is greater than the triangular voltage and this pulse is used to trigger the respective inverter switches.



[]

Figure 2.11: SPWM output [11].

2.5 Control system

Control system is used in any system when there is some physical quantity that needs to be controlled in a way that the ensured quantity takes on the value that is specified. Basically, it is as a way to implement any scheme that is to be devised. Basic type controller is called the feedback controller. In this type of controller, the variable required to be controlled is measured and is then given a set point. The controller will takes this error and decides what action should be taken by manipulating variable to compensate for the error and hence removing it. Advantage of this controller is that it is simple to implement as it requires no knowledge of the source, the nature of disturbance and require minimal information about the process involved. Control method is an important properties in any inverter system as it provides a mean to control parameters like locking frequency, injecting current, voltage stabilizer and much more. It usually involves in creating a feedback system. Current control techniques can be divided into two main groups that is linear and nonlinear techniques. Among the famous linear current control techniques are Proportional (P), Proportional Integral (PI), Proportional Integral (PID), Proportional Resonant (PR) and Repetitive Controller (RC). Example for nonlinear controller is dead beat and hysteresis [19]. Figure 2.12 shows the typical control system.

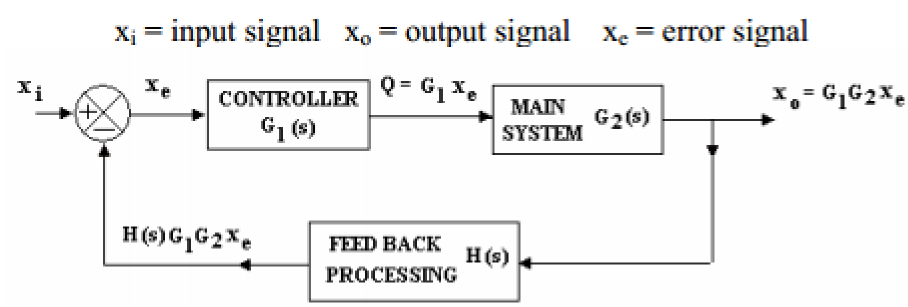


Figure 2.12: Typical control system block [12].

2.5.1 Proportional controller

As the name implies, this controller use proportional behavior as it main mode. Generally, this controller sets the manipulated variable in proportion to the difference between the setpoint and the measured variable [20]. P controller cannot stabilize higher order processes. By changing the controller gain, K, the closed loop dynamics can be changed. The output of this controller is the multiplication product of the error signal and proportional gain and can be expressed as:

$$P_{out} = K_p e(t) + p0 \qquad (2.2)$$

Where the symbols are defined as follows:

P_{out}: Output of the proportional controller

p0: Controller output with zero error

K_p: Proportional gain

e(t): Instantaneous process error at time t.

A large controller gain will result in having a control system with a smaller steady state error, faster dynamics and also smaller amplitude and phase margin. When this controller is used, large gain is needed to improve the steady state error. It is advisable to only use this controller when a system can accept a constant steady state error [21]. Disadvantage of this implementing this type of controller only will result in an offset in the output in which there is always a difference between the setpoint and the actual output. Figure 2.13 shows the block diagram of the P controller and the effect of changing the gain for the output.

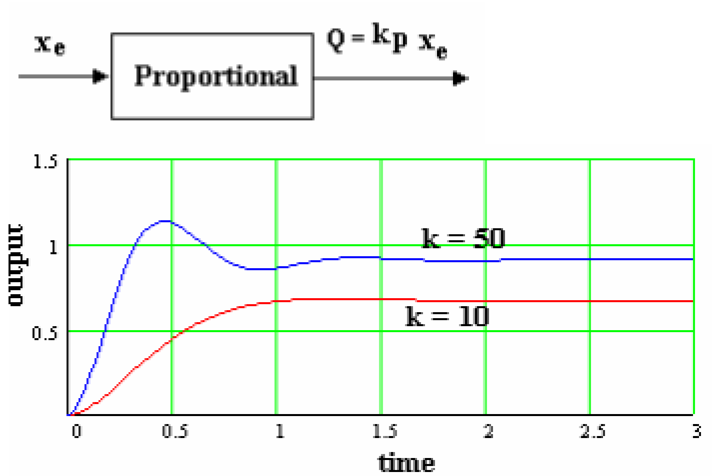


Figure 2.13: P controller block diagram and effect of changing gain [13].

