DEVELOPMENT OF SYNCHRONVERTER CONTROL FOR INDUCTION MOTOR CONNECTION

ZAKRIA AHMED S. BAHRON

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

JUNE 2014

ABSTRACT

More and more attention has been paid to the energy crisis due to the increasing energy demand from industrial and commercial applications. The utilization of renewable energy considered as one of the most promising electrical energy sources, which has grown rapidly in the last three decades. In this day and age, many power converter techniques have been developed to integrate renewable energy with the electrical grid. In this work, there is a new technical control is known as synchronverter control which is using the synchronous generator mathematical equations as a reference. This synchronverter control is connected with DC-AC three phase inverter to work as controller of output power to feed the load. In this control strategy, the output current of the controllable inverter is controlled by a feedback load current according to the current reference. The synchronverter technology has been applied to control the inverter for the induction motor connection. An experimental setup based on DSP (Digital Signal Processing) and dc drive board have been designed to implement the open and closed loop experiments. All experiments have been implemented on a test rig based on Matlab 20013a/simulink software and Code Composer Studio V6.0 to demonstrate the excellent performance of the proposed control strategies with stability of the system, sinusoidal currents and good dynamics. Finally, an improve control strategy based on the synchronverter control technology has been tested for three phase inverter for renewable energy applications to make the whole system behave as a synchronous generator.

CONTENTES

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

AC	-	Alternative current
A	-	Area swap
ADC	-	Analag digital converter
BJT	-	Bipolar junction transistor
C	-	Capacitor
Dp	-	Damp coefficient
DSP	-	Digital signal processing
DC	-	Direct current
EMF	-	Electrical magnetic field
F_0	-	Frequency
f_c	-	Cut off filter
F	-	Farad
hrs	-	Hours
IGBT	-	Insulated gate bipolar transistor
IM	-	Induction motor
i_f	-	Current field
L	-	Self-inductance
L	-	inductor
M	-	Mutual inductance
mf	-	Mutual field
MPPT	-	Maximum power point taking

MOSFET - Metal-on-semiconductor field-effect
PID - Proportional integral derivative
PWM - Pulse width modulation
PMSM - Permanent magnet synchronous motor
P - Power generated
Q - Reactive power
R - Resistor
V - Voltage
VSC - Voltage source converter
VSI - Voltage source inverter
VC - Vector control
v - Rotor speed
VISMA - Virtual synchronous machine
W - Watt
λ - Speed ratio
Ω - Ohm
µH - Micro farad
θ - Virtual angle
$\dot{\theta}$ - Virtual angle speed

LIST OF APPENDICES

CHAPTER 1

1.1 Introduction

There has been a sharp increase in the use of voltage source dc/ac converters connected to the power networks for renewable energy systems such as wind turbines, hydraulic generators, biomass and geothermal generators, photovoltaic systems, fuel cells, storage devices, and power quality improvement units (flexible AC transmission systems (FACTS), active power filter (APF), voltage source converter (VSC) transmission) [1-3].

DC-AC converters is knows as inverter. An inverter is an electrical device that converts direct current (DC) to alternating current (AC), and this alternated power can be maintained in any frequency or voltage with the use of appropriate transformers, circuits and switches to supply the grid or load with power.

Inverters are the devices used to interface renewable energy sources to the utility grid, most of renewable energy sources are connected to the utility grid through a three-phase voltage source inverter (VSI). For efficient connection, the three-phase voltage source inverter is controlled through a grid-side controller dedicated to meeting the power demands of the grid and controlling the quality of the injected current [1, 4].

Although the basic circuit for an inverter may seem simple, accurately switching these devices provides a number of challenges for the power electronic engineer. The most common switching technique is called Pulse Width Modulation (PWM). PWM is a powerful technique for controlling analog circuits with a processor’s digital outputs. PWM is employed in a wide variety of applications, ranging from measurement and communications to power control and conversion. The PWM inverters make it possible to control both frequency and magnitude of the voltage and current applied to system.

This three-phase inverter system for renewable energy sources are operated as stand-alone- or grid-connected mode. For the stand-alone mode operation, it keeps the voltage and frequency constant, but it is difficult to regulate the voltage and frequency constantly due to the continuous change of load. Therefore, it has been strongly recommended to design the inverter controller with fast and stable response. Renewable energy sources their control system is traditionally based on current vector control (VC) and pulse width modulation (PWM). The vector control decouples the converter current into active and reactive power components, which are then regulated separately by current controllers. The performance of such a vector-controlled dc/ac converter largely depends on the accuracy of the current decoupling, the design of the current controllers, and the tuning of their parameters. Recently, current control based on predictive methods has been proposed, which provides direct regulation of the current using the converter voltage [5-7].

The control techniques that are commonly used in grid connected converter systems could be classified as direct or indirect control strategies. The indirect control is characterized by a modulator (pulse width modulation (PWM) that computes the turn-on/turn-off times of a converter’s switches along a switching period through the evaluation of the voltage reference. This voltage reference is issued by the controller, which idealizes the converter as a dependent continuous voltage source. On the other hand, direct control techniques establish a direct relation between the behaviour of the controlled variable and the state of the converter’s switches [8].

Generally, the inverter controller has a double loop controller with an outer voltage controller and an inner current controller. Those are designed basically by using synchronverter controller, and it can be implemented using the virtual angular speed comparing with the angular frequency reference.

However, the more controllers are added the higher the system order and it makes the controller design difficult and complex. Additionally, a high order system is very weak to the noise, therefore, it is necessary to choose a controller to be low order as well as fast time response.

Nevertheless, indirect control strategies generally lead to good transient behavior and acceptable steady-state operation; they operate at a constant-switching frequency, which makes the use of advanced modulation techniques possible. Thus, it becomes easier to optimize conversion power losses or simplify the line side filter design.

1.2 Problem Statement

The demand for electricity for commercial, industrial and domestic loads in rural, semi-urban and urban areas has grown tremendously over the years. The increase of energy consumption increases the demand on renewable energy, and more grid-connected systems are used. However, it is an important to design three phase dc/ac grid inverter to back up this grid with power.

The main point in this project is to design a three phase inverter which operates as a current source to feed the induction motor load with current. This is required to develop a synchronverter feedback current controller to dominate of this load current. However, it is a significant major to design a control system to integrate into the existing system and behave in the same way as synchronous generators.

All expected obstacles should overcome by depth in searching and by using different control system ways to develop simulation model of controlled three phase grid inverter, also implement three phase hardware inverter circuit with DSP board to obtain output current to supply induction motor connected load.

1.3 Project objectives

The significant objectives of this project are:

i. To design the three phase inverter and inverter circuit driver model.
ii. To interface the MATLAB Simulink and the TMS320F28335 microcontroller to generate PWM signal.
iii. To control the current that supply from three phase inverter into the load.
iv. To improve the existing synchroconverter model controller by using MATLAB Simulink.

