MODELLING & SIMULATION OF VOLTAGE SOURCE CONVERTER WITH DIFFERENT CONTROL TECHNIQUE FOR OFFSHORE WINDFARM APPLICATION

by

Afiq Asyraf Bin Romlan

14357

Project dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Electrical & Electronic)

SEPTEMBER 2014

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

MODELLING AND SIMULATION OF VOLTAGE SOURCE CONVERTER WITH DIFFERENT CONTROL TECHNIQUE FOR OFFSHORE WINDFARM APPLICATION

by

Afiq Asyraf bin Romlan

A project dissertation to the
Electrical & Electronic Engineering Programme
Universiti Teknologi PETRONAS
In partial fulfilment of the requirement for the
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

Approved:

____

(Ms. Khairul Nisak Md Hasan)
Project Supervisor

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsibly for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Afiq Asyraf bin Romlan

ABSTRACT

The uses of Voltage Source Converter is not something new in wind farm power generation. Advance technologies in rebuilding VSC that can control the output of alternating current (AC) through several current control technique produces from the wind energy, sometime lead to distortion that can disturb another component whether in VSC itself or effecting another equipment. In wind farm power generation, power VSC commonly used in order to deal with large value of voltage and current produced from wind energy. Hence, more electronic device and components will be used to deal with this situation. This is to some extent will create disturbances to the system that will not be seen through human naked eye. Through this paper, a conventional current control method, that is linear PWM is present. This method is much more complicated compare to proposed method, that is predictive current control. The function of multi predictive control (MPC) in determining the future value for the feedback signal into inverter is explained in 4.3. The result of this two method is analyse in aspect of total harmonic distortion (THD) for both voltage and current during transient state and steady state. During transient state for current, both of the methods exceed the IEEE-519 standards. Hence it is recommend to install several equipments to protect the facility of windfarm itself. While for steady state, both of the methods succeed maintain the THD below 5% for voltage and current.

ACKNOWLEDGEMENT

First and foremost, all praise to Almighty for His guidance and blessings throughout my entire studies in Universiti Teknologi PETRONAS.

I would like to express my gratitude and appreciation to Ms. Khairul Nisak Md Hasan, my Final Year Project Supervisor who was responsible to supervise myself throughout this semester period. Her guidance, endless support, encouragement and supervision is very valuable towards my learning process in finishing my research and work.

Special thanks to Dr. Nasreen Badruddin, Final Year I and II coordinator from Electrical and Electronic Engineering department, whose helping me and my fellow course mates to coordinate the whole courses and make sure the report submission being delivered in a timely manner.

Finally, I would like to deliver my utmost appreciation to my parents, whom never giving up in inspiring and supporting me to accomplish this program. Last but not least, thanks to my colleagues, who contributed explicit or implicit towards accomplishing the final year project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

Voltage source converter basically have two type of circuits to operate. Whether to convert AC voltage source to DC voltage source (rectification) or from DC voltage source to AC voltage source (inverter). In wind farm power plant, this two type of converter is implement to transfer the power into the grid system. For this project, the author main focus is the inverting type, that is from DC voltage source to AC voltage source.

Rapid development in microprocessors, had increase the detailed research regarding predictive current control method in VSC. This method are quickly growing in medium and high performance systems, especially in the filed of high involving power units[1]. Hence, the author would like to discover more the current control technique that is predictive current control at conversion from DC voltage source to AC voltage source using voltage source converter.

1.1 Background

Implementation of wind farm at offshore is not something extraordinary nowdays. Wind farm is used because renewable energy become an important things in reducing greenhouse effect emissions [2]. The purpose of this implementation is to utilise another renewable sources beside coal, oil, uranium and natural gas.

To generate alternating current (AC) and sending it to the load or grid connection system, there are several equipment that involves in system such as wind turbine, mechanical and electrical stuff such as gear box, rotor blade, rotating shaft, wind turbine generator (WTG). Generally the operation of a wind farm can be show from figure 1. It started when the energy from wind create a difference pressure at the rotor blade. This rotor blade is connected to the rotating shaft. This rotating shaft will turn on the synchronous generator and produced AC three phase output.

Voltage source converter is used to convert AC current to DC current (rectification) and from DC to AC current (inverter) through DC link, mostly High Voltage Direct Current (HVDC) transmission. This illustration can be seen from figure shown below.

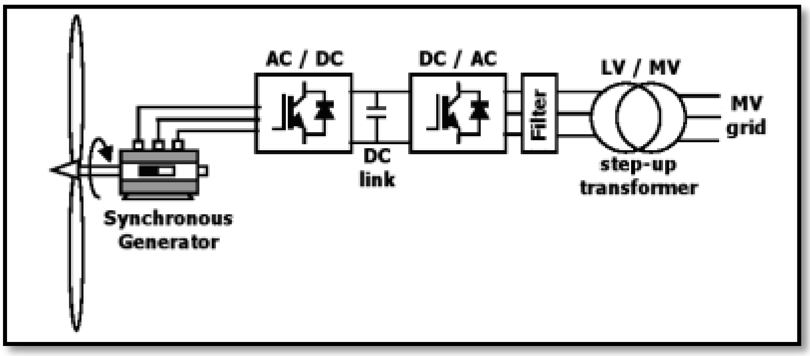


Figure 1: WTG (permanent magnet syncronous generator) variable speed system[17]

Using inverter, the DC voltage souce that being transfer from rectified devices is inverted back to AC voltage sources. Based from figure 1, the output from inverter is filtered in order to obtain low current distortion. Then the ouput will be step-up using transformer and send it to the grid system.

To maximise the quality of output power to the grid system from generator distribution, a suitable power converter is used between generator and step-up transformer [3]. The term 'quality' mean the voltage and current error can be minimized, hence more accurate response can be obtained. As being stated by Malesani (1993), predicitve current control method have regulator that contain information rather than error signal, thus a faster and more accurate response can be achieved.

1.2 Problem statement

This work aimed to address the following problems:

1) The limitations of hysteresis and linear PWM control technique.

The switching frequency of hysteresis current control method, change according to load variable. This will lead to resonance problems. As a consequences, it will give effect to switching losses and restrict the application usage. While in the other hand, (proportional-integral) PI controller in linear PWM current control, process the error between the reference and measured load current. At the same time, this PI controller can produce error for sinusoidal references. As error increase, it will also increase the frequency of the reference current and might be unbearable for several applications.

By implementing predictive current control (PCC), a few of possible switching states can be generated by a quality of function. This quality function will evaluated the predicted values of the variables that are to be controlled. In comparison with hysteresis current control, the switching frequency will be minimized as high power converters is used. Besides that, quality function in predictive current control method evaluated the error with the reference and predict the variable in next sampling rate. While in linear PWM, the sinusiodal reference that being generated also contain error which is not present for model predictive current control.

2) The effect of harmonic analysis with the implementation of predictive current control method to the grid system.

Due to large area of installation in the wind farm, the probability to capture wind energy is vary from time to time. This mean that the power from WTG will not be the same all the time. This unstable power together with harmonic distortion will create a heating effect of power cables that carry the current and may get a risk to catch a fire or burnt. Major power quality issue face right now is harmonic distortion encountered at the output of the voltage source converter.

This harmonic issue is due to low switching frequency of high power converter. Low switching frequency will produce side band harmonics. Suitable filter need to be figure out in order to make sure the power that being suply to the grid is within the harmonic distortion percentage.

1.3 Objectives

1) To perform an extensive research and understanding the detailing current offshore wind farm nowadays.
2) To simulate the voltage source converter using linear PWM using MATLAB software.
3) To simulate and analyse the harmonic distortion at low switching frequency when using predictive current control technique in voltage source converter.
4) To make the comparison between the predictive current control with linear PWM and hysteresis control technique.

1.4 Scope of study

Throughout this paper, the author will broaden the scope regarding the information of wind farm mechanism especially in voltage source converter (DC to AC). The current control technique that being developed in this wind farm will be highlighted. Such as parameter that being used, how's the behaviour output from VSC will be, type of wind turbine generator (WTG), simulation of voltage source converter with propose technique, type of grid filter after converting DC to AC, control mechanism of predictive current control (PCC) and other methods. Besides that, the author will analyze the modern type of windfarm whether using induction or synschronous generator.

CHAPTER 2

LITERATURE REVIEW

2.1 Wind Power Plant (WPP)

Wind energy nowadays become a main highlighted for those company that want clean environment in supplying electrical energy to the grid system. Because of that, innovation and modification to the structure of wind plant such as material used for rotor blade, rotating shaft, generator were increase rapidly. Common type of wind turbine used is horizontol – axis turbine where the wind energy flow horizontolly to the rotor blade. It create a high and low pressure at the rotor that will force the blade to rotate. The blade is connected to the hub through the shaft. In this structure also, the gearbox have its own function. Same concept that being installed in a car, it is to increase rotational speed of the shaft from low to high speed. This speed will turn on the generator and produce maximum electrical energy.

In general, there are two types of wind turbine generator (WTG), that is constant speed wind turbine generator and variable speed wind turbine (VSWT). Currently, the variable speed type is much preferred due to its control ability for voltage and power factor to the grid system. Using variable speed wind turbine (VSWT), it will increase the production of ouput produced from 20 to 30 percent more energy compared to constant speed wind turbine [4]. Table 1 shows the comparison between constant speed WTG and variable speed WTG. For off-shore wind power plant (WPP), mostly they are using the one with variable speed due to control ability of the WTG itself.

Table 1: Type of wind turbine generator

	Constant speed	Variable speed		
	Directly connected squirrel cage asynchronous generator	Back to back connected squirrel cage asynchronous generator	Permanent magnet synchronous generator	Wound rotor asynchronous generator
Advantages	Cheap	High energy extraction	Voltage and power factor control	Voltage and power factor control
	Robust	100% speed variation	100% speed variation	Good energy extraction
		Voltage and power factor control	High energy extraction	30% of power processed by the converter
			Robust	
			Self-excitation	
Disadvantages	Flicker	Expensive	Vey expensive	Limited speed variation
	No voltage control			
	No power factor control		Generator complexity	Expensive
	Low energy extraction			

2.2 Transmission line

The electrical energy that being produced from wind turbine generator is converted from AC voltage source to DC voltage source through power electronic converter (rectification) and transmitted it to the onshore base power plant [12]. The transmission line that being used currently is High Voltage Direct Current (HVDC) and High Voltage Alternating Current (HVAC). One of advantage using HVDC transmission line is the losses that occur in each stage of system such as generation, transmission and distribution can be reduced compare to HVAC. Besides that, this transmission line have no restriction on line length as no reactance in DC lines. Thus, its suitable for long distance transmission. While for HVAC transmission line, the uses is widely adapted from a decades ago[6]. The changes voltage and current of electrical power like transformer and circuit breakers are less expensive for AC power.

2.3 Voltage source converter

As being mentioned in 2.1, there are two type of generator, which is fixed speed WTG and variable speed WTG. Each type of WTG in voltage source converter at the wind farm have different function. For fixed speed, the VSC is used to reduce inrush current and torque oscillation during the start-up of the generator. While for variable speed, VSC is used to control the speed or torque of the generator and also the active and reactive power that being supply to the grid system.

Mainly there are two type of power electronic converter that is voltage source converter and current source converter (CSC). Each type of converter has a different functionality. For current source converter (CSC), the value of DC is kept constant with a small ripple using a large inductor. While for VSC, the converter operates independently with controlling of active and reactive power at both end [7]. Basically, using VSC is far more convenient and flexible since the VSC allow the controlling the active and reactive power independetly [6].

Voltage source converter have two functions, voltage source rectifier (VSR) and voltage source inverter (VSI) [8]. The arrangement of VSR and VSI in wind farm diagram can be shown from figure 2. For VSR, the AC voltage source will convert to DC voltage source while for VSI the DC voltage source will be converted back from DC voltage source to AC voltage source. VSI play an important role to convert electrical energy from DC to AC or vice versa.

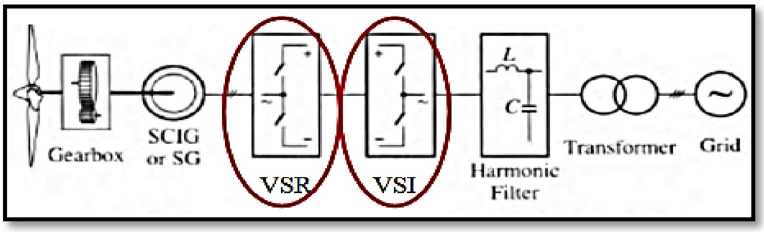


Figure 2: The arrangement of VSC in wind farm[18]

In these configuration, there are two-level and three-level connection. Two-level VSC can be shown from figure 3:

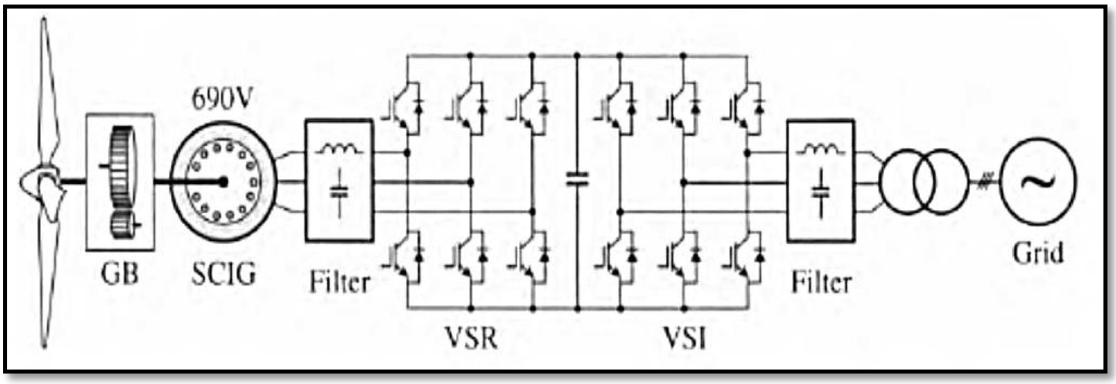


Figure 3: Two-level VSC in wind turbine generator[18]

VSC converter with two-level output voltage is the most frequently used three-phase power converter in wind turbine system. An advantage of the two-level VSC is the relatively simple structure and several components, which contributes to well-proven robust and good performance [9]. Unfortunately, as the voltage from turbine is generated, it may experience larger switching losses and lower efficiency at higher power level.

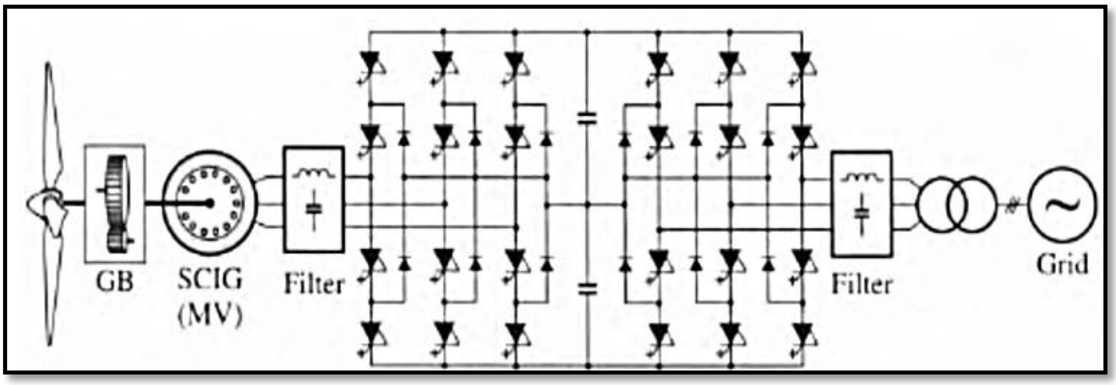


Figure 4: Three-level VSC in wind turbine generator[18]

As power rating of wind turbines increases, it becomes more difficult for two-level VSC to achieve acceptable performance. With the three-level VSC, the output of voltage amplitude can be double compared to the two-level VSC. It achieves one more output voltage and less *dv/dt* stress to the configuration. This implementation of three-level VSC is suitable with medium voltage (MV) generator that produce output power more than 0.75MW.