2.5.2 Proportional Integral controller

Proportional (P) controllers are used before but it has an inherent steady – state error [22]. The P controller's steady state error was eliminated by adding integral component to the transfer function [19], which forms a PI controller. This controller eliminate steady state error and forced oscillations but it introduce negative effect on speed of the response and overall stability of the system,PI controller's applications are mostly in dq control and can also be used in abc frame as well [19]. In the controller, current errors can appear in transient condition and transient response is limited by the proportional gain. PI controller is used when a fast response of the system is not required, large disturbance and noise are present in system, there is only one energy storage in process and a large transport delays in the system. Equation 2.3 shows the integral term given by:

$$I_{out} = K_i \int_0^t e(\tau)d\tau \qquad (2.3)$$

K_p and K_i are proportional and the integral gain of the PI controller. For this, the controlled current must be in phase with the grid voltage. Average Current Mode Control (ACMC) was introduced to solve the problem regarding the transient response. By this, steady state error can be removed and fast transient response is achieved. Figure 2.14 shows the block diagram of the integral control and the graph on how the error is reduced with time.

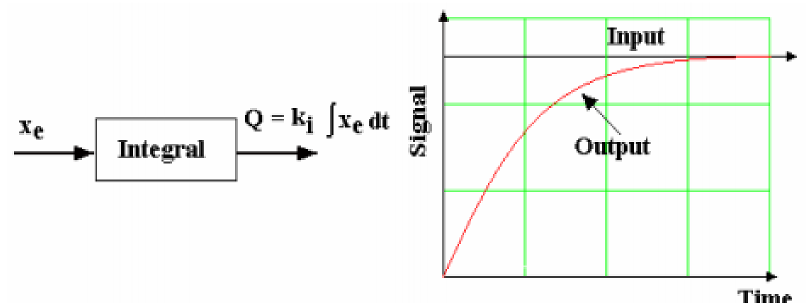


Figure 2.14: Integral control block diagram and the state of the system graph [14].

2.5.3 Proportional Integral Derivative controller

PID controller has all the necessary components or behavior that will allow it to have a fast reaction on changes of the controller input (from derivative behavior), increasing control signal to lead error towards zero (integral behavior) and suitable action inside control area to eliminate oscillations (proportional behavior). Derivative term is given by:

$$D_{out} = K_d \frac{d}{dt} e(t)$$

(2.4)

Derivative component eliminate the stability issue as in integral mode and enable increment in gain K and decrement in integral time constant Ti in which will improves the speed of the controller's response [23,20]. PID controller is used when dealing with a higher order processes and also when stability and precise controls are required. Example of the application is the autopilot system. Figure 2.15 shows the block diagram of the differential component.

REFERENCES

[1] Aarti Gupta, Preeti Garg "Grid Integrated Solar Photovoltaic System Using Multi Level Inverter". Electronics and Instrumation Engineering, International Journal of Advanced Research in Electrical, Volume 2, Issue 8, August 2013.

[2] P. Thirumuraugan, Preethi R. "Closed Loop Control of Multilevel Inverter Using SVPWM for Grid Connected". Electronics and Instrumation Engineering, International Journal of Advanced Research in Electrical, Volume 2, Issue 4, August 2013.

[3] M.A. Mueller, "Electrical generators for direct drive wave energy conversion" in Proc. Inst. Elect. Eng. Gen. Transm. Distr, vol.149, 2002, pp.446-456.

[4] Ackermann, T., Andersson, G. and Soder, L., Overview of Government and Market Driven Programs for the Promotion of Renewable Power Generation, Renewable Energy Vol. 22, 197-2004 (2001).

[5] Beaumont, "Losses in Transformer and Reactors," Session, Cigre 12-10, 1988.

[6] P.S.N Rao, R. Deekshit, "Energy Loss Estimation in Distribution Feeders," IEEE Transactions on Power Delivery, Vol. 21, No. 3, pp. 1092-1100, July 2006.

[7] Kassakian, J.G., Schlecht, M.F., and Verghese, G.C." Principles of power electronics". Addison Wesley, 1991.

[8] Ned Mohan, Tore M. Undeland and William P. Robbins. “Power Electronics-Converters, Applications and Design” 3rd. ed. John Wiley & Sons, Inc, New York.(2003).

[9] Agrawal, J. P. “Power Electronic Systems: Theory and Design”. Upper Saddle River, NJ, Prentice Hall, 2001.

[10] R. H. Baker and L. H. Bannister, “Electric Power Converter,” U.S. Patent 3 867 643, Feb. 1975.