1.4 Scope of project

This project is primarily concerned with development of synchronverter control for three phase inverter. The scope of this project is divided into two parts which can be hardware and software Simulink as follows:

i. The synchronverter control using synchronous generator equation will be designed in the MATLAB.
ii. The connection between the inverter and the load must be established using MATLAB Simulink.
iii. Design and build an electric circuit for three phase DC/AC inverter induction motor connection.
iv. Understanding the concept of synchronverter controller that uses for close loop control.

CHAPTER 2

2.1 Switching Technologies

Historically, inverters have been made with every kind of switching apparatus such as rotating or vibrating mechanical contacts, gas-filled electronic valves and thyristors (SCRs). However, in contemporary use the field is led by two special kinds of transistor.

The first kind is the Metal-On-Semiconductor Field-Effect Transistor (MOSFET); this device has a very rapid switching action and can be designed with a low resistance so that it will pass high currents efficiently. MOSFETs designed to withstand high voltages have a much higher ‘ON’ state resistance making them less efficient, whatever the voltage rating, MOSFETs are electrically robust and difficult to destroy by excessive voltage or current.

Complementing the MOSFET is the Insulated Gate Bipolar Transistor (IGBT) when designed for high ‘OFF’ state voltages, this outperforms MOSFETs although the MOSFET is still best at lower voltages, IGBTs switch rather slower than MOSFETs and are not quite as resistant to damage by overloads.

Given these advantages and disadvantages, the actual device chosen will depend on what sort of inverter circuit is chosen. This determines the voltages and currents imposed on the devices and on what control algorithm is chosen. This determines the speed at which switching must be performed [9].

2. 2 Type of Inverter

Inverter can divide into two are which current source inverter and voltage source inverter. Voltage source inverter produces square wave output and the output depends on source as is illustrated in Figure 2.1, output frequency depends on frequency output voltage square wave. Advantage of this inverter is the circuit is simple and capable whereas disadvantage is high harmonic factor.

For current source inverter the output can control by using PWM technique, this inverter capable to reduce harmonic factor and not needed filter but the circuit is complex and expensive, the circuit diagram of the current source inverter is illustrated as in Figure 2.2.

A power MOSFET is a voltage controlled device and requires only a small input current, the switching speed is very high and the switching times are in the order of nanoseconds. Power MOSFET finds increasing applications in the low-power frequency converters. MOSFET does not have the problem of second breakdown phenomenon as do Bipolar Janction Transistor (BJTs). Second breakdown phenomenon is a destructive phenomenon, results from the current now to a small portion of the base, producing localized hot spots other than that Power MOSFET are low switching loss and simple gate drive circuit [10].

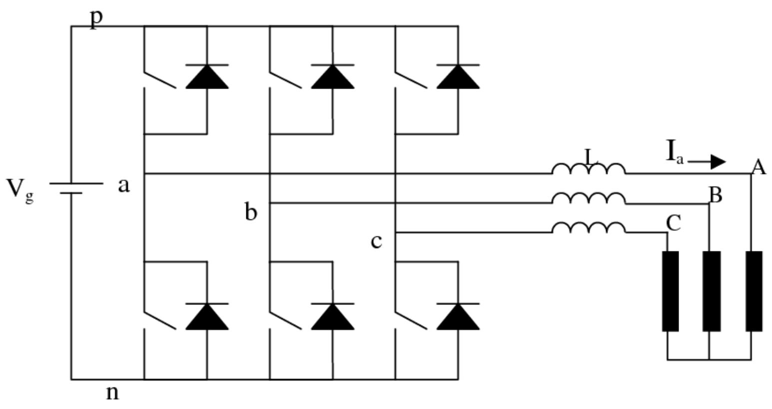

Figure 2.1: Circuit diagram of voltage source inverter.

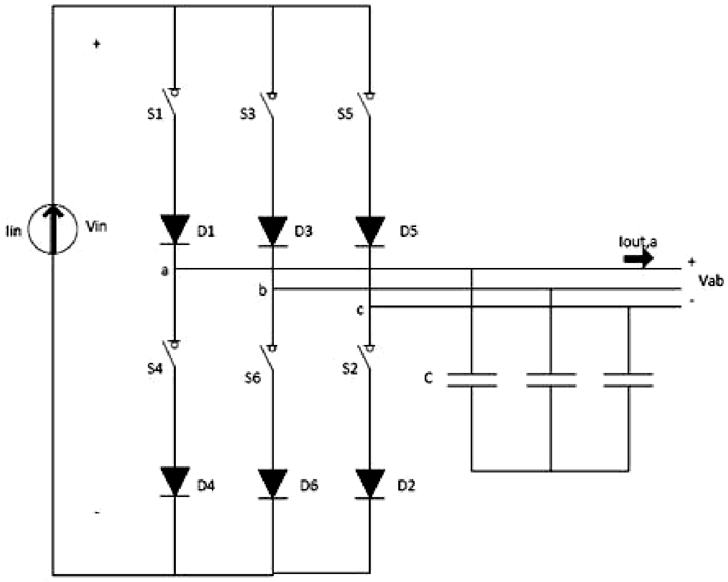

Figure 2.2: Circuit diagram of Current Source Inverter.

2.3 History of Control System

Control systems are older than humanity, numerous biological control systems were built into the earliest inhabitants of the planet. Knowledge of the control system of the Hellenic period was preserved within the Islamic culture that was rediscovered in the west toward the end of the renaissance, new invention and application of hold principles began to appear during 18th century [11].

Speed control has been introduced since 17th century, James Watt (1736-1819) was invented the fly ball speed governor to control the speed of rotary engine governor, he was provided proportional speed control and hence exact control of speed at only one operating condition, it also can operate only over a small speed range. In 1745 Edmund Lee was control the speed of windmill; he was increasing wind pitched blades further back, so that less area was available. As the wind increased, more blades were available; William Siemens (1823-1883) substituted integral action for proportional action and hence produced controllers with no fix point. The early years of the 20th century saw the rapid and widespread application of feedback control for voltage, current and frequency regulation such as motor speed and position control, temperature, pressure and flow in process industry.

Elmer Sperry (1911) developed the automatic ship steering mechanism that incorporated PID controller and gain adjustment to compensate for the disturbances caused when the sea condition changed. In 1922 Nicholas Minorsky presents a clear analysis of the control involve in position control system and formulated a control law that we now refer to as three-term or PID controller [12].

2.4 Wind Turbine

Energy shortage and environment pollution are the important problems for the human lives and social development. Traditional mineral energy such as coal, oil and gas will be used out in a few years and will cause serious environmental problems. So the renewable energy, especially wind energy and solar energy have become more and more considerable all over the world. In the wind energy conversion system, the wind turbine captures the wind energy. Then the generator converts it to the electrical power. So the characteristic of the wind turbine is very important. Because the wind turbine is big and expensive, it is not convenient to do the research in the practical wind farm. To develop a wind turbine simulator which can simulate the real wind turbine in the steady state and dynamic state is very meaningful for laboratory research. It can improve research effectiveness and efficiency [13].