2.4 Current control methods

The current control methods are the highlight of this project. A conventional current control method, that is linear PWM and a predictive current control will be implemented. The review of these methods are presented in this section along with detail description of PCC method.

Hysteresis control method basically measured the line current and compared with a reference value within a boundary of error called hysteresis (h). In the other hand, linear PWM depends on comparing triangle wave (carrier) to a reference wave. In the predictive current control, it will determine how much the error voltage and current will be minimized from VSC [10].

As the power converter use pulse width modulation (PWM), it regulate the voltage of the waveform, and establish fundamental frequency and basic wave shape. High power converters (around 4MW) can help the power loss to be reduced and also can contribute to minimize the switching frequency[14]. Power semiconductor that were available in the industry are only operated below 600Hz, while for three-level VSC is 1200Hz.

Predictive current control technique can be implemented in DC-link capacitors voltage balancing, switching frequency reduction and current reference tracking and filter resonance damping [14]. The remaining method, linear PWM control and hysteresis control can be compare as shown from table 2.

PCC method is based on calculating the required inverter output voltage such that the actual current follow with the reference current. Nowadays, the present of fast and low cost digital signal processor boards makes the implementation of predictive controllers more simpler.

Table 2: Comparison between three different current control technique

Technique / Function	**Linear PWM control**	**Hysteresis control**	**Predictive control**
	Error between reference is processed by PI controller	Compared with reference using hysteresis comparators	Include nonlinearities to the system
Effect of switching frequency	Constant switching frequency is fixed	Switching frequency change according to load parameters	Minimize switching frequency
Effect/handling error parameters	Error with sinusoidal and frequency reference will not suitable for some applications	Current error not strictly limited	Evaluate current behaviour
Complexity	Modulator is needed to generate drive signals for inverter switches	Not require complex circuits or processors	Avoid complex modulation technique

To implement the linear PWM current control in the simulation, several term is needed to control the output current in voltage source converter. Figure 5 show the electrical schematic, where the reactance is connected between voltage source inverter and the grid. In this figure, we assume that the voltage DC source is a constant.

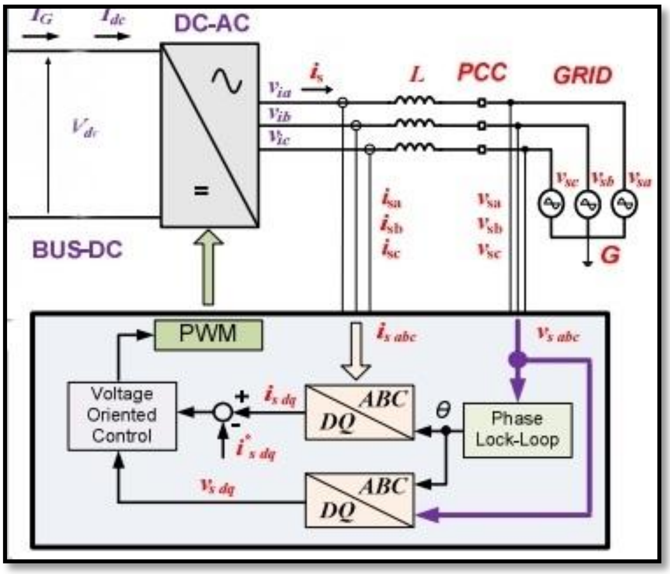


Figure 5: Electrical schematic for current control method[20]

The output current from voltage source inverter and reactance is parallel to the control diagram block where it contain phase locked loop, abc to dq block, PWM and voltage oriented control. Figure 6 show the detailing of the the control scheme.

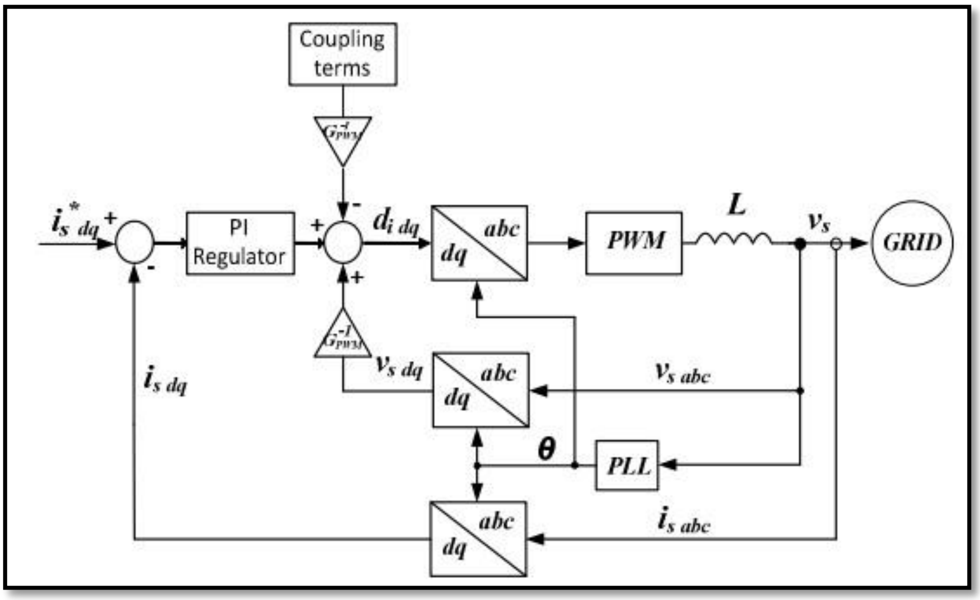


Figure 6: VOC control scheme[20]

The three phase current from inductive load are transformed into dq-axis current. The measured current will be compared with their reference current. The errors are sent to PI regulator, which generate the dq –axis reference voltage for the voltage source inverter. PI regulator can also achieve zero steady-state error by acting on current control signals. While for phase locked loop (PLL), it wil adjust the output signal and synchronize it to the feedback of dq-axis frame.

PLL track and identify the voltage vector and generate the grid voltage angle for voltage oriented control (VOC). The positive and negative feedback of coupling terms in the figure is a non-linear PWM modulator gain. The purpose is to adjust the period for duty-cycle averaging.The dq current from the gain will be fed to the transformation block. As effect from that, the signal produced by PWM will be injected to the leg component of voltage source inverter. The current demand will flow according to the grid and load.

2.5 Grid filter

In order to stabilize the energy output and to give it some defined shape and value, the filter must be connected between VSC and the grid system. The filter must be designed precisely, because it must have sufficient attenuation at the inverter switching frequency and most importantly, not to bring oscillatios to the whole system. There are several grid filter in industry such as L-filter, LC-filter and LCL-filter. Each filter has their own purposes and characteristics. The output filter reduces the harmonics in generated voltage and current caused by semiconductor switching. Figure 7 shows the variant of connection to the VSC. Table 3 show some of the comparison between each filter.

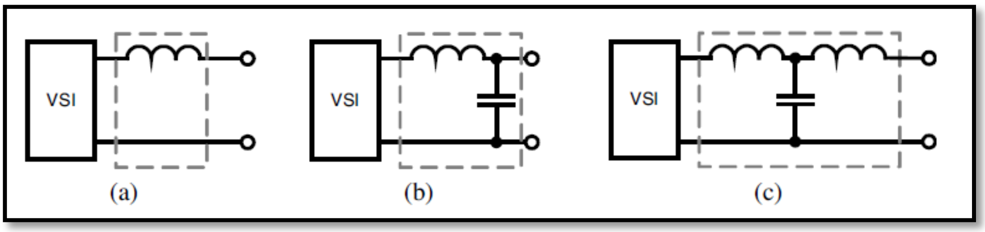


Figure 7: Basic filter topologies; (a)L-filter; (b)LC-filter; (c)LCL-filter [19]

Table 3: Comparison between three different filter

L-filter	LC-filter	LCL-filter
First oder with 20dB attenuation over whole frequncy range	Second order with 12dB per octave of attenuation after cut-off frequency	60dB/decade fro frequency above resonant frequncy
Suitable for high switching frequency	Value of capacitance and inductance affect the designing of filter	Suitable for low switching frequency
Value of inductance can decrease dynamics of the VSC-filter system	High capacitive give positive impacts on voltage quality	Provide better decoupling between filter and grid impedance
	High inductance is needed to cut-off frequncy of the filter	Good current ripples attenuation with small

		inductance(lead to resonance and unstable state to the system)
	Not suitable to used in grid system due to dependent resonant frequency to the grid system	Need damping resistor to reduce voltage across the capacitor

As being stated in 2.4, low switching frequency(1200Hz) from three-level NPC converter will produce side band harmonics that cannot be reduced by inductive filter (L) and inductive-capacitance filter (LC). Thats the reason why inductive-capacitive-inductive (LCL) filter is choosen.

While implementing the LCL filter to the inverter system, both capacitive and inductive will produce resonant behaviour. This will lead to harmonic distortion near to resonance frequencies. The resonant frequencies are given as below:

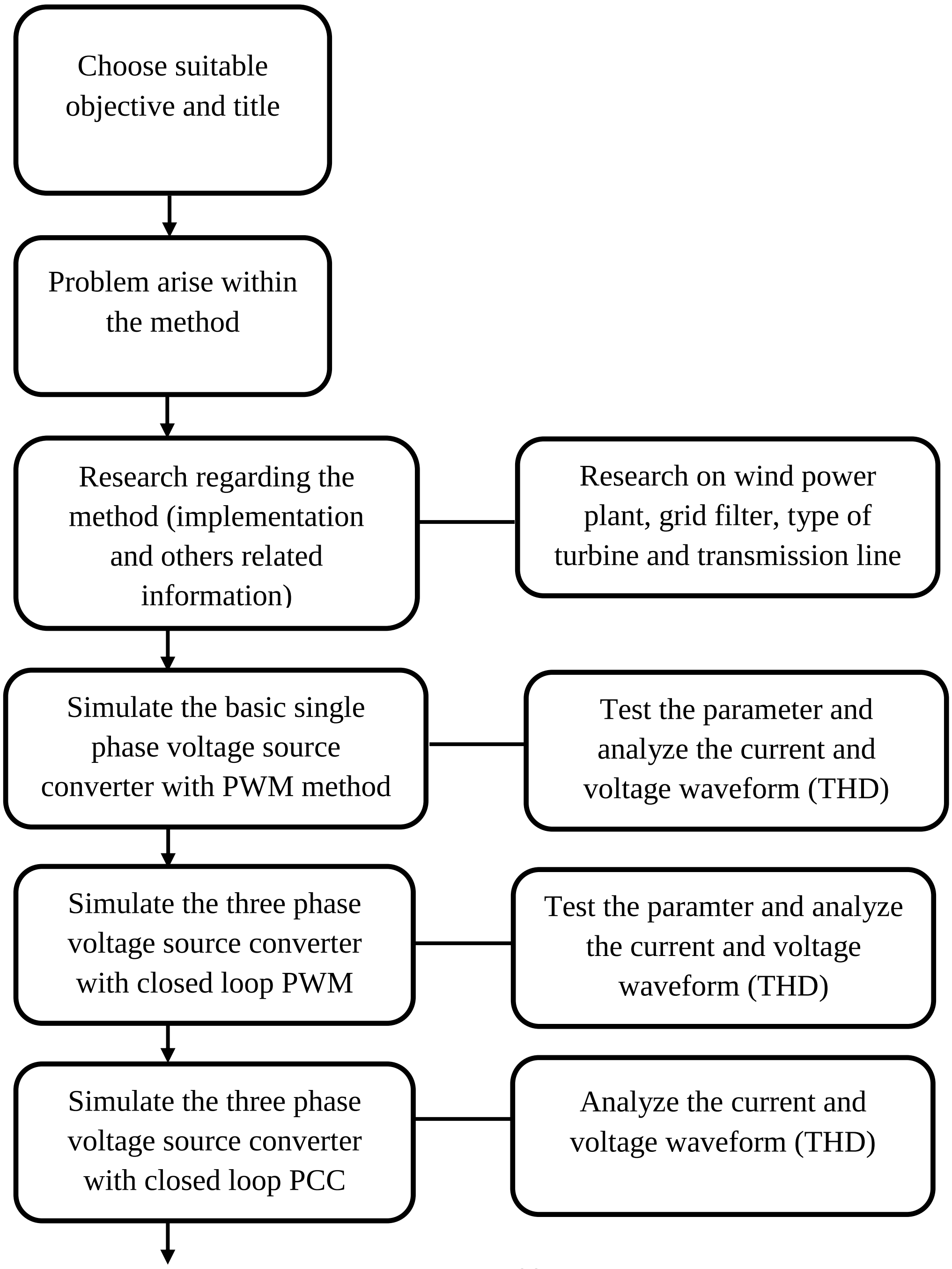
$$\boldsymbol{\omega} = \frac{\mathbf{1}}{\sqrt{\mathbf{LC}}} \quad (1)$$

By modelling the VSC with implement PCC, the author will show and demonstrate the ouput of power, voltage and current after being filter by LCL filter before transmitted it to the grid system.

CHAPTER 3

METHODOLOGY

3.1 Procedure Workflow



Data analyzing and discusion

3.2 Research Methodology

The methodology for this work project can be described as below.

A. Identify objective and scope

   Objective and scope of study in this project is very important as they lead how the project will be carry out. This objectives should match with the current wind farm system and also to extend a research regarding current control method implementation in voltage source inverter.

B. Research on modern wind farm and wind turbine generator

   This research mostly from internet sources and several books. Many research paper that have been found regarding this section. Such as suitable location of wind farms in Malaysia, power control in VSC for distributed generation and others. There are two type wind farm that operated either using synchronous generator or asynchronous generator. Each of type wind farm, depends on the location of highest wind energy receive. For wind turbine generator, each of it, that is synchronous and asynchronous have several advantages and disadvantages. This can be seen from table 1.

C. Research on VSC and current control technique

   Basic of inverter can be seen from VSC. Due to high requirement of specification for wind farm, the component for VSC need to be altered. There are few research and book that elaborate about this topic. For example, like VSC there are two and third level inverter. Each of the level depend on the usage and demand from the load. While for current control technique, research paper based on PWM itself is very important as it can differentiate the method being carry out in predictive current control.

D. Familiarize with MATLAB and implementing the simulation

The simulation software that being used in this project is MATLAB. To get started, simply go to Simulink Icon in the MATLAB. In the Simulink Library browser, there will be a few type of simulation beside Simulink. From this point, insert any block, function block and so on to the empty model and insert any value to it. In order to get familiarize with the MATLAB software, simulation is done using simple PWM system in inverter. Then insert any value to the block to see the waveform behaviour. Later, this simulation will be developed until predictive current control technique is achieved.