[11] Surin Khomfoi, Leon M. Toolbert, “Multilevel Power Converters” The Universiti of Tennessee, Chapter 31..

[12] Rodriguez, J.; Jih-Sheng Lai; Fang Zheng Peng; “Multilevel Inverters: a Survey of Topologies, Controls, and Applications”, Industrial Electronics, IEEE Transactions on, Volume: 49, Issue: 4, Aug. 2002.

[13] Rodriguez, J.; Bernet, S.; Steimer, P. K.; Lizama, I. E.; “A Survey on Neutral-Point-Clamped Inverters”, Industrial Electronics, IEEE Transactions on, Volume: 57, Issue: 7, July 2010.

[14] Das, A.; Sivakumar, K.; Ramchand, R.; Patel, C.; Gopakumar, K.; “A Pulsewidth Modulated Control of Induction Motor Drive Using Multilevel 12-Sided Polygonal Voltage Space Vectors”, Industrial Electronics, IEEE Transactions on, Volume: 56 , Issue: 7, July 2009.

[15] Rojas, R.; Ohnishi, T.; Suzuki, T.; “Neutral-Point-Clamped Inverter with Improved Voltage Waveform and Control Range”, Industrial Electronics, IEEE Transactions on, Volume: 42, Issue: 6, Dec. 1995.

[16] Pou, J.; Zaragoza, J.; Rodriguez, P.; Ceballos, S.; Sala, V.M.; Burgos, R.P.; Boroyevich, D.; “Fast-Processing Modulation Strategy for the Neutral-Point-Clamped Converter With Total Elimination of Low-Frequency Voltage Oscillations in the Neutral Point”, Industrial Electron

[17] A. Nabae, I. Takahashi, and H. Akagi, “A New Neutral-point Clamped PWM inverter,” IEEE Trans. Ind. Applicat., vol. IA-17, pp. 518-523, Sept./Oct. 1981.

[18] Afarulrazi Abu Bakar, Md Zarafi Ahmad and Farah Salwani Abdullah. “Design of FPGA Based SPWM Single Phase Inverter”. Malaysian Technical Universities Conference on Engineering and Technology MUCEET2009, June 20-22, 2009, MS, Garden, Kuantan, Pahang, Malaysia.

[19] Mojgan Hojabri, Abu Zaharin Ahmad, Arash Toudeshki and Mohammadsoroush Soheilirad. “An Overview on Current Control Techniques for Grid Connected Renewable Energy Systems” Faculti of Electrical and Electronic Engineering, University Malaysia Pahang (UMP), 26600 Pekan, Malaysia, Department of Electrical and Electronic Engineering, University Putra Malaysia (UPM), 43300 Serdang, Malaysia.

[20] David Sellers, “An Overview of Proportional plus Integral plus Derivative Control and Suggestions for Its Successful Application and Implementation” Senior Engineer, Portland Energy Conservation Inc, Portland, Oregon.

[21] Kemal ARI, Faik Tekin ASAL, Mert COSGUN, “PI, PD, PID CONTROLLERS” Middle East Technical University, Electrical & Electronics Engineering.

[22] Grandpicrre et al. “Study of an autopiloted inverter current fed synchronous machine used for a robotic axis.” International Conference on Electrical Machines. Munchen. 1996. p. 532–5.

[23] Karl Johan Astrom, “PID Control”, Control System Design, 2002.

[24] G. Kolumb´an, “Phase-Locked Loops” Article in The Encyclopedia of RF and Microwave Engineering, K. Chang, (Ed.), vol. 4, pp. 3735–3767, Wiley, New York, 2005.

[25] John L. Stensby, “Phase-Locked Loops, Theory and Applications”.

[26] Analog Devices, “Fundamentals of Phase Locked Loops (PLLs)”, MT – 086 Tutorial.

[27] Paula Berinstein, “Alternative Energy: Fact, Statistics, and Issues”, Oryx Press, Westpot, CT, 2001.

[28] Godfrey Boyle, “Renewable Energy: Power for a Sustainable Future”, Oxford University Press, Oxford, 1996.

[29] M. Liserre, T. Sauter, J.Y. Hung, “Future energy systems: integrating renewable energy sources into the smart power grid through industrial electronics,” *IEEE Industrial Electronics Magazine*, vol.4, no. 1, pp. 18-37, Mar. 2010.

[30] F. Kininger, “Photovoltaic systems technology”. Kassel, Germany: Universität Kassel, Institut für Rationelle Energiewandlung, 2003. Available at: www.uni-kassel.de/re.