A few research works about wind turbine simulator have been done in the past few years, presented a wind turbine simulator based on a DC machine. The armature and the field current were controlled so that the DC machine can generate the static characteristics of a wind turbine [14], presented a wind turbine based on SCR-DC motor controlled by a microcomputer. But the DC machine is big, expensive and it need to frequent maintenance because of brushes compared with an AC machine. Presented an IGBT inverter-controlled squirrel cage induction motor (IM) instead of a dc motor. Wind turbine simulator based on the permanent magnet synchronous motor (PMSM) has some advantages such as high power density, small size, high precision and easy to control.

The typical structure of variable-speed wind energy conversion system is shown in Figure 2.3. The system comprises wind turbine, generator, rectifier, inverter and LC filter. In this system, the wind turbine captures the wind energy and the generator converts it to the electrical power. Then the power electronics equipment converts it to the high quality power and controls the rotor speed of the generator, the inputs and output variables of wind turbine can be broken into the following:

1. The independent input quantity wind speed, determines the energy input to the wind turbine.
2. Machine-specific input quantities, arising particularly from rotor geometry and arrangement (i.e., different configurations like horizontal axis or vertical axis turbines, area of the blades, etc.).
3. Turbine speed, rotor blade tilt, and rotor blade pitch angle, arising from the transmission system of the wind energy conversion system.
4. Turbine output quantities, namely Power or Drive torque, which may be controlled by varying the above three input quantities, the aerodynamic model of wind turbine is given by [15]:

$$P = \frac{1}{2}\rho A C_p(\lambda) v^3 \tag{2.1}$$

Where P is the power generated by the wind turbine, ρ is air density, A is the area swept and λ is tip speed ratio, where v is wind turbine rotor speed in revolutions per minute(r/min).

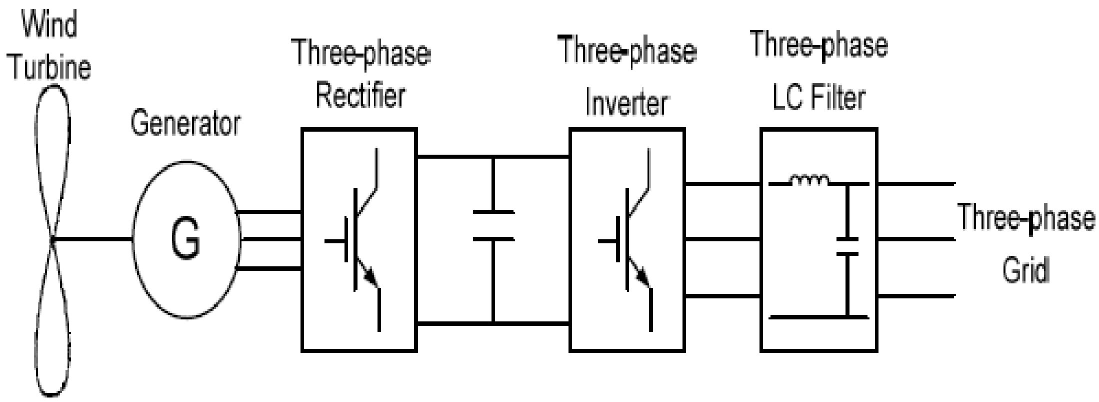

Figure 2.3: The structure of variable-speed wind energy conversion system.

Renewable energy plays an important role in the supply of energy, when renewable energy sources are used; the demand for fossil fuels is reduced. Unlike fossil fuels, non-biomass renewable sources of energy “hydropower, geothermal, wind, and solar” do not directly emit greenhouse gases.

2.5 Solar Energy

In tropical countries, solar energy potential in wide range of applications of remote and urban areas is growing rapidly. There are also new research interests shown by the universities and R&D institutions to assess the solar energy application potential in these countries for proper utilization.

Since solar energy depends on solar presence in a particular zone, correct and accurate information from the sun, seasonal changes of the solar energy and the amount of solar energy received from the sun are necessary to be evaluated and the basic parameters of solar energy system are needed to be as accurate as possible. This paper presents forming practical and standard guidelines for feasibility studies, solar development studies, solar engineering studies and selecting solar energy equipment while implementing any viable solar energy scheme. It describes the best steps necessary to take into account for implementing practical solar scheme successfully. It discusses complete analysis of practical evaluations of all factors, which involve practical solar energy scheme in terms of assessment, application design, effective energy production [l6, 17].

The output of a solar panel is commonly expressed in watts, and the wattage is determined by multiplying the rated voltage by the rated current for example, a 12 V, 60 W solar panel measuring in inches of "20 x 44" has a rated voltage of 17.1 V a rated current of 3.5A which is, V (volts) x A (amps) = W(watts), 17.1 V x 5A= 60W.

If an average of 6 hours of peak sun per day is available in an area, then the above solar panel can produce an average of 360 watt-hour of power per day; 60W x 6 hrs= 360 W.hrs. Since the intensity of sunlight contacting the solar panel varies throughout the day, the term "peak sun hours" is used as a method to smooth out the variations into a daily average. Early morning and late-in-the day sunlight produces less power than the mid-day sun [l6, 17, 18].

Naturally, cloudy days will produce less power than bright sunny days as well. When planning a solar power system the geographical area is rated in average peak sun hours per day based on yearly sun data. Although Average peak sun hours for various geographical areas arc known but it is very important to exactly utilize the daily peak sun hour’s in a particular zone in a particular period [18]. This will do away any daily planning which could be based on assumption of the former data while ignoring the exact data available in the particular day at the particular zone.

Solar panels can be wired in series or in parallel to increase voltage or current respectively, and they can be wired both in series and in parallel to increase both volts and amps. Series wiring refers to connecting the positive terminal of one panel to the negative terminal of another.

The resulting outer positive and negative terminals will produce voltage the sum of the two panels, but the current stays the same as one panel. So two 12vo1t/3.5 amp panels wired in series produces 24 V at 3.5 A. Four of these wired in series would produce 48V at 3.5 A. Parallel wiring refers to connecting positive terminals to positive terminals. And negative to negative. The result is that voltage stays the same, but current becomes the sum or the number of panels, so two, 12V/3.5A panels wired in parallel would produce 12 V at 7 A. Four panels' would produce 12 V at 14 A. Series- parallel wiring refers to doing both of the above; increasing volts and amps to achieve the desired system voltage as in 24 or 48 V systems. In addition to that, the four panels can then be wired in parallel to another four and so on to make a larger array.

As a rule-of-thumb each so-called peak-Watt (Wp) of solar panel power can deliver around 4 -5 watt-hours of energy per day in tropical countries like Malaysia. Therefore a 40Watt solar panel would supply about 40 x 4 = 160Watt- hours per day. As a further example, an array of 10 x 50W = 500 solar panels can provide 500 X 4 = 2000 Watt-hours per day.

2.6 Power Control

There are two methods to control power: instantaneous and average power control. In the instantaneous power control method, the fundamental current component and higher frequency components are controlled to compensate for the grid voltage disturbances in a similar way to the operation of active power filters. A consequence of regulating the instantaneous power is that if the grid voltage is distorted then the current will necessarily be non-sinusoidal in order to keep the power instantaneously constant. If the objective is to provide high power quality then instantaneous power control should not be used. The average power control method provides high quality sinusoidal output current and controls the average power flow.