E. Testing period

During the testing period, several implementation and ways will be done to find the correct tune for each of the current control method. That is linear PWM and predictive current control. Which mean the correct setting (value) in order to get the desired output

F. Data collection

In this section, the data is collected at the transient state and steady state. So that the comparison between this methods can be seen clearly. Besides that, for every parameters such as output voltage, current and frequency will also be shown.

G. Documentation

Documentation will be including all the results that have been done. A discussion will be made to see the pro and cons for each current control method. Also its suitablity to the conventional wind farm.

EVENT	EXPECTED COMPILATION
Identify objective and scope	Week 1 – Week 2
Research related information (type of turbine,grid filter,transmission line)	Week 3 – Week 5
Highlight research on PWM and PCC method	Week 4 – Week 9
Implement three phase PWM inverter using Matlab/SIMULINK	Week 5 – Week 11
Implement three phase PCC inverter using Matlab/SIMULINK	Week 13 – Week 18
Analyze the waveform of voltage and current for both method	Week 18 – Week 24

3.3 Key Milestones

Discuss the harmonic distortion (THD)	Week 19 – Week 24

Table 4: Key milestones for this project (FYP2)

CHAPTER 4

RESULTS AND DISCUSSION

As for the result, the author begin with simulation using MATLAB Simulink.To get familiar with this converter, the author simulate the single phase full bridge voltage source inverter with linear PWM. Figure 8 shows the simulation and the output.

4.1 : Simulation of single phse inverter

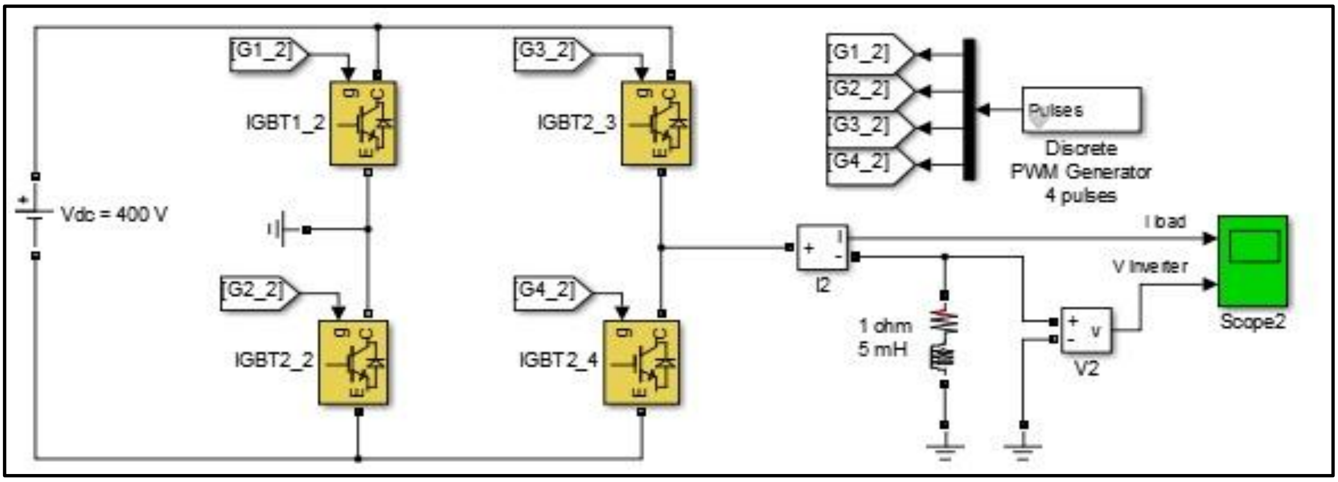


Figure 8: Full-Bridge VSI

In this simulation, the converters were built with IGBT block which is the basic buiding block of all voltage source converters. The IGBT block is a simplified model where the forward voltages of the forced-commutated devoce and diode are ignored. VSC (inverter) are controlled in open loop with the PWM generator block. The circuit use DC voltage (V_{dc}= 400V). Figure 9 shows the setting block and parameters for the PWM generator 4 pulse. The PWM signal is feed to the gate of each IGBT.

Table 5: Simulation parameters for Full-Bridge VSI

Parameter	**Values**
Input voltage, V_{dc} (V)	400
Load resistance,R (Ω)	1
Load inductance,L (H)	5*m*
Output frequency,f (Hz)	60
Carrier frequency,f (Hz)	1080
Modulation index,m	0.8
Simulation stop time,t (s)	0.2
Power factor,pf	0.99

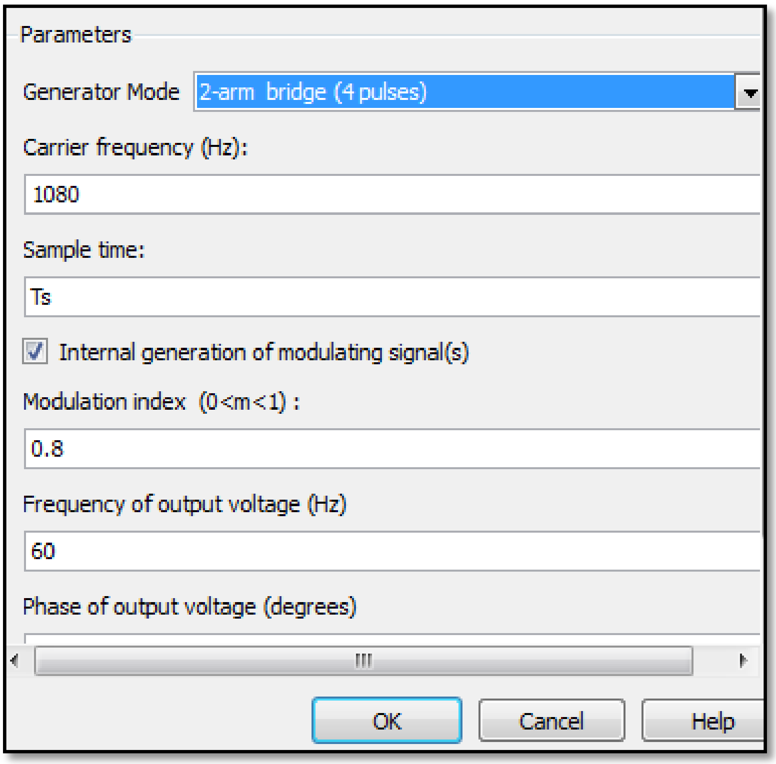


Figure 9: Block Parameter for PWM Generator

Figure 10 and figure 11 shows the frequency spectrum of current and voltage at transient state. Harmonics generated by the full-bridge are high for current load. Total demand distortion (TDD) of current load is 20.85%. Figure 10 shows the frequency spectrum.

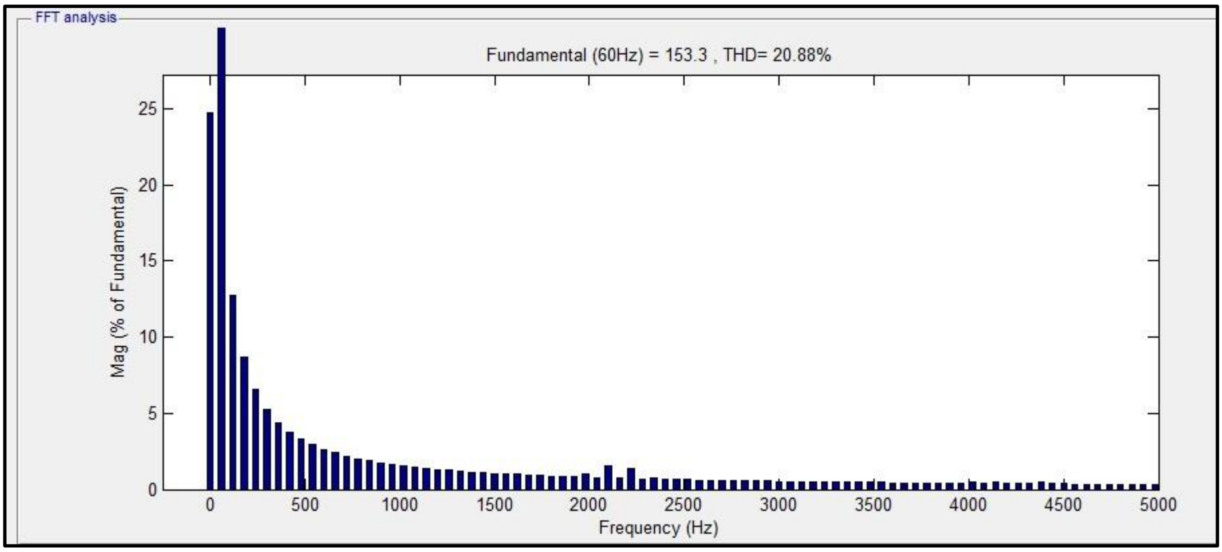


Figure 10: Frequency spectrum of THD for transient state (current)

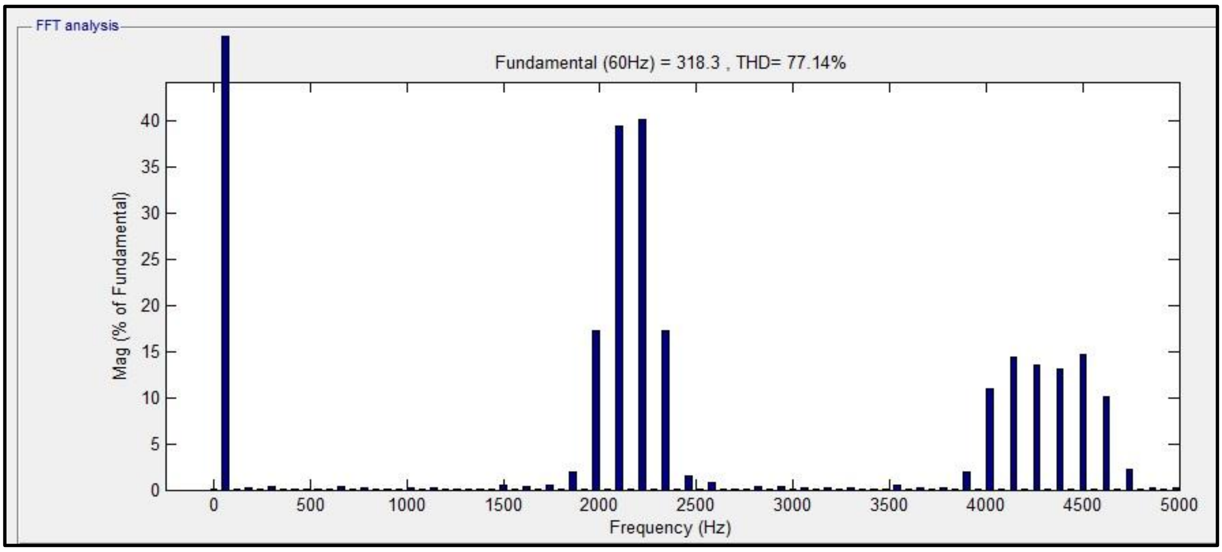


Figure 11: Frequency spectrum of THD for transient state (voltage)

Total harmonic distortion (THD) of voltage inverter is 77.14%. While for current, THD is 20.88%. Both THD are measured in one cycle. Starting from zero simulation time until it reach the highest peak of waveform produced.

For steady state, the harmonic distortion of each parameter can be shown from figure 12 and figure 13. Total harmonic distortion (THD) of current load is 2.31% while for total harmonic voltage distortion is 77.12%. Steady state is measured from maximum amplitude until the waveform reach steady state.

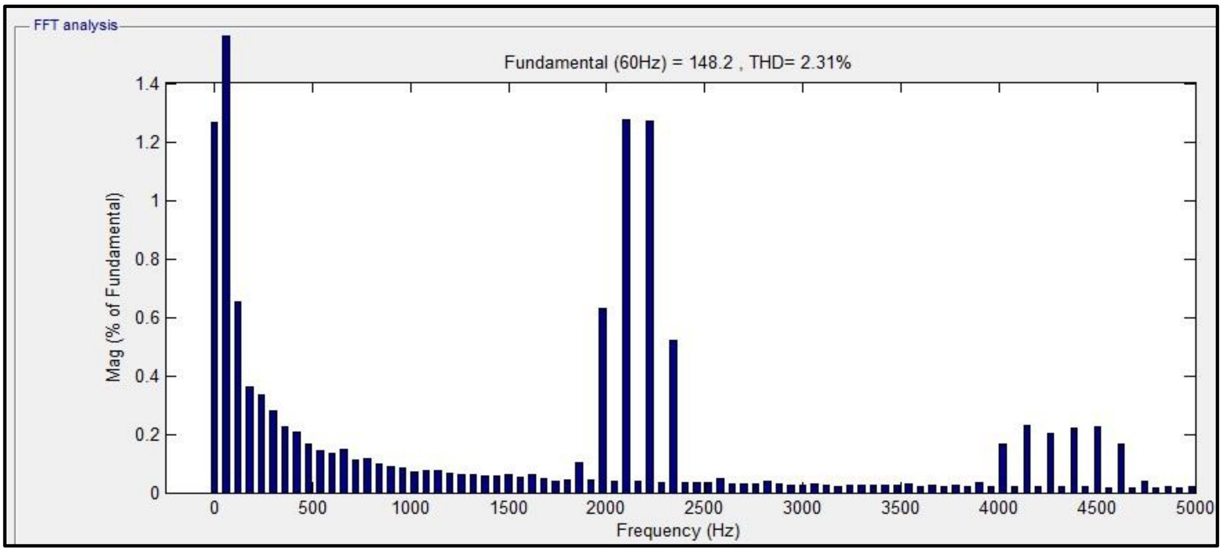


Figure 12: Frequency spectrum of THD for steady state (current)

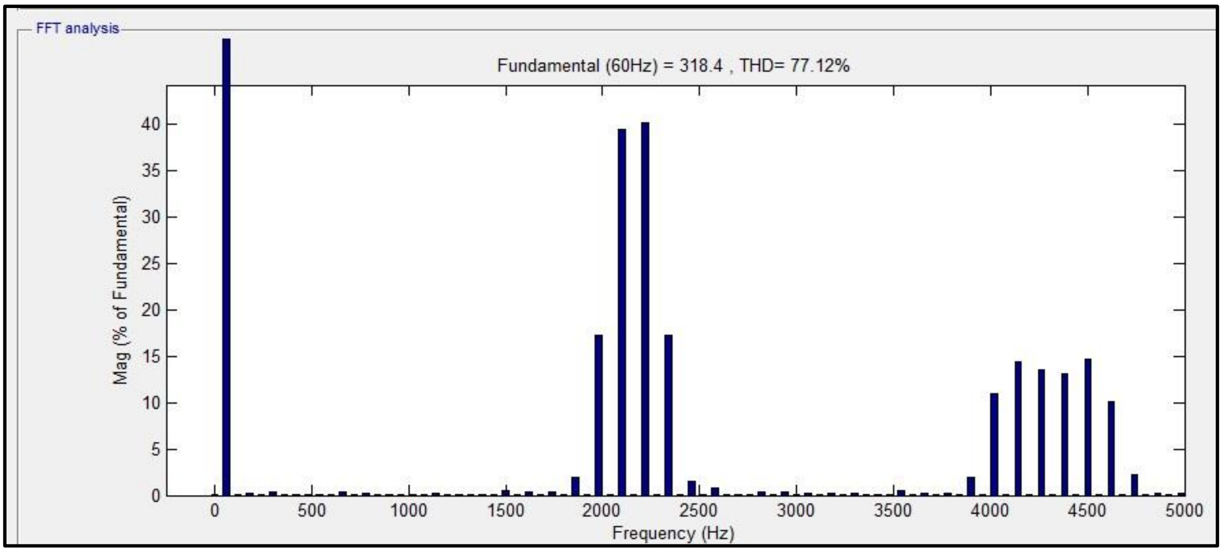


Figure 13: Frequency spectrum of THD for steady state (voltage)

Transient state state for both voltage and current shows that, it exceed the standard of IEEE-512. This is due to low switchng frequency that being set up for PWM generator. The signal will be inserted into inverter gate. As being mentioned from objective of this project, the study of switching frequency will carry out in next discussion, that is three phase PWM inverter (closed loop) and three phase PCC inverter (closed loop). The THD from starting time until it reach the maximum amplitude indicate that the current react ununiformly with component of the load. Supposely the current drawn from the system is sinusoidal waveform. But due to this unlinear load, the harmonic distortion exceed the limit of IEEE-512 standards.