The role of the power controller is to generate output current references by filtering out higher harmonic content from the power spectrum in Figure 2.4. Since the power control transient response time is of the order of 100 ms, the filtering provides a slowly changing current reference to ensure high quality inductor current. A consequence of average power control is that if the grid voltage is distorted then the instantaneous power fluctuates. The fluctuations are reflected to the dc side as harmonic frequencies that are sourced from the dc-link capacitor.

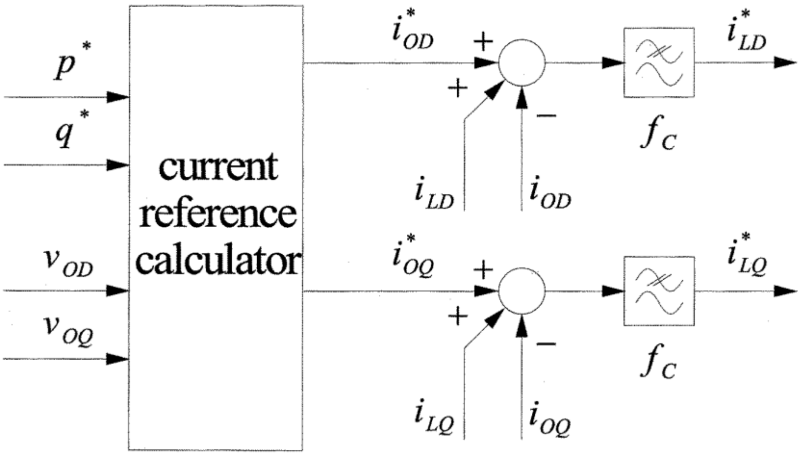

Figure 2.4: Power controller structure.

If current control is established and the current and components are kept constant, then the output power variation depends only on the variation of output voltages. When the power references (P*) and (q*) and output voltages are known, a power calculator can be used (instead of a power controller) to calculate output current references (i_{OD}) and (i_{OQ}):

$$\begin{bmatrix} i *_{OD} \\ i *_{OQ} \end{bmatrix} = \begin{bmatrix} v_{OD} & v_{OQ} \\ -v_{OQ} & v_{OD} \end{bmatrix}^{-1} \begin{bmatrix} P * \\ P * \end{bmatrix} \tag{2.2}$$

The references are calculated according to calculate inductor current references ($i*_{LD}$) and (i_{LQ}) the capacitor currents and decoupling terms must be added to the output current references. Therefore, the difference between the inductor currents ($i*_{LD}$), (i_{LQ}) and output currents (i_{OD}), (i_{OQ}) is added to the output current reference (i_{OD}), (i_{OQ}).

The power controller structure is shown in Figure1. To limit the power controller bandwidth and to filter out harmonic content from the voltage and current spectrum a low-pass filter is applied. The filter cut-off frequency (f_C) must be set low to provide sufficient suppression of voltage harmonics and unbalance, but high enough to provide good response of the power control loop [19].

2.7 PID Controller

Proportional integral-derivative (PID) control is certainly the most widely used control strategy today. It is estimated that over 90% of control loops employ PID control, quite often with the derivative gain set to zero (PI control). Over the last half-century, a great deal of academic and industrial effort has focused on improving PID control, primarily in the areas of tuning rules, identification schemes, and adaptation techniques. It is appropriate at this time to consider the state of the art in PID control as well as new developments in this control approach.

The three terms of a PID controller fulfill three common requirements of most control problems. The integral term yields zero steady-state error in tracking a constant set-point, a result commonly explained in terms of the internal model principle and demonstrated using the final value theorem. Integral control also enables the complete rejection of constant disturbances. While integral control filters higher frequency sensor noise, it is slow in response to the current error. On the other hand, the proportional term responds immediately to the current error, yet typically cannot achieve the desired set-point accuracy without an unacceptably large gain.

For plants with significant dead time, the effects of previous control actions are poorly represented in the current error. This situation may lead to large transient errors when PI control is used. Derivative action combats this problem by basing a portion of the control on a prediction of future error. Unfortunately, the derivative term amplifies higher frequency sensor noise; thus, a filtering of the differentiated signal is typically employed, introducing an additional tuning parameter. While the three PID terms are sufficient to parameterize a structure that permits successful control of many plants, the number of terms is small enough to allow manual tuning by an operator. Furthermore, the small number of terms lends itself to both direct adaptive control and self-tuning through heuristics. Figure 2.5 shows the block diagram of PID controller [10].

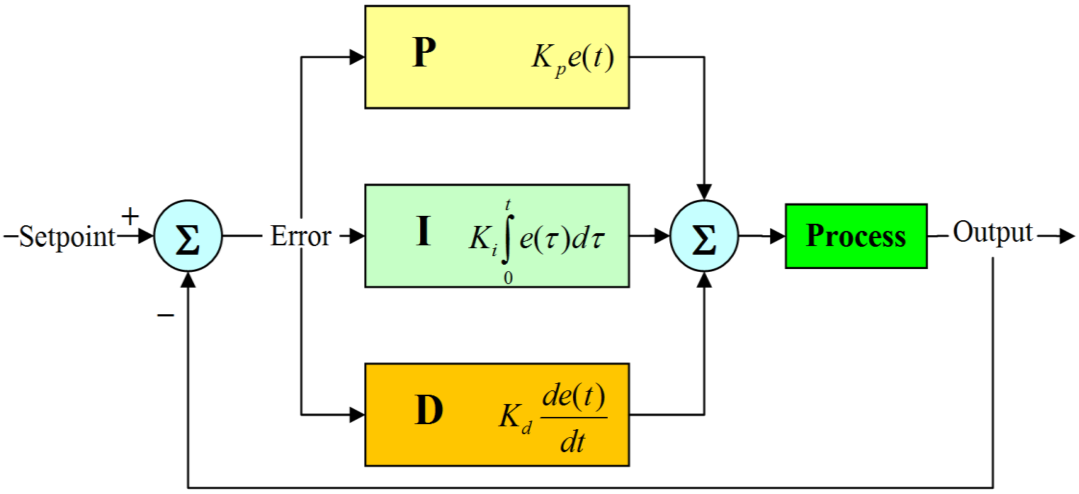

Figure 2.5: Block diagram of PID controller.

2.8 Overview of the Synchronverter Technology

Power systems currently receive more and more contributions from distributed energy sources, in particular, from renewable energy sources. Renewable energy sources are uncontrollable and highly non-linear. If their share in a power system becomes significant, a modem control strategy is required not only to preserve, but also to improve the stability of the power system. It is one of the biggest challenges for all researchers working in this area to propose the most efficient way to send renewable power to the grid without degrading the system stability.

In general, the control schemes for sending power from a renewable energy source to the utility grid are quite similar and include two stages. In the first stage, the source power is converted into electrical power, often in the form of DC, using appropriate techniques. The second stage is to feed the electrical power to the utility grid, often via DC-AC converters, also called inverters. Various control strategies can be applied at this stage to control the power flowing into the grid from the DC bus. Different control strategies have different ways of feeding the power to the grid and therefore the impact on the stability of the power system is different.

Different control methods can be applied at the second stage to control grid-connected inverters. The two most-studied methods are power (torque) angle control and current vector control for voltage source inverters (VSI). Generally, the current vector control method aims at delivering current flows with low harmonic distortion to the grid while maintaining a stable DC bus voltage [20, 21]. Because the source model for the inverter in this method is a current source mode, maintaining the DC bus voltage means transferring all the available power from the source to the grid to avoid fluctuations of the DC bus voltage. In most renewable energy systems, the power available on the DC bus is achieved from maximum power point tracking (MPPT) algorithms and hence, the inverter simply feeds the maximum power available to the grid.

Because of the fast response and the ability of limiting the currents within the control loops, this strategy is popular and is dominant in most grid-connected applications nowadays [22, 23].

The strategy for sending the maximum power extracted to the grid with current control methods is considered to be suitable as long as the share of the renewable source is not significant. In this case, the power surge from renewable sources would be compensated by large synchronous generators within the power system. In other words, the main large generators in the system are responsible for the whole system stability, taking care of any disturbances on the grid. When the share of renewable energy sources reach a certain level, the strategy to inject all maximum power from renewable sources to the grid is untenable and is very likely to cause instability to the whole power system.

The power (torque) angle control method is another control method. The real power flowing to the grid is controlled by the phase difference, called the power angle or torque angle, between the generated voltage and the grid voltage, the reactive power is controlled by regulating the amplitude of the generated voltage. This control method is in line with the behavior of a synchronous generator connected to the grid and has been proposed to control high power grid-connected inverters to improve system stability, such as the HVDC system and STATCOM [24]. The control strategy proposed in is a variant of the power angle control method, taking into account the current control as an auxiliary function.

Several strategies are based on the operational principles of SG from different angles. Since synchronous generators have been studied for more than 100 years and the technology has now reached high maturity, it makes sense to design a controller to mimic the behavior of an SG connected to the grid. Implementations along this line include the virtual synchronous machine (VISMA) [25], the VSGs and the synchronverters, the synchronverter includes the mathematical model of a synchronous machine and behaves in the same way as a synchronous generator mathematically to provide a voltage supply, it can be operated in standalone mode or grid-connected mode and the transition between the modes is seamless. It can send a set power to the grid and is also able to take part in the regulation of the system frequency and voltage. Moreover, it is able to be operated in parallel to share the real power and reactive power accurately. Because of the embedded mathematical model, a utility company is able to control a synchronverter in the same way as controlling a synchronous generator, which considerably facilitates the grid connection of renewable energy and smart grid integration, the power part of a synchronverter is illustrated in Figure 2.6.

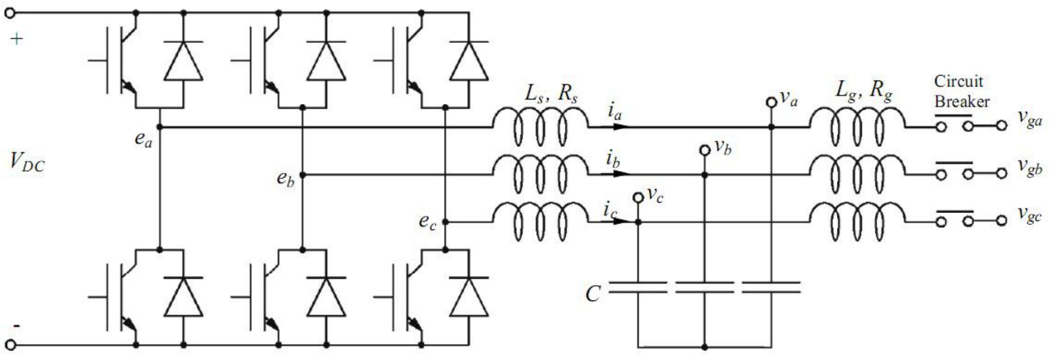

Figure 2.6: The power part of a synchronverter [26].

2.8.1 Synchronverter Technology

A synchronverter is an inverter that mimics a synchronous generator [27, 28]; the core of the controller is the mathematical model of a synchronous generator, which is then wrapped with some functions to regulate the real power and reactive power, voltage and frequency. As a result, grid-connected renewable energy and distributed generation can easily take part in the regulation of the system frequency and voltage. A synchronverter consists of a power part and an electronic part as shown in Figure 2.7. The controller includes the mathematical model of a three-phase round-rotor synchronous generator described as follows.

The structure of an idealized three-phase round-rotor synchronous generator is shown in Figure 2.8. Assume that the three identical stator windings of a synchronous generator are distributed in slots around the periphery of the uniform air gap; the stator windings can be regarded as concentrated coils having self-inductance L, mutual inductance -M “with M > 0, the negative sign is due to the $2\frac{\pi}{3}$ phase angle” and resistance Rs. Denote the flux vector and the current vector as:

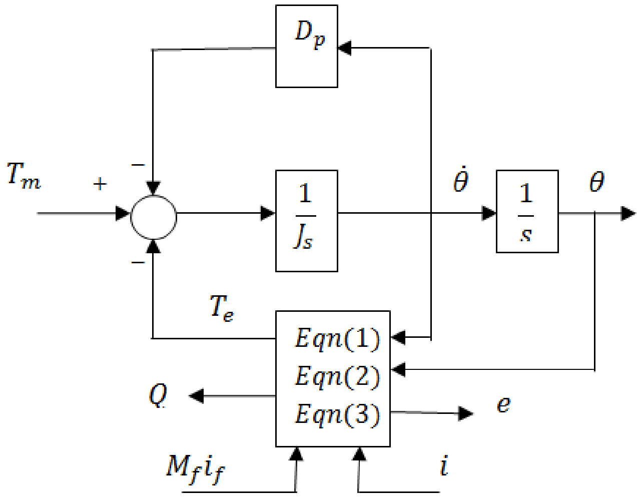

Figure 2.7: The electronic part (controller) of synchronverter [29].

$$\varphi = \begin{bmatrix} \varphi_a \\ \varphi_b \\ \varphi_c \end{bmatrix} \quad , \quad i = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2.3}$$

Respectively, and the vectors:

$$\widetilde{cos\theta} = \begin{bmatrix} cos\theta \\ \cos\left(\theta - \frac{2\pi}{3}\right) \\ \cos(\theta - \frac{4\pi}{3}) \end{bmatrix} \quad \widetilde{s\imath n\theta} = \begin{bmatrix} sin\theta \\ \sin\left(\theta - \frac{2\pi}{3}\right) \\ \sin(\theta - \frac{4\pi}{3}) \end{bmatrix} \tag{2.4}$$

Where θ is the rotor angle with respect to the Phase A winding. Then the phase terminal voltages $v = [va\ vb\ vc]^T$ of a generator can be written as:

$$v = e - R_s i - Ls\ \frac{di}{dt} \tag{2.5}$$

Where Ls = L+M and $e = [\ e_a\ e_b\ e_c]^T$ is the back EMF due to the rotor movement given by:

$$e = M_f i_f \theta \widetilde{s\imath n\theta} - M_f \frac{\mathrm{di_f}}{\mathrm{dt}} \widetilde{cos\theta} \tag{2.6}$$