While for steady state measurement, the harmonic distortion is low compare to transient state. This is because the time taken or period for measurement of steady state is taken differently from transient state. The current ripple for steady state in that measurement is less compare to transient state. With this result, it show that the inverter can produce good output current in steady state and can provide more stability to its load. While for steady state in voltage, the waveform show the voltage of the inverter itself when the signal from PWM generator is feedback to the gate of inveter.

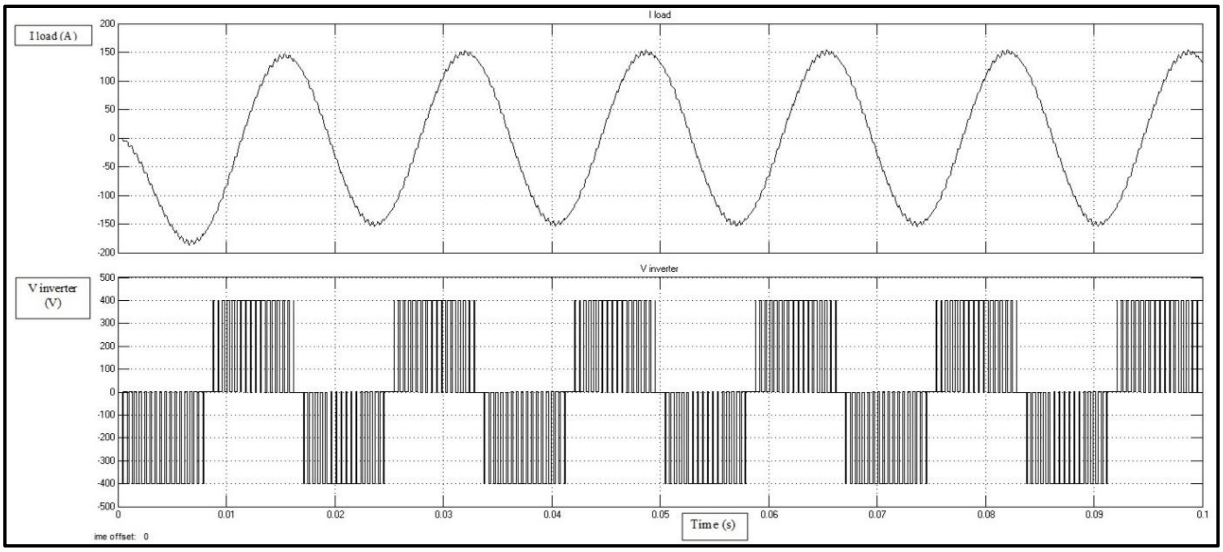


Figure 14: Output waveform(I load,V inverter)

From figure 14, the simulation stoptime is set until 0.2. This is done in order to see the steady state of current behaviour of waveform. The starting waveform of load current is fluctuate and almost reached negative -200A. But, as it approaching to the stoptime, the waveform seems quite stable and smooth. For voltage waveform, the actual calculation for V2 or voltage inverter is shown below.

$$\mathrm{V2} = \mathrm{m} * \mathrm{V_{dc}} \qquad (2)$$

$$\mathrm{V2} = 0.6 * 400$$

$$\mathrm{V2} = 240\mathrm{V}$$

Comparing with the waveform from figure 14, voltage maximum is 400.2V (positive cycle). Percentage error can be calculates from below.

$$\left|\frac{240-400.2}{240}\right| \times 100\% = 66.75\% \qquad (3)$$

4.2 : Simulation of three-phase inverter with implementing PWM

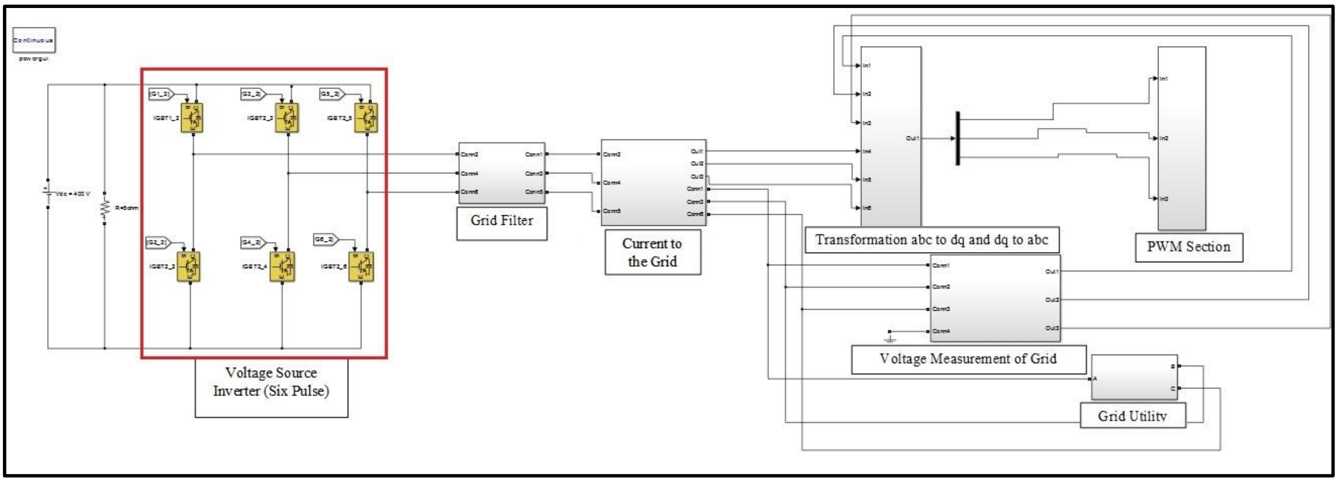


Figure 15: Three-phase inverter with pulse width modulation

In this simulation, the converters are built with six IGBT's block. Six pulses will be generated from PWM section block into each of the gate of IGBT. This PWM signal is produced through comparing triangular signal (carrier signal) with sinusoidal waveform from transformation block. Discrete virtual block PLL is used to generate grid voltage angle and synchronize with abc-to-dq block transformation block. The circuit use DC voltage (V_{dc}= 400V). Table 6 shows the parameter value that being used in this simulation.

Table 6: Simulation parameter for three phase PWM inverter

Parameter	Values
Input voltage, V_{dc} (V)	400
Reference voltage, V^*_{dc} (V)	400
Resistance, R (Ω)	5
Capacitance filter, C (F)	0.1m
Inductance filter,L (H)	5*m*
Active Power, (W)	1M
Voltage phase to phase, (V)	10k
Fundamental Frequency,f (Hz)	60
Carrier frequency,f (Hz)	1080
Simulation stop time,t (s)	0.2
Modulation index,m	0.8
Power factor,pf	0.95 (lagging)

Practically, the grid voltages might contain harmonics and distorted waveform, hence phase locked-loops is used for the detection of grid voltage angle. This angle will reduce current harmonics by an additional feedback path.

With VOC schemes, the three phase currents that in stationary frame I_a, I_b and I_c will be transformed into two phase currents, that is I_d and I_q which are active and reactive components of the three phase-currents.

As from table 6, the simulation is set to power factor 0.95 lagging. This value is a assumption for the system as many wind power plant try to achieve this target nowadays. Q_g is the reference for the reactive power. It can be set to zero for unity power factor, negative value for leading power factor and also positive value for lagging power factor.

The q-axis reference current i^*_{qg} can be obtained from

$$i^*_{qg} = \frac{Q^*_g}{-1.5 v_{dg}} \qquad (4)$$

Where;

$$v_{dg} = v_g \qquad (5)$$

The PI controller generates the reference current I^*_{dg} according to the operating conditions. This reference value will be compare with actual I_{dg} from abc-to-dq block transformation. Since the DC voltage, V_{dc} of inverter is set by its reference V^*_{dc}, it is kept constant by PI controller. Hence generate the new voltages, V_{di} and V_{qi} into the dq-to-abc transformation block.

Figure 17,18 and 19 shows the fast fourier transform (FFT) analysis of current for each phase at transient state. The measurement taken starting from zero second until three cycle. Figure 16 shows output waveform for current drawn to the grid load.

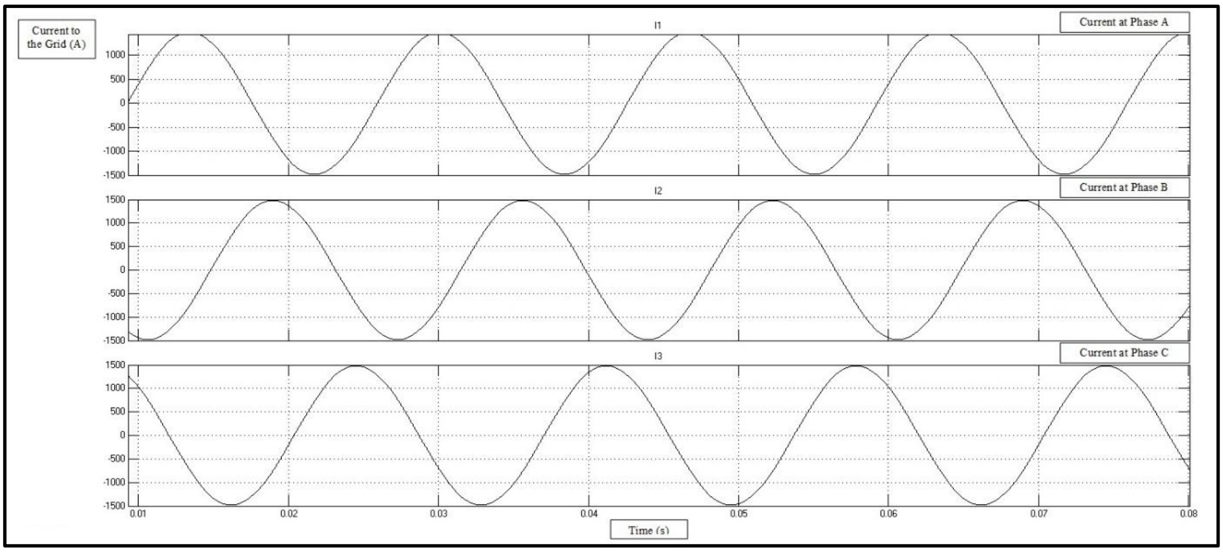


Figure 16: Output current waveform (I_a ,I_b and I_c)

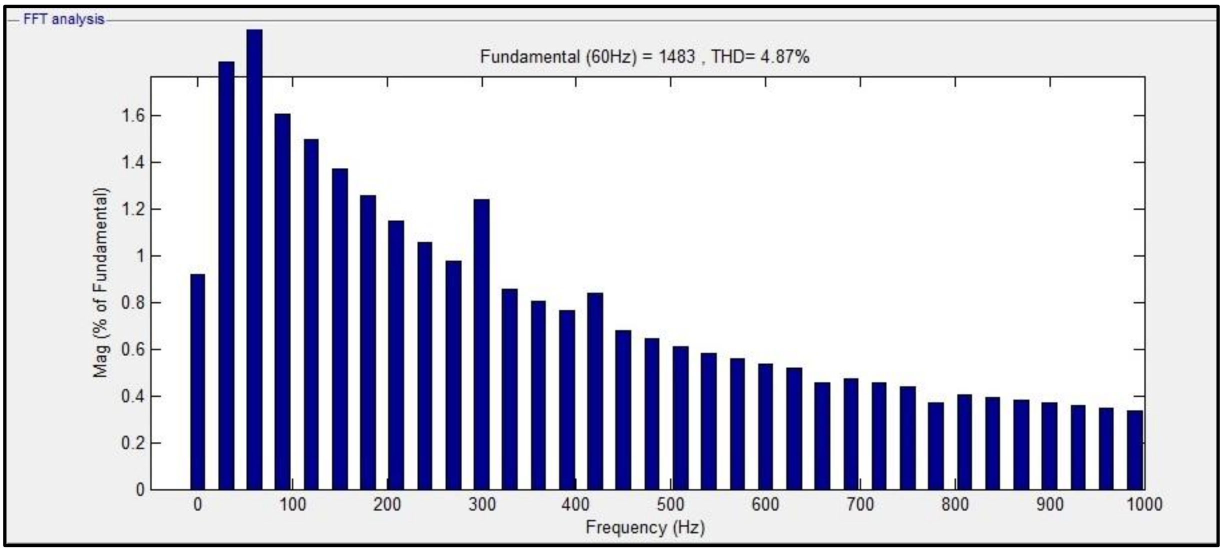
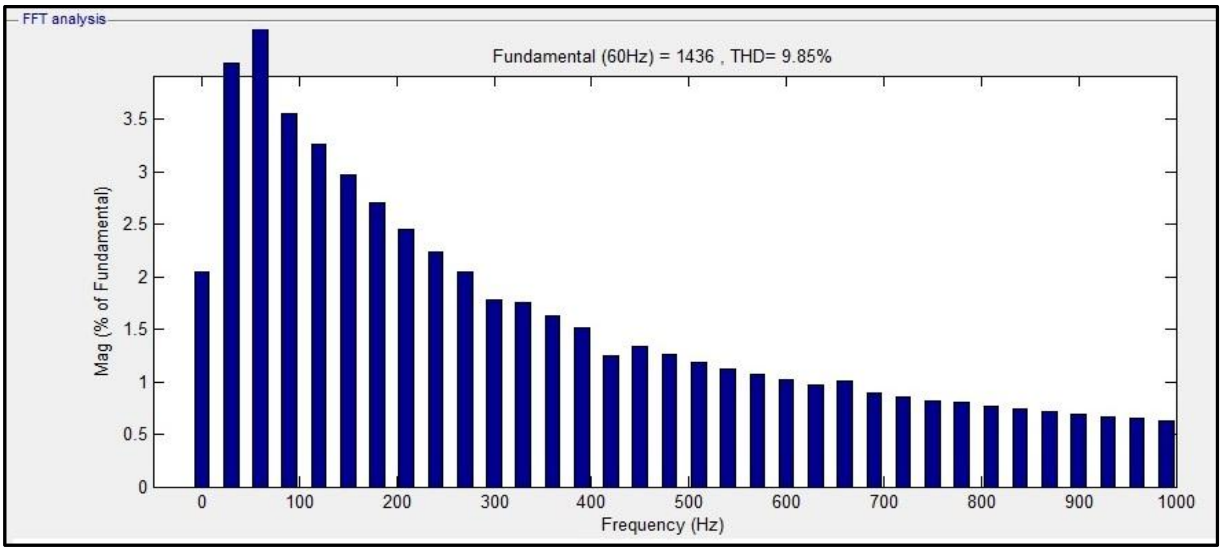