The mechanical part of the generator is governed by:

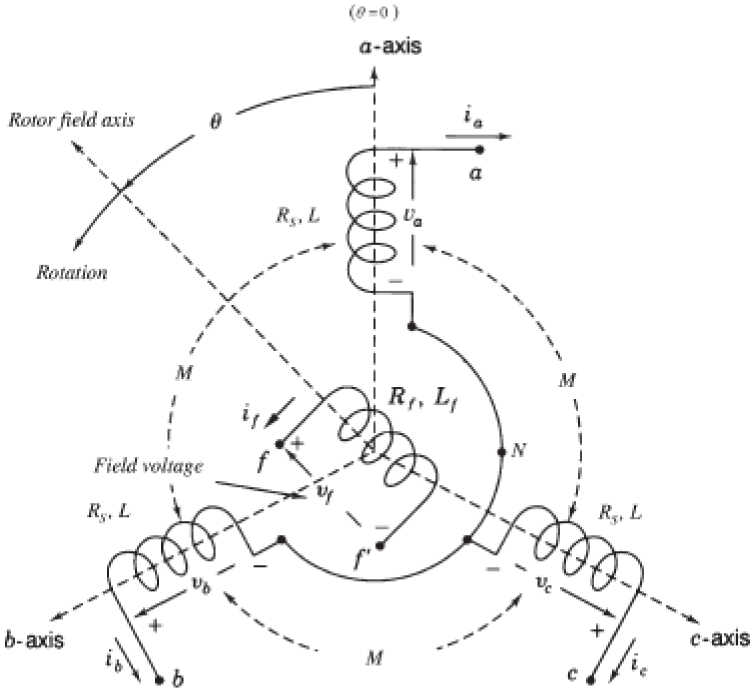

Figure 2.8: Structure of an idealized three-phase round-rotor synchronous generator [30].

$$J\ddot{\theta} = \frac{1}{J}\left(T_m - T_e - D_p\dot{\theta}_g\right) \qquad (2.7)$$

Where J is the moment of inertia of all the parts rotating with the rotor; Dp is a damping factor; Tm is the mechanical torque and Te is the electromagnetic torque:

$$T_e = M_f i_f (i, \widetilde{sin\theta}) \qquad (2.8)$$

The real power and reactive power are, respectively;

$$P = \dot{\theta} M_f i_f (i, \widetilde{sin\theta}) \qquad , \qquad Q = -\dot{\theta} M_f i_f (i, \widetilde{cos\theta}) \qquad (2.9)$$

Similarly to the control of a synchronous generator, the controller of a synchronverter has two channels: one for the real power and the other for the reactive power. The real power is controlled by a frequency droop control loop, which is implemented in a synchronverter by comparing the virtual angular speed $\dot{\theta}$ with the angular frequency reference $\dot{\theta}_r$ (which normally would be equal to the nominal angular frequency of the grid $\dot{\theta}_n$), and adding this difference, multiplied with a gain, to the active mechanical torque Tm. The mechanical friction coefficient plus the frequency drooping coefficient is represented by D_p. This loop regulates the virtual angular speed $\dot{\theta}$ of the synchronous generator and creates the phase angle θ for the control signal$e$. The regulation of reactive power flowing out of the synchronverter can be realized similarly. The reactive power is controlled by a voltage droop control loop, using the voltage droop coefficient$\mathrm{D_q}$. This loop regulates the field excitation $\mathrm{M_f i_f}$, which is proportional to the amplitude of the voltage generated [31].

CHAPTER 3

3.1 Project Methodology

This research is adopted methods approach involving develops and designs three phase inverter synchroconverter controlled hardware system.

3.2 Block Diagram and Description

The block diagram representing the project is shown in Figure 3.1. The three phase inverter gives output voltage waveforms that can be controlled by PWM which is generated from DSP board through DC gate driver circuit. The three phase inverter uses a dc power supply and the gate driver signals to produce balanced three-phase sinusoidal output which drives the induction machine. With a current sensor as illustrated below, the three phase induction motor current can be controlled by using control system through this current sensor.

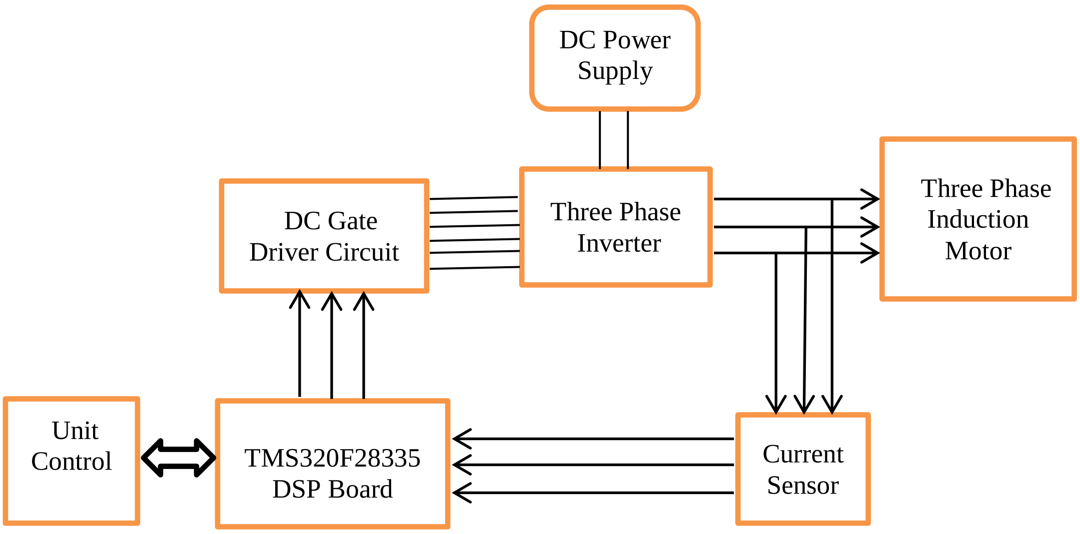

Figure 3.1: Block Diagram of synchronverter three phase inverter system.

3.3 Synchronverter control design in Matlab

Modern Control Design with MATLAB and Simulink offers a straightforward treatment and applications of control system theory. Contemporary engineering control systems of various kinds are covered in a clear and concise manner. In this section, the details on how to design and implement a synchronverter is illustrated in Figure 3.2, where mutual field (m_f) and current filed (i_f) are represented as constant input value of synchronverter, while the input current (i_a) is variable and depends on current source inverter output. Thus, the electromagnetic torque (T_e) is depends on (i_a) and virtual angle speed.

The control inputs of the synchronverter are Tm and (M_f i_f). In order to operate the synchronverter in a useful way, we need a controller that generates the signals Tm and Mf if such that system stability is maintained. The generated voltage of synchronverter is [29]:

$$e = \dot{\theta} M_f i_f \sin\theta \qquad (3.1)$$

Where: θ is virtual angle and $\dot{\theta}$ is a virtual angular speed.