Figure 17: Frequency spectrum of THD at I_a for transient state (current)

Figure18: Frequency spectrum of THD at I_b for transient state (current)



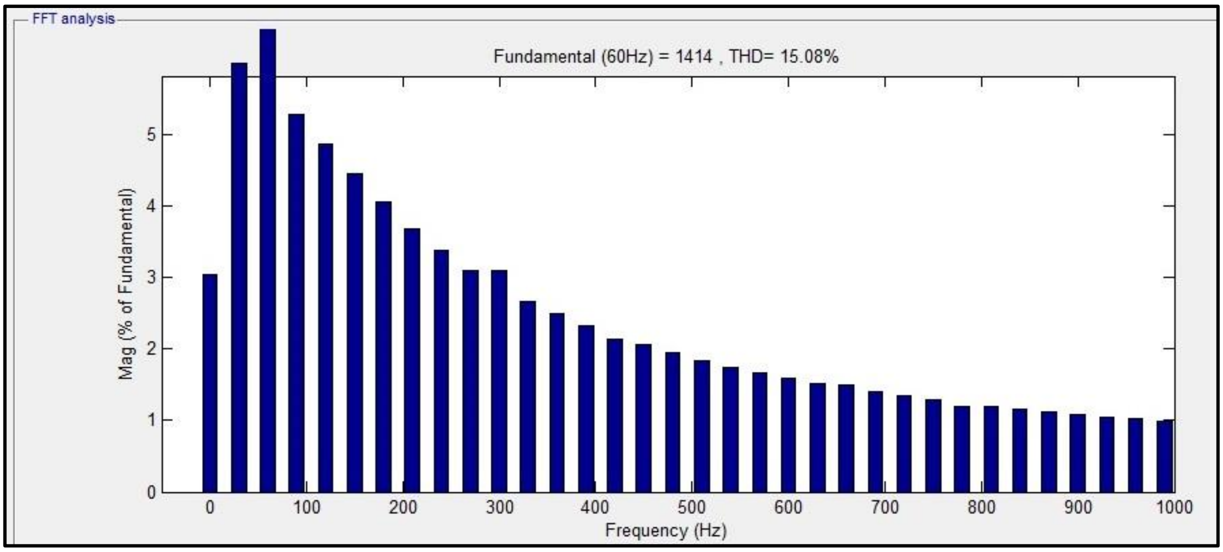


Figure 19: Frequency spectrum of THD at I_c for transient state (current)

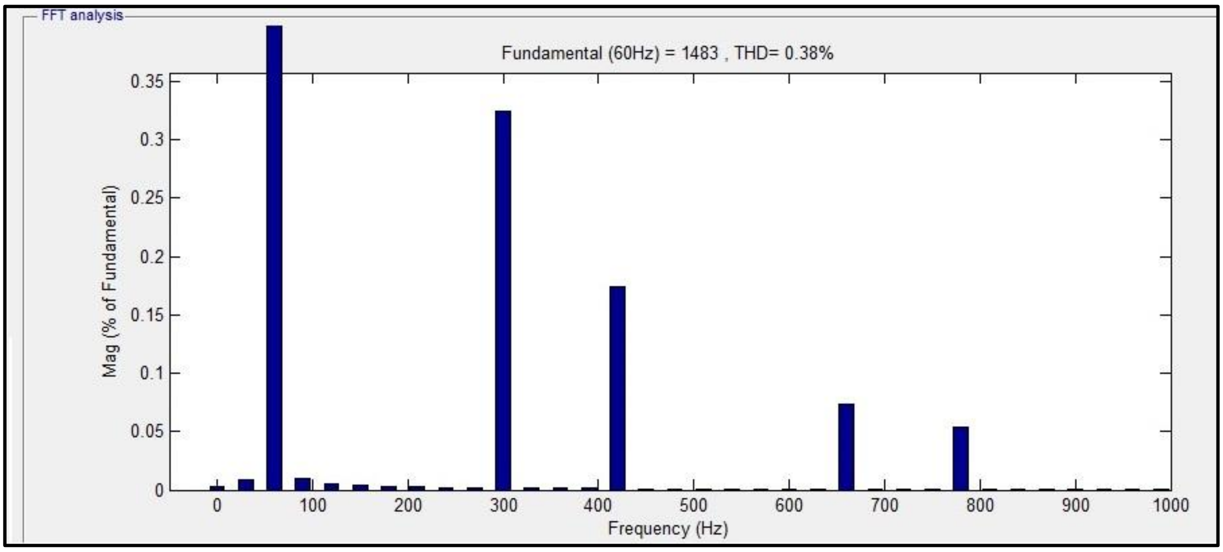


Figure 20: Frequency spectrum of THD at I_a for steady state (current)

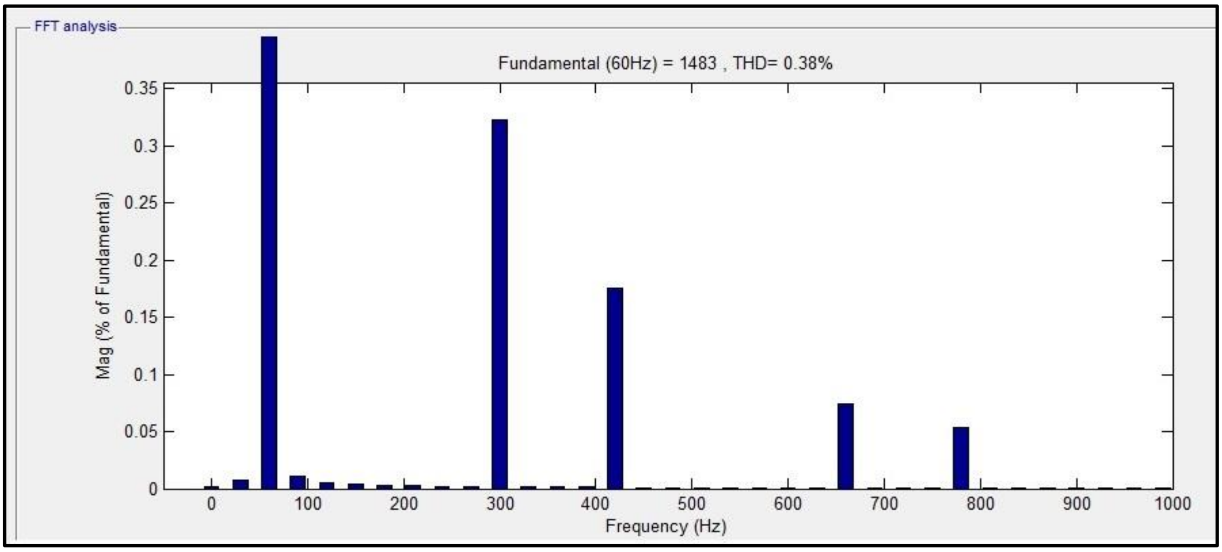


Figure 21: Frequency spectrum of THD at I_b for steady state (current)

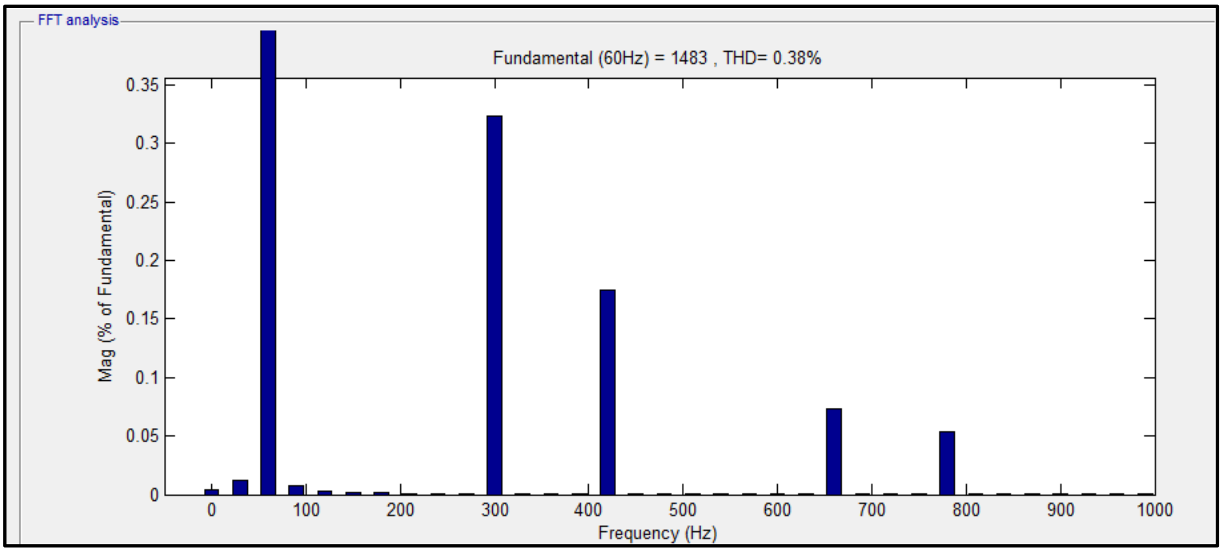


Figure 22: Frequency spectrum of THD at I_c for steady state (current)

The highest total harmonic distortion in transient state between each phase is phase C, that is 15.08% (Figure 19). Among the three phase, this is the highest one. This is because PWM signal that been produced through comparing carrier signal with sinusoidal form experienced low switching frequency from the ripples of current waveform inside phase locked loop. Phase locked loop identify the angle of the load from grid utility. As it synchronize with abc to dq block and dq to abc block transformation, it create ripples waveform for each phase during transient state. Besides with the addition of PI controller in the system, it produced some error to the sinusoidal waveform itself after converting dq frame to abc state and has a poor performance at low switching frequency.

From figure 17, 18 and 19, it can be show that the highest harmonic order is in third order. Although harmonic distortion of current in steady state is low, later in future it can give impact to the cabling system from upstream to downstream, busbar in aspect of isolation and also damage (burn) in equipment such as circuit breaker and relay. High distortion for third order that normally happen nowadays in the industry cause a sharp increase in zero sequence current and hence increase the neutral conductor. This effect need the engineer to design proper electronic system to serve the non-linear loads beside the grid filter that being implement.

Figure 20,21 and 22 shows the fast fourier transform (FFT) analysis of current for each phase at steady state. Harmonics generated by the full-bridge are low for current load. The measurement is taken starting from maximum amplitude of waveform until three cycle. It can be noticed that the harmonic content is significantly reduced compare to transient state.

THD for steady state of current in each phase is same, 0.38%. Low THD indicate that simulation system can maintain the state if the load is not injected or rejected from the system. It is good system to conclude that the THD is below from 0%. But unfortunately, in windfarm power generation system, energy variation will be not same for all the time.

For transient state and steady state of grid load voltage, the harmonic distortion of each parameter can be shown from figure 24,25, 26,27,28 and 29 through frequency spectrum graph. The total harmonic distortion (THD) of grid load is almost the same, 0.02%, 0.01% and 0.02% for both state. Figure 23 shows the output waveform of grid load voltage. The output waveform is almost equal or approximate to fundamental sinusoidal waveform.

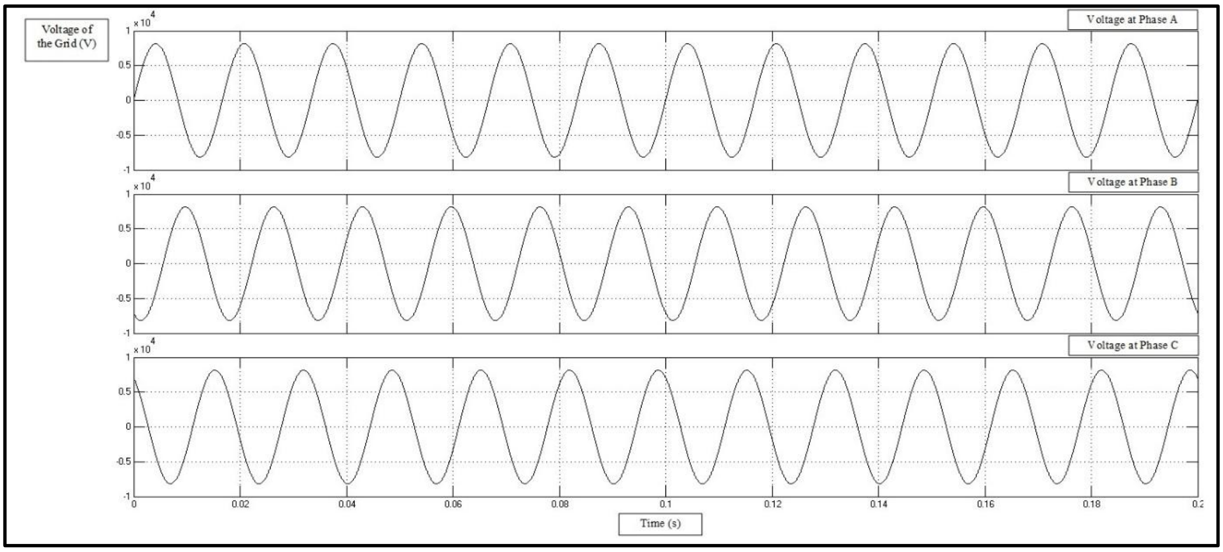


Figure 23: Output voltage waveform (V_a ,V_b and V_c)

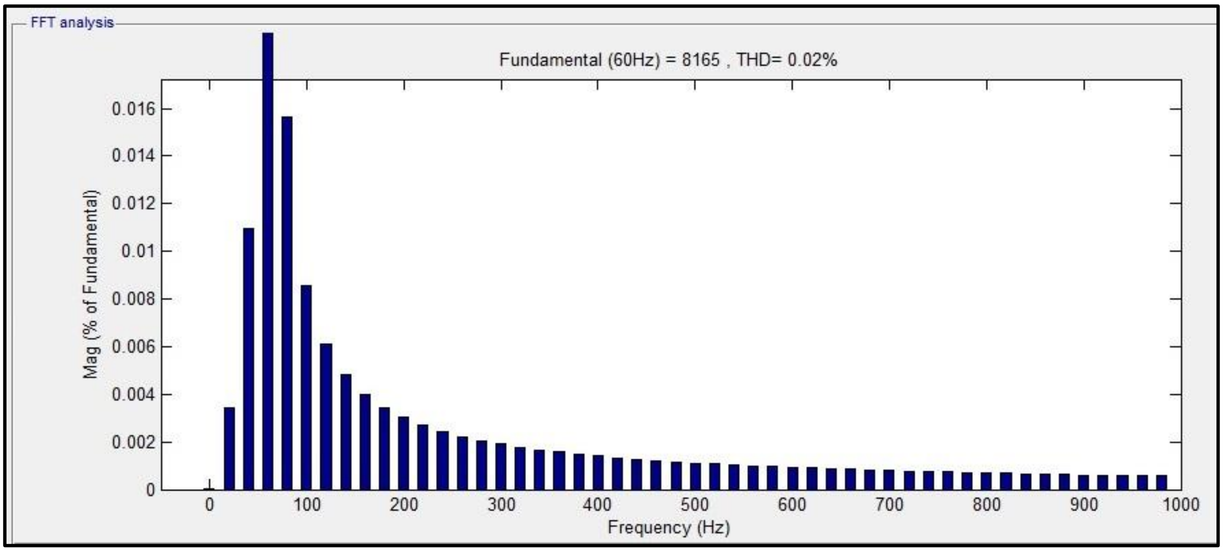


Figure 24: Frequency spectrum of THD at V_a for transient state (voltage)

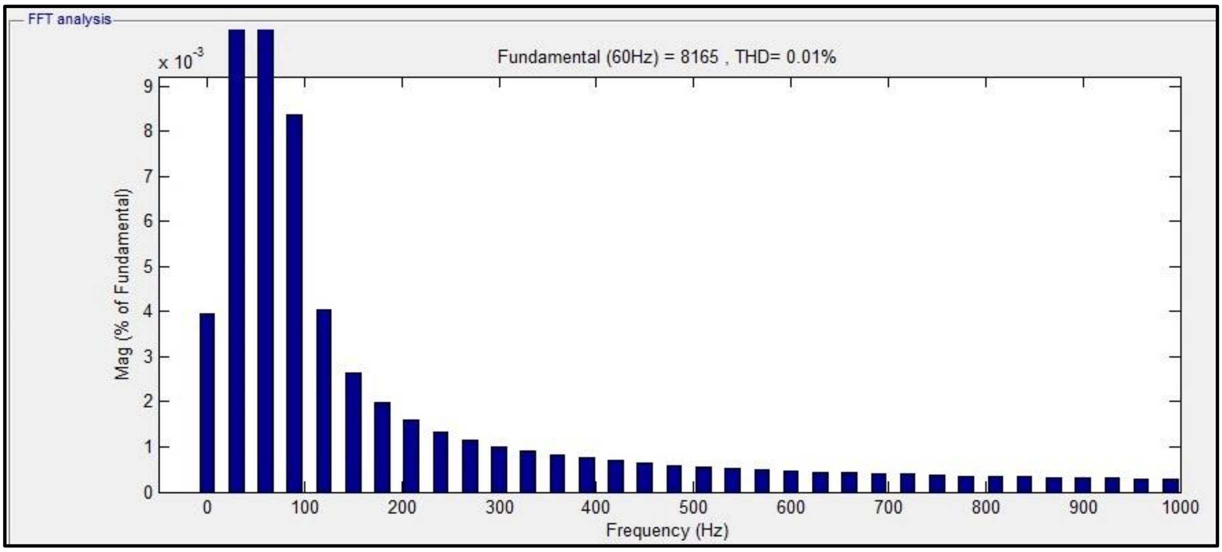


Figure 25: Frequency spectrum of THD at V_b for transient state (voltage)

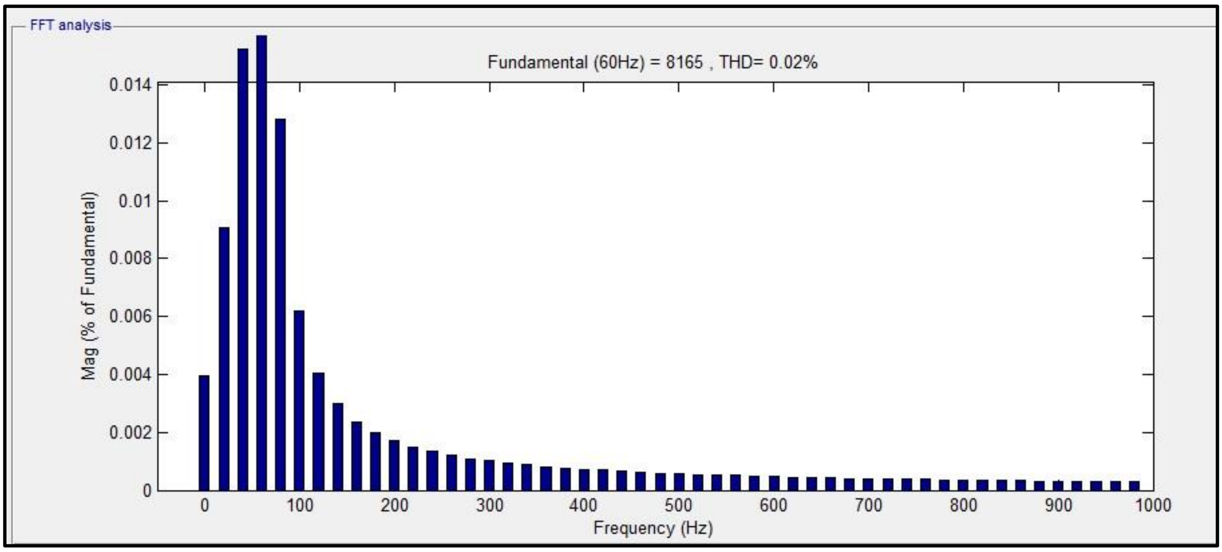


Figure 26: Frequency spectrum of THD at V_c for transient state (voltage)

Total harmonic distortion of voltage for transient state can still give impact eventhough the percentage is low. Because, the simulation that been carry out in this project is theoretically not practically. In real industry, there will be a voltage sag and swell that cause the system to malfunction or component to burn.

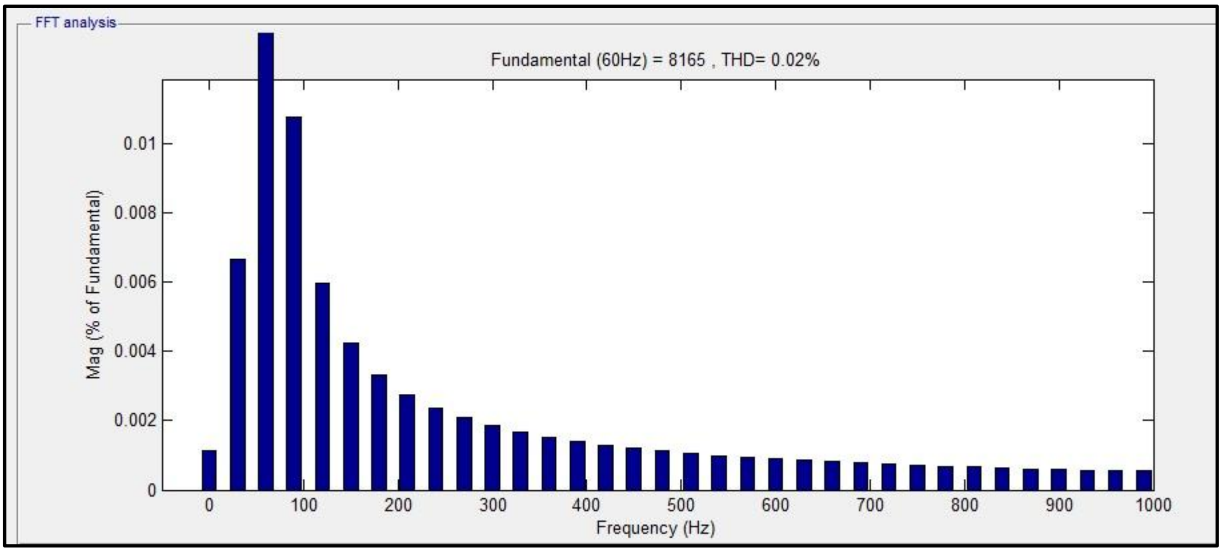


Figure 27: Frequency spectrum of THD at V_a for steady state (voltage)

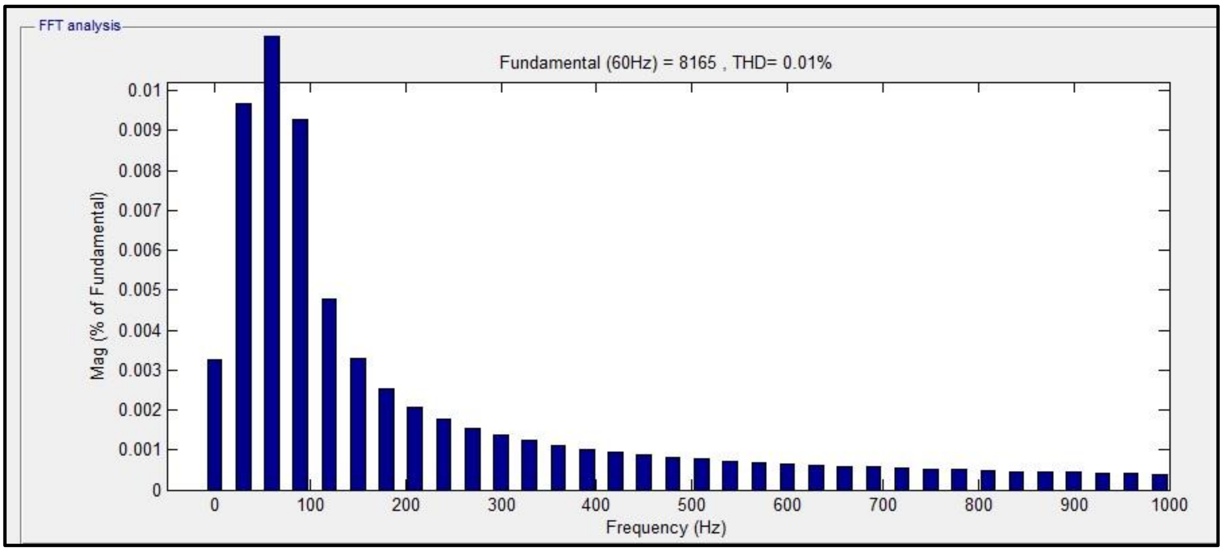
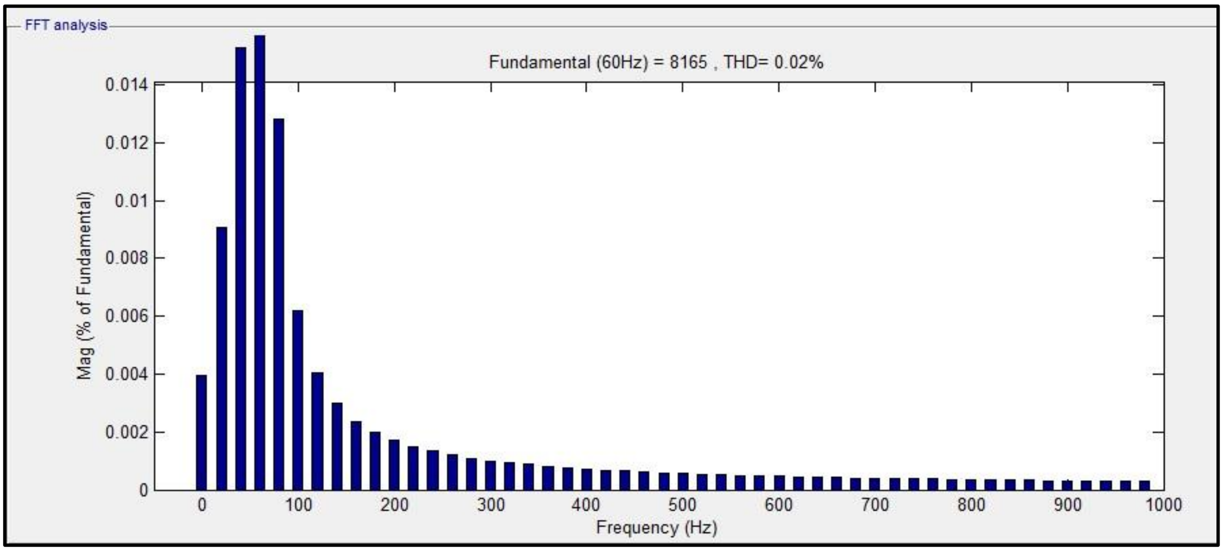


Figure 28: Frequency spectrum of THD at V_b for steady state (voltage)

Figure 29: Frequency spectrum of THD at V_c for steady state (voltage)

Figure 27, 28 and 29 shows the steady state of voltage during steady state. As being mentioned, THD is almost the same with transient state. This is because the grid utlity that being used in this simulation does not experience larger significant during injecting of load



grid or rejecting load grid to the system. In addtion, the grid filter that being used is LCL type. This grid filter gives good voltage and current ripples attenuation. Thus from figure 23, the attenuation of voltage ripples inside the waveform is very low. Resulting the voltage of total harmonic distortion is also low.

From figure 23, the simulation stoptime is set until 0.2. This is done in order to see the behaviour of waveform and amplitude of grid load. Based from the load grid calculation :

$$S = VI \qquad \textbf{(6)}$$

$$1M = 1k * I_{rms}$$

$$I_{rms} = 1M/1k$$

$$I_{rms} = 1000A$$

Irms indicate the current rating for the grid. For three phase(curernt), the maximum amplitude is almost to 1549A. This is due to the 0.95 lagging power factor that being set up based on table 6.

4.3 : Simulation of three-phase inverter with implementing PCC

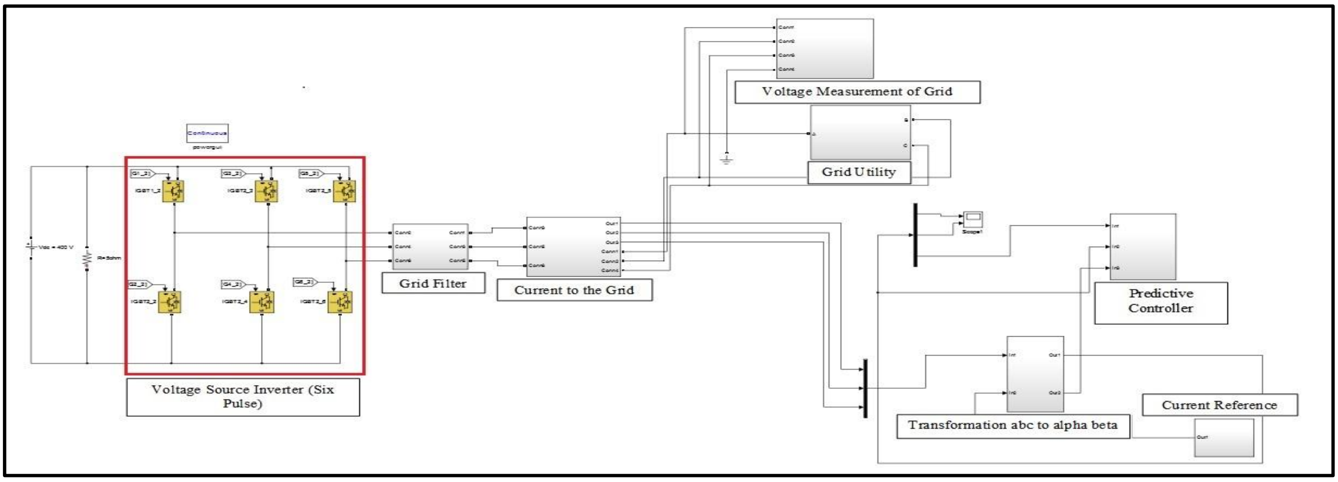


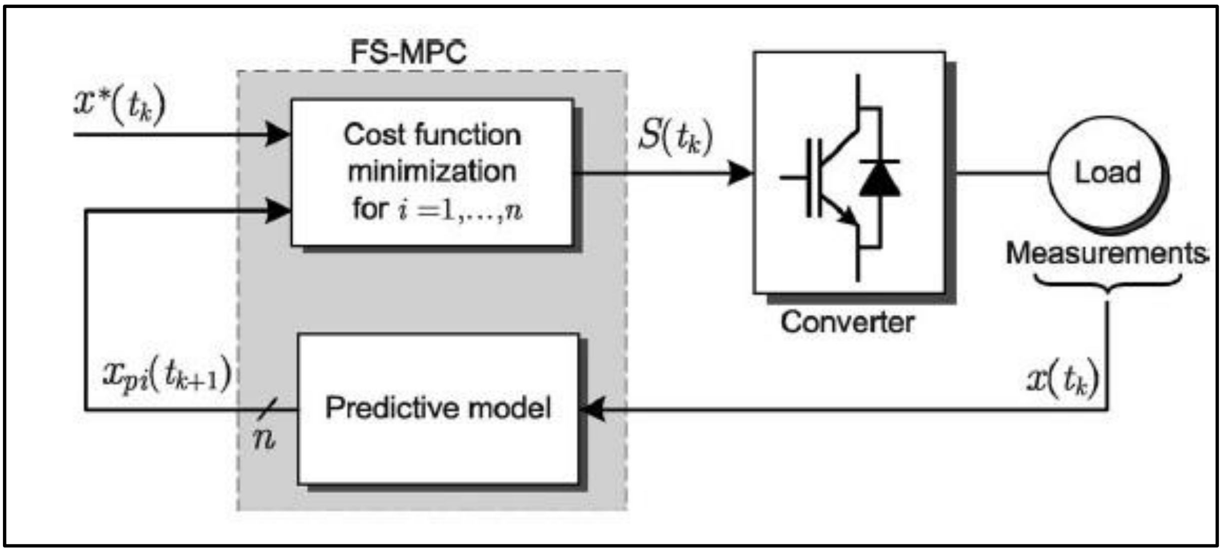
Figure 30: Three-phase inverter with predictive current control