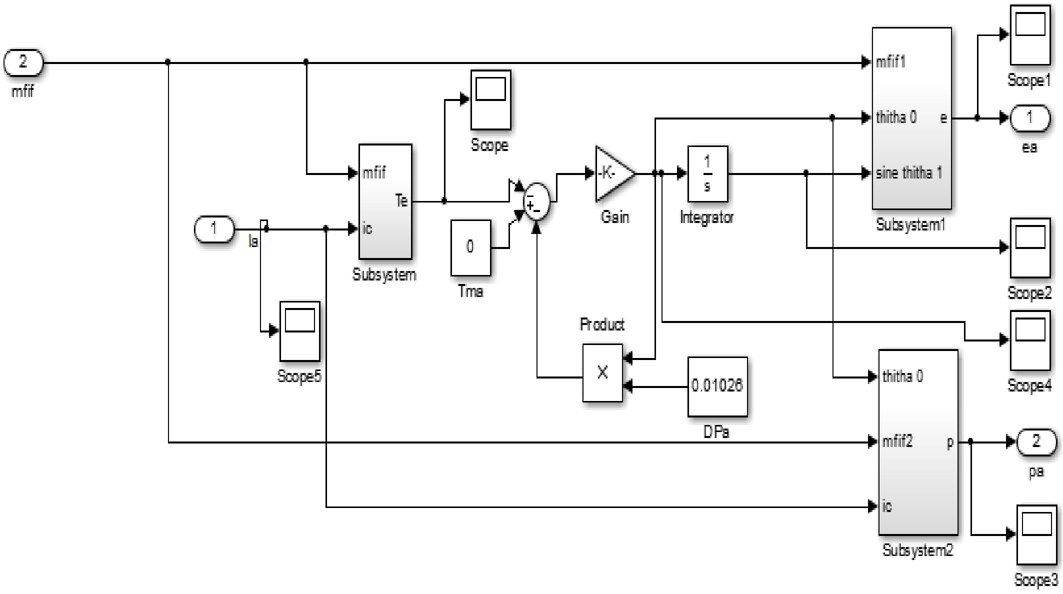

Figure 3.2: Synchronverter control design in Matlab.

3.4 Synchronverter control design with open and closed loop in Matlab

Simulink is especially useful for generating the approximate solutions of mathematical models that may be prohibitively difficult to solve by hand. The following open-loop system simulation of synchronverter shown in Figure 3.3. The system output should adjust in order to specific the input value, in this open loop control the controlled output current that consumes by the load is equal to input current (i_a).

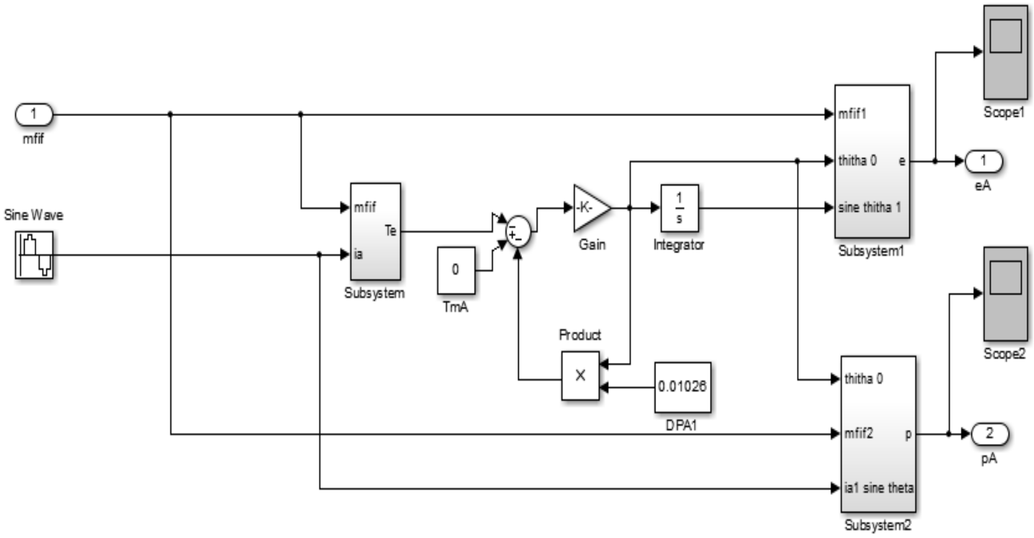

Figure 3.3: Synchronverter open loop control design in Matlab.

Whereas, the closed loop synchronverter control works in different way to control the output current. In this case of closed loop as designed in Figure 3.4 there is a feedback current value to subtract of reference value to supply this error to the controller to maintain current load in stable value.

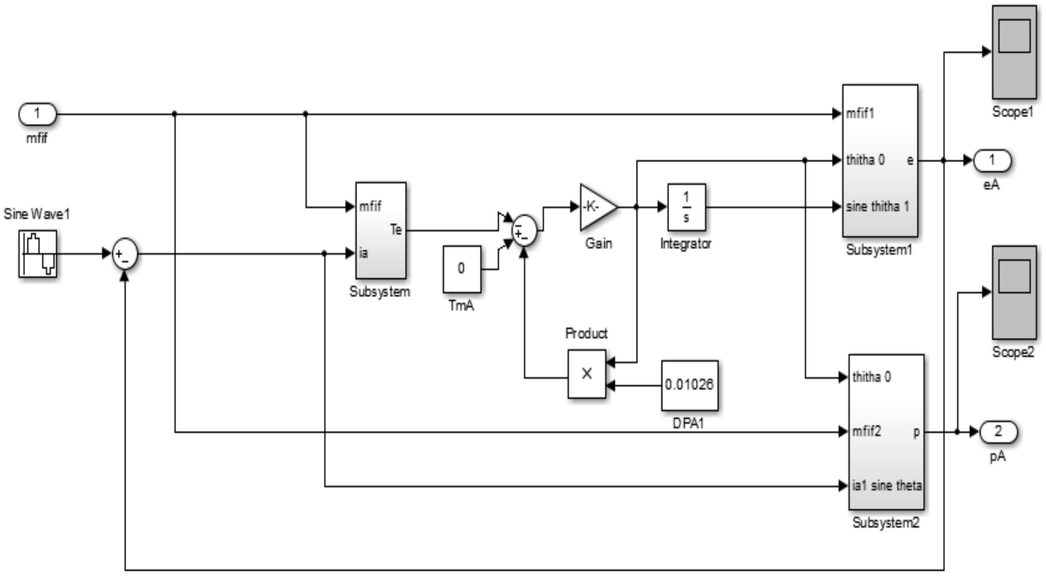

Figure 3.4: Synchronverter closed loop control design in Matlab.

3.5 Hardware design

In three phase synchronverte project, the hardware circuit consists from the flowing parts:

3.5.1 Gate driver design

The gate driver circuit is an important circuit to drive up the three phase inverter by sending the PWM into the gate pin at the power transistor. The main function of this circuit is to double the input PWM from the controller in term of the number and amplitude of the signal. The circuit consists of several components as listed in the Table 3.1.