In this simulation, the converters are built with six IGBT's block like in previous 4.2. Six pulses will be generated from Model Predictive Controller (MPC) section block into each of the gate of IGBT. The MPC controller predicts the behaviour of the inverter for finite possible current vector on each sampling interval. While the cost function is used to evaluate the current vector for the next sampling interval based on predicted grid load. The optimal switching state is selected and applied to the gate of inverter during next sampling interval in which minimizes the cost function. The MPC block diagram of predictive controller can be shown from figure 30. The circuit use DC voltage (V_{dc}= 400V). Table 7 shows the parameter value that being used in this simulation.

Table 7: Simulation parameters for three phase PCC

Parameter		**Values**
Input voltage, V_{dc}	(V)	400
Reference voltage, V^*_{dc}	(V)	400
Resistance, R	(Ω)	5
Capacitance filter, C	(F)	0.1m
Inductance filter,L	(H)	5m
Active Power,	(W)	1M
Voltage phase to phase,	(V)	10k
Fundamental Frequency,f	(Hz)	60
Carrier frequency,f	(Hz)	1080
Simulation stop time,t	(s)	0.2
Modulation index,m		0.8
Power factor,pf		0.95 (lagging)

Figure 31: generic MPC control



diagram

A much more simplier control block diagram for the implementation of MPC shown from figure 31. Variable $x(t_k)$ is consider as sampled parameter that being taken into predictive model, in this case is the current value (phase a, b, and c). Variable $x_{pi}(t_{k+1})$ is a predictive function that its objective is to predict all possible system transition. While cost function depend on the reference value, $x^*(t_k)$ and predictive function to minimize the cost function by calculate it to the near future reference value. This control method is not limited to three phase system only, but also in multiple variables, system constraints, saturations and every properties that can be mathematically modeled and measured inside MPC model and cost function.

From figure 30, the currents $i_{(abc)}$ in stationary frame inside transformation abc to alpha beta block are transformed into $i_{\alpha\beta}$ by Clarke transformation. In previous simulation system, the transformation that were used is Park transformation. Both are the similar concept but different in phase quantities of reference frame. For Park transformation, the dq0 transform is the projection of the phase quantites onto a rotating two-axis reference frame. In other hands, the Clarke transformation, is the projection of phase quantities onto a stationary two-axis reference frame.

Compare with linear PWM method, MPC provide more flexibility and potential in controlling the variable. In this project, the variable that will be controlled is three phase current that flow into grid utility.

Figure 33,34 and 35 shows the fast fourier transform (FFT) analysis of current for each phase at transient state. The measurement is taken starting from zero second until three cycle. Figure 32 shows output waveform for current drawn to the grid load.

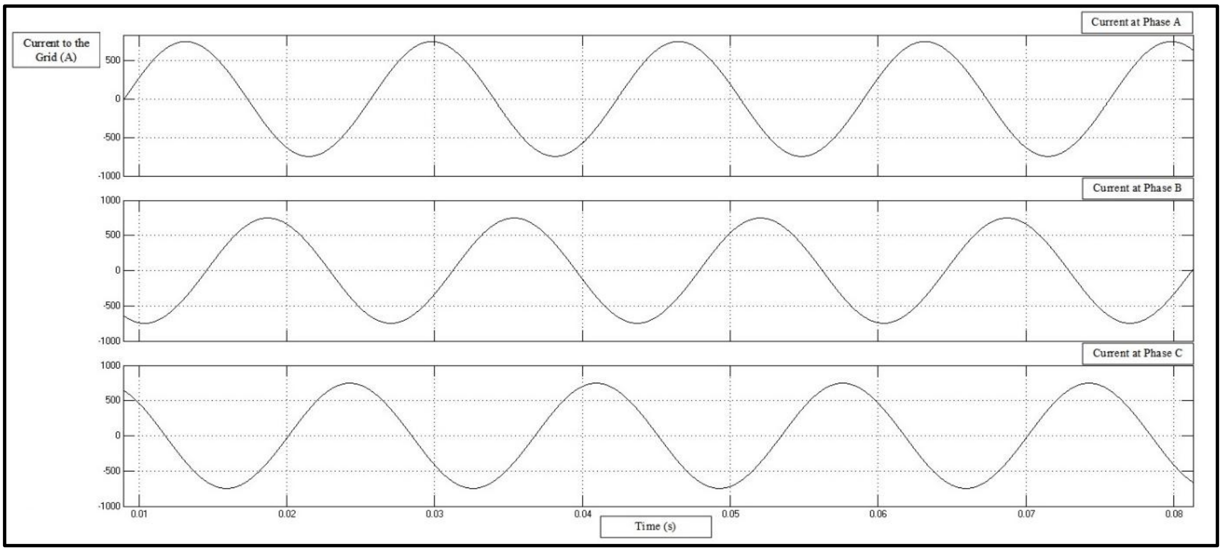


Figure 32: Output current waveform (I_a ,I_b and I_c)

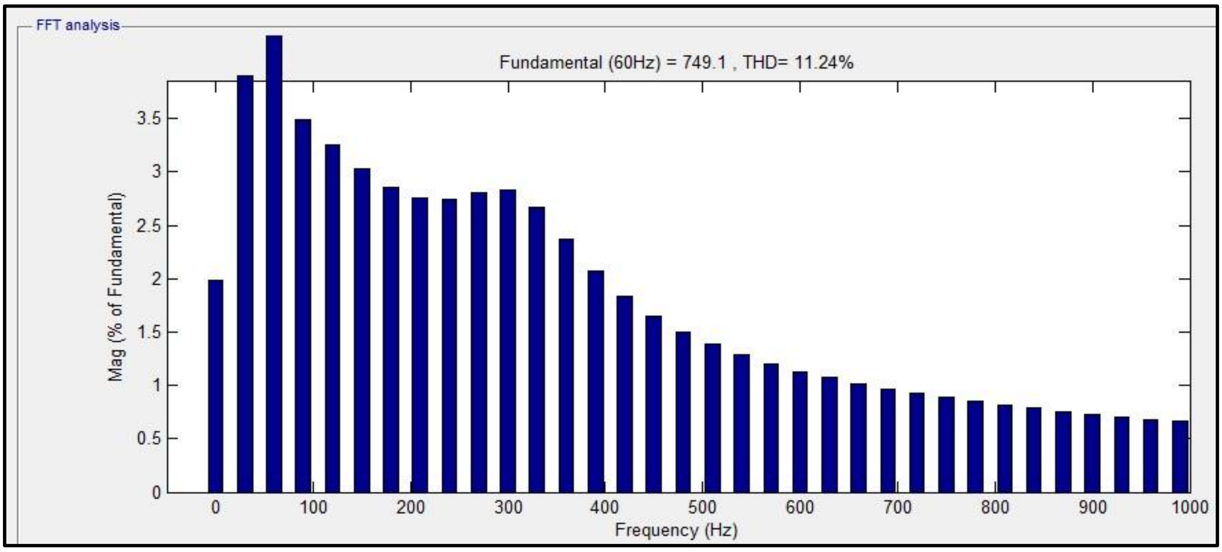
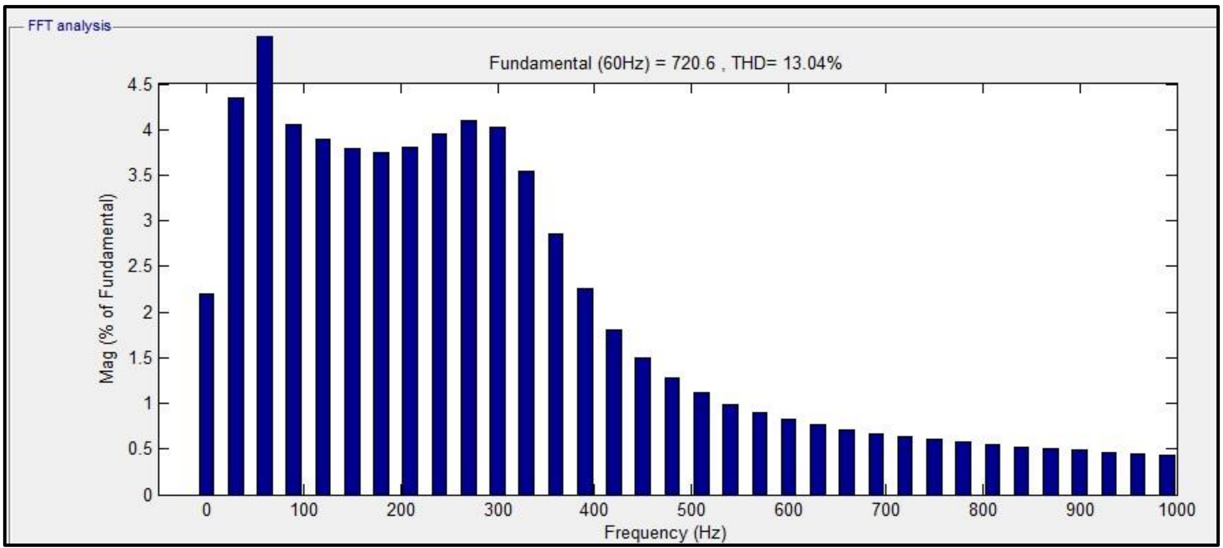


Figure 33: Frequency spectrum of THD at I_a for transient state (current)

Figure 34: Frequency spectrum of THD at I_b for transient state (current)



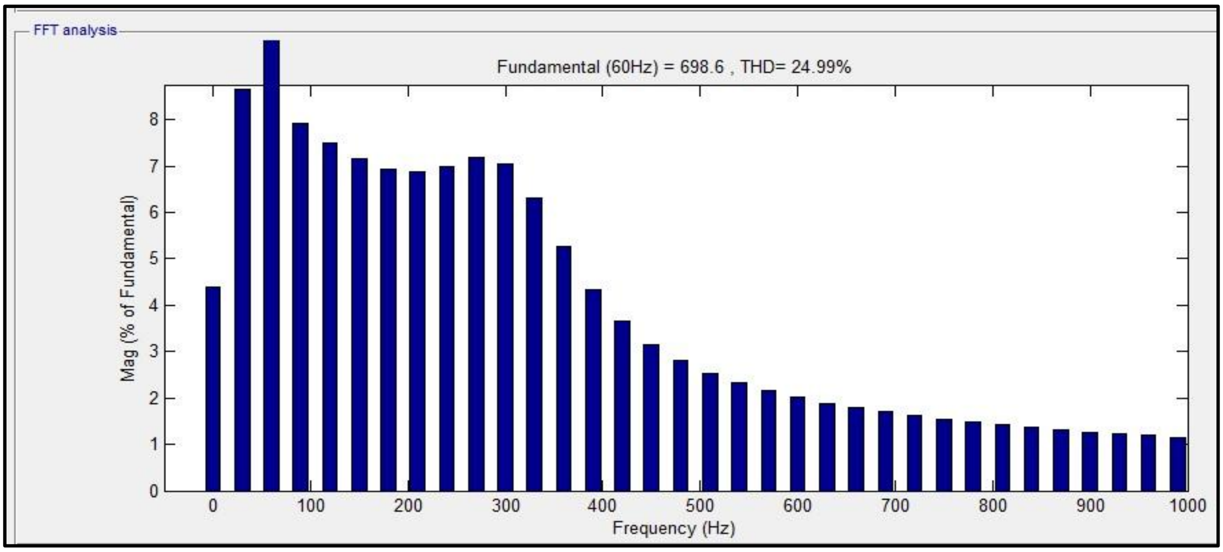


Figure 35: Frequency spectrum of THD at I_c for transient state (current)

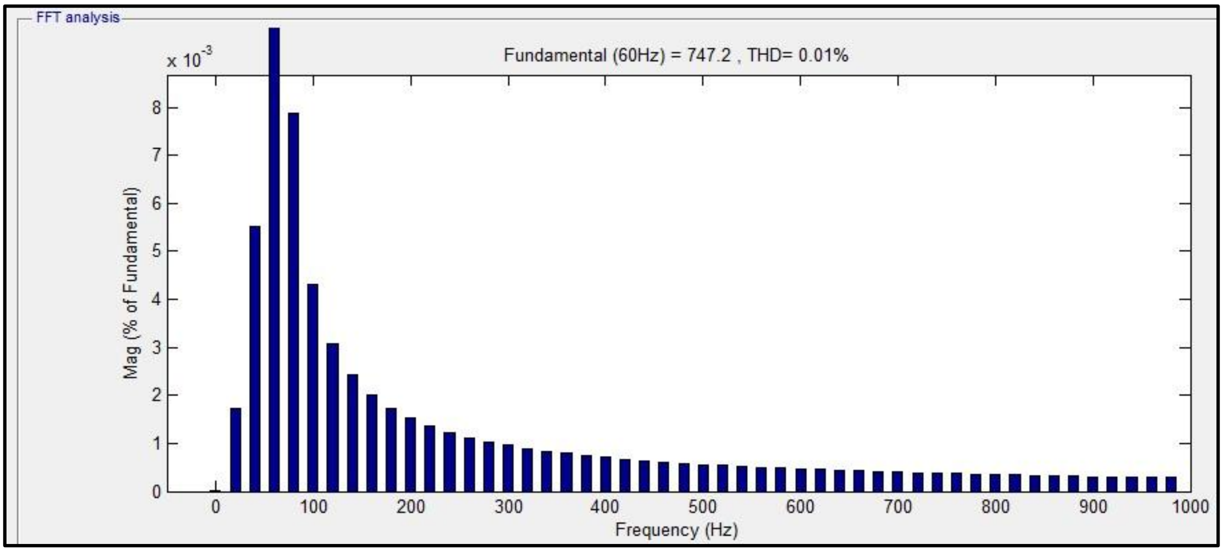
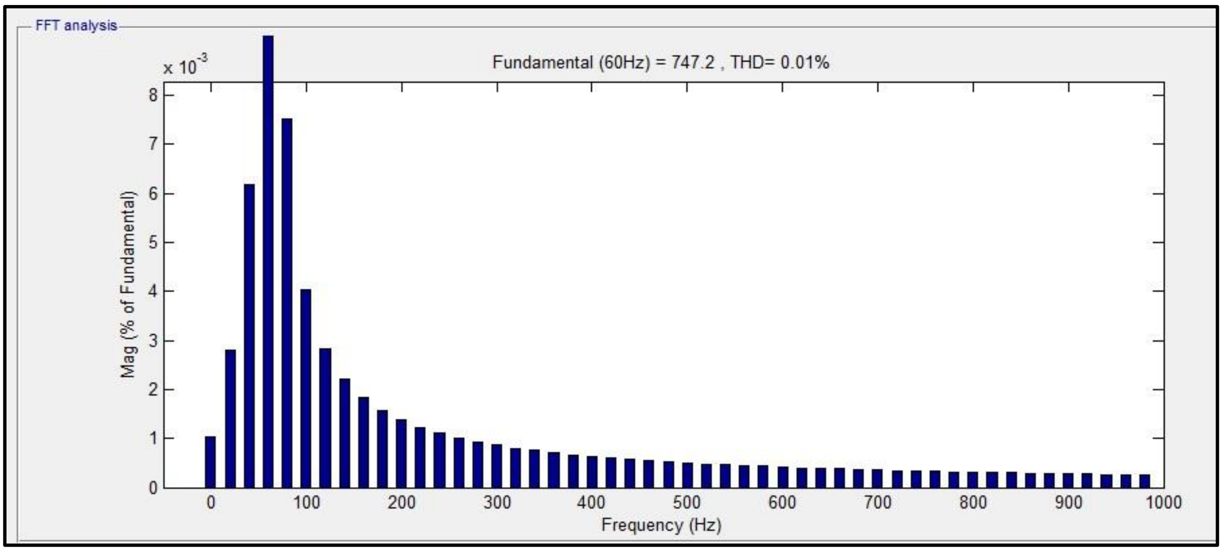


Figure 36: Frequency spectrum of THD at I_a for steady state (current)

Figure 37: Frequency spectrum of THD at I_b for steady state (current)



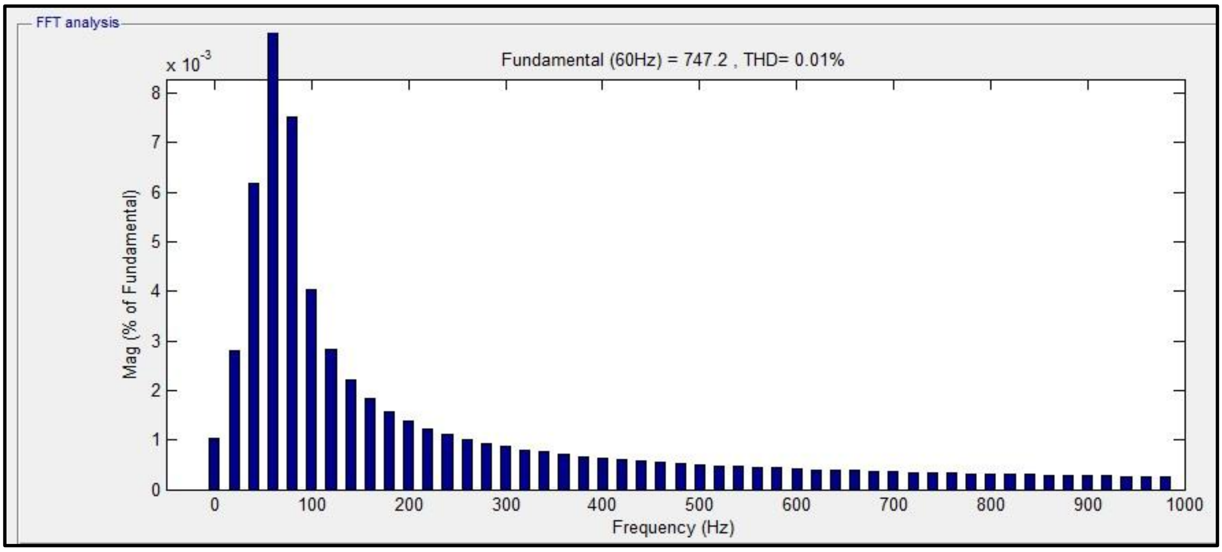


Figure 38: Frequency spectrum of THD at I_c for steady state (current)

Total harmonic distortion (THD) in transient state for figure 33, 34 and 35 shows that the highest one in phase C, 24.99%. THD for phase A and phase B is 11.24% and 13.04%. Increment between each phase indicated that the multi predictive control (MPC) contain distortion element at low switching frequency. This distortion is formed when the MPC block is linearize. Linearize is a compulsory way for MPC block to run the simulation. The main variables for this MPC block is the measured output, measured disturbance and measured variable. Measured output is a variable taken from transformation of alpha beta. The measured disturbance is any kind of external distortion such as frequency variation of inverter three phase. While for measured output is the output from MPC block that will be inserted to signal generator. The signal is feedback to the gate of IGBT. Frequency spectrum for figure 33, 34, 35 shows that the THD occur in third order harmonic during transient state. This is due to cost function where the grid filter minimize the switching-state transition inside the function and later producing harmonic components in the simulation system.

The steady state of current waveform can be shown from figure 36, 37 and 38. It shows the frequency spectrum of the predictive three phase with a THD of 0.01%. It means the MPC controller provide an accurate current tracking ability with a low THD distortion and low current ripple. Its ability to maintain the THD almost to zero shows that the predictive method can provide stability and low THD during converting DC voltage source into AC voltage source. The highest event of harmonic occur at fourth order of harmonic. Basically, even-order harmonic frequency current is a product of dissimilar current draw during two half cycles. Metering equipment, will not read and identify the even harmonics because these harmonics are cancel themselves out. This even order of harmonic is created in inverter switching part by low switching frequency of IGBT gate. As effect it will cause the unbalance group distortion to the system. This can be seen from phase A, phase B and phase C.

For transient state and steady state of grid load voltage, the harmonic distortion of each parameter can be shown from figure 40,41, 42,43,44 and 45 through frequency spectrum graph. The total harmonic distortion (THD) of grid load is almost the same, 0.01% for both state. Figure 39 shows the output waveform of grid load voltage. The output waveform is almost equal or approximate to fundamental sinusoidal waveform.

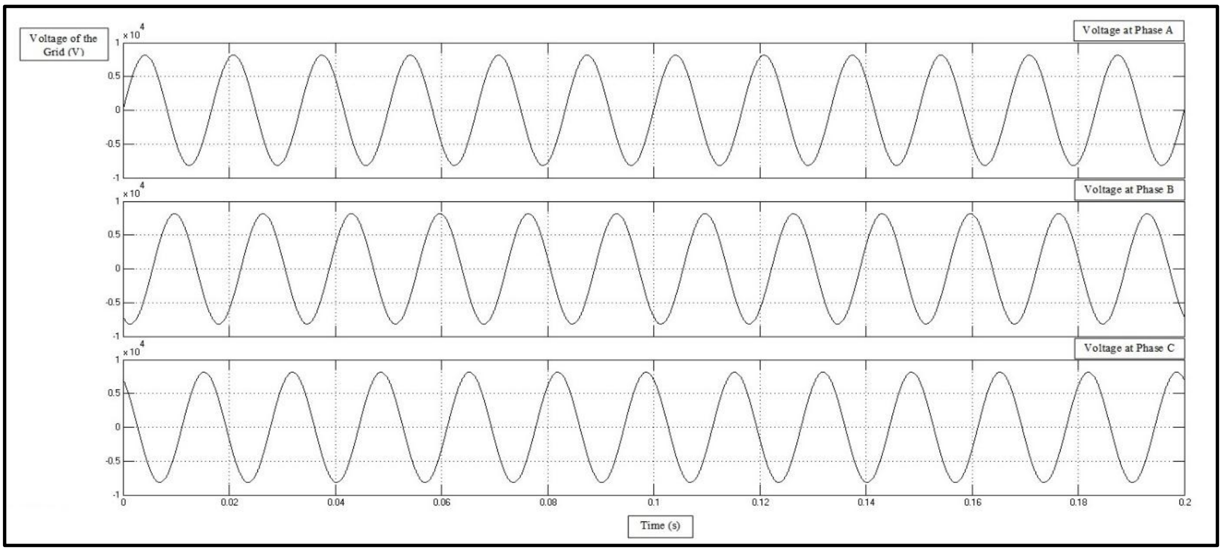


Figure 39: Output voltage waveform (V_a ,V_b and V_c)

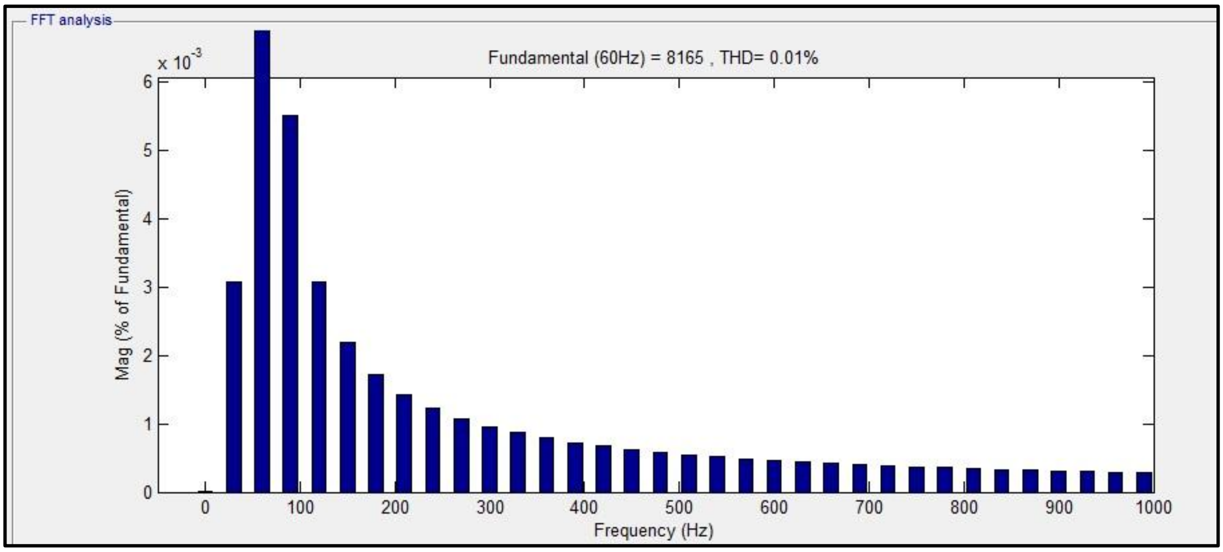


Figure 40: Frequency spectrum of THD at V_a for transient state (voltage)

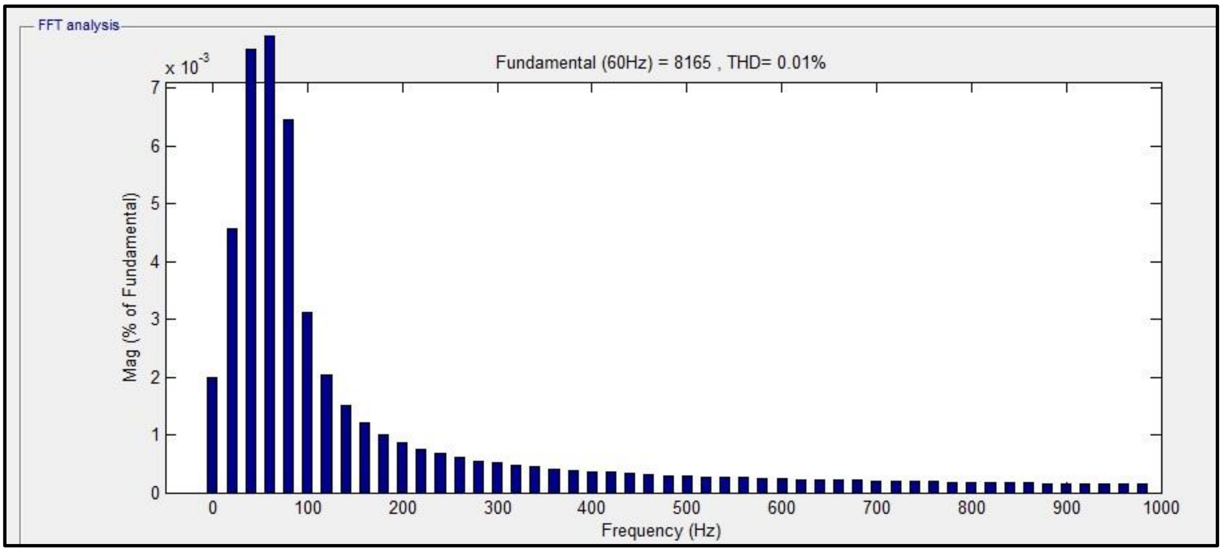


Figure 41: Frequency spectrum of THD at V_b for transient state (voltage)

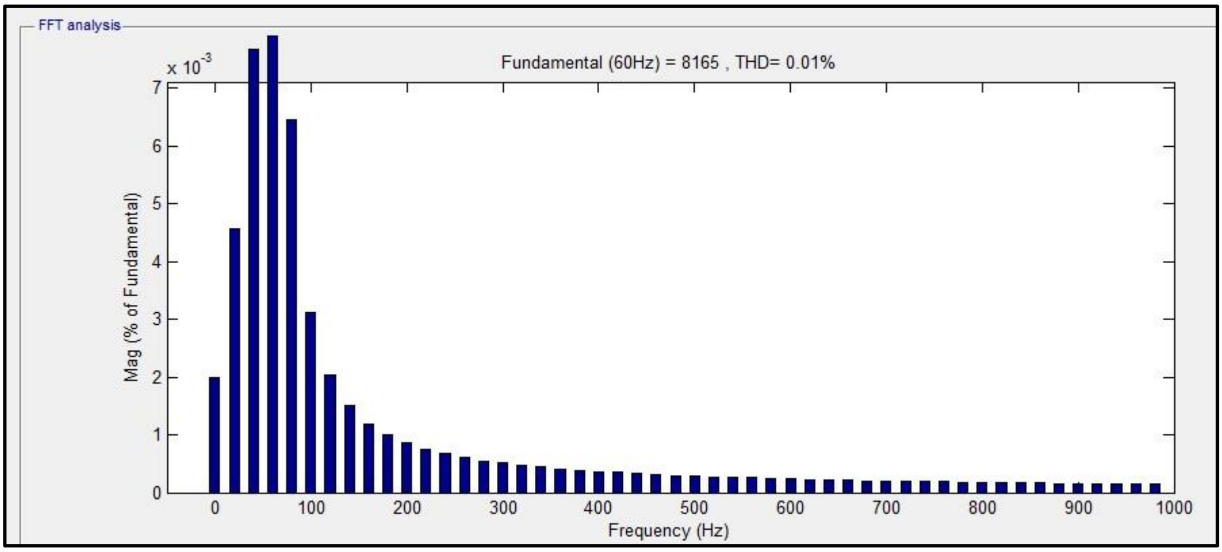