REFERENCES

[1] F. Blaabjerg. R. Teodorescu. M. Liserre, and A. V. Timbus, “Overview, of Control and Grid Synchronization for Distributed Power Generation Systems,” IEEE Transactions on Industrial Electronics, pp. 1398-1409, Vol. 53, No. 5, October 2006.

[2] H. M. Kojabadi, Y. Bin, I. A. Gadoura, L. Chang, and M. Ghribi, “A novel DSP-based current-controlled PWM strategy for single phase grid connected inverters,” IEEE Trans. Power Electron., vol. 21, no. 4, pp. 985– 993, Jul. 2006.

[3] Z.Wang and L. Chang, “A DC voltage monitoring and control method for three-phase grid-connected wind turbine inverters,” IEEE Trans. Power Electron., vol. 23, no. 3, pp. 1118–1125, May 2008.

[4] IEEE Standard 1547-2003 “IEEE Standard for Interconnecting Distributed, Resources with Electric Power Systems,” 2003.

[5] S. J. Jeong and S. H. Song, “Improvement of predictive current control performance using online parameter estimation in phase controlled rectifier,” IEEE Trans. Power Electron., vol. 22, no. 5, pp. 1820–1825, Sep. 2007.

[6] Y. A. Mohamed and E. F. El-Saadany, “Robust high bandwidth discretetime predictive current control with predictive internal model—A unified approach for voltage-source PWM converters,” IEEE Trans. Power Electron., vol. 23, no. 1, pp. 126–136, Jan. 2008.

[7] P. Cortes, J. Rodriguez, D. E. Quevedo, and C. Silva, “Predictive current control strategy with imposed load current spectrum,” *IEEE Trans. Power Electron.*, vol. 23, no. 2, pp. 612–618, Mar. 2008.

[8] Sergio Aurtenechea Larrinaga and Angel Rodríguez Vidal, “Predictive Control Strategy for DC/AC Conv erters Based on Direct Power Control”, IEEE transactions on industrial electronics, VOL. 54, NO. 3, JUNE 2007.

[9] Suposcillation Method for three phase inverter, Mohamed Fadzli Bin Ahmed Radzi, University techniqual Malaysia, Melaka, May 2007.

[10] DC Motor Speed and position control using analog PID controller, Ahmed Ismail Bin Man, Faculty Electrical Engineering, “Control Instrumentation & Automation”, University Teknikal Malaysia Melaka.

[11] Ahmad Ismail, Man. "DC Motor Speed and Position Control Using Analog PID Controller." (2008).

[12] Bolognani, Silverio, Roberto Oboe, and Mauro Zigliotto. "Sensorless full-digital PMSM drive with EKF estimation of speed and rotor position." Industrial Electronics, IEEE Transactions on 46.1 (1999): 184-191.

[13] A. A. C. Nunes, P. F. Seixas, P. C. Cortizo, and S. R. Silva, “Wind turbine simulator using a DC machine and a power reversible converter,” in Proc. Int. Conf. Elect. Mach., vol. 3, Adelide, Australia, 1993, pp. 536–540.

[14] L. Jian and W. C. Xu, “The simulation system of wind turbine performance using a microcomputer controlled SCR-DC motor,” in Proc. Beijing Int. Conf. Electrical Machines, Beijing, China, 1987, pp. 865–868.J.

[15] Z. Chen and E. Spooner, “Simulation of a direct drive variable speed energy converter,” in Proc. Int. Conf. Electrical Machines, Istanbul, Turkey, 1998, pp. 2045–2050.

[16] Event Horizon, Advanced Energy Group authorized dealer. Michigall, USA.

[17] Robers, S. [99], Solar Electricily: A practical guide to designing and Installing Small Photovoltaic Systems, 434 p. Prentice Hall International, UK.

[18] Musse Mohamud Ahmed and MarizanSulaiman, “Design and Proper Sizing of Solar Energy Schemes for Electricity Production in Malaysia”, national power and Energy Conference (PECon) 2003, Proceedings.

[19] Milan Prodanovic, Student Member and Timothy C. Green, Member, “Control and Filter Design of Three-Phase Inverters for High Power Quality Grid Connection”, IEEE transactions on power electronics, VOL. 18, NO. 1, JANUARY 2003.

[20] E. Figueres, G. Garcera, J. Sandia, F. Gonzalez-Espin, and J.C. Rubio, Sensitivity study of the dynamics of three-phase photovoltaic inverters with an lcl grid filter, IEEE Trans. Ind. Electron, 56(3):706_717, Mar. 2009.

[21] S. Alepuz, S. Busquets-Monge, J. Bordonau, J. Gago, D. Gonzalez, and J Balcells, Interfacing renewable energy sources to the utility grid using a three-level inverter, IEEE Trans. Ind. Electron., 53(5):1504_1511, Oct. 2006.

[22] M.P. Kazmierkowski and L. Malesani. Current control techniques for three-phase voltage-source PWM converters: a survey. IEEE Trans. Ind. Electron, 45(5):691_703, Oct. 1998.

[23] Lidong Zhang, L. Harnefors, and H.-P. Nee. Power-synchronization control of grid-connected voltage-source converters. IEEE Trans. Power Syst, 25(2):809_ 820, May 2010.

[24] B. Singh, R. Saha, A. Chandra, and K. Al-Haddad. Static synchronous compensators, (STATCOM): A review. IET Proc. Power Electron., 2(4):297_324, Jul, 2009.

[25] H.-P. Beck and R. Hesse. Virtual synchronous machine. In Proc. of the 9th International Conference on Electrical Power Quality and Utilisation (EPQU), pages 1_6, 2007.

[26] Qing-Chang Zhong, Senior Member, IEEE, Phi-Long Nguyen, Zhenyu Ma, and Wanxing Sheng. Self-Synchronized Synchronverters: Inverters without a dedicated Synchronization Unit. IEEE transaction on power electronics, vol. 29, no. 2, FEBRUARY 2014.

[27] Q.-C. Zhong and G. Weiss. Static synchronous generators for distributed generation and renewable energy. In Proc. of IEEE PES Power Systems Conference & Exhibition (PSCE), 2009.

[28] Q.-C. Zhong and G. Weiss. Synchronverters: Inverters that mimic synchronous generators. IEEE Trans. Ind. Electron, 58(4):1259_1267, Apr. 2011.

[29] Qing-Chang Zhong, Senior Member and George Weiss. Synchronverters: Inverters That Mimic Synchronous Generators, IEEE transactions on industrial electronics, VOL. 58, NO. 4, P 1261, April 2011.

[30] J. J. Grainger and W. D. Stevenson, Power System Analysis. New York: McGraw-Hill, 1994.

[31] Qing-Chang Zhong, Senior Member and George Weiss. Synchronverters: Inverters That Mimic Synchronous Generators, IEEE transactions on industrial electronics, VOL. 58, NO. 4, April 2011.

[32] P. Piagi and R. H. Lasseter, “Autonomous control of micro grids,” in Proc. IEEE. Power Eng. Soc. Gen. Meet, 2006. [Online]. Available: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1708993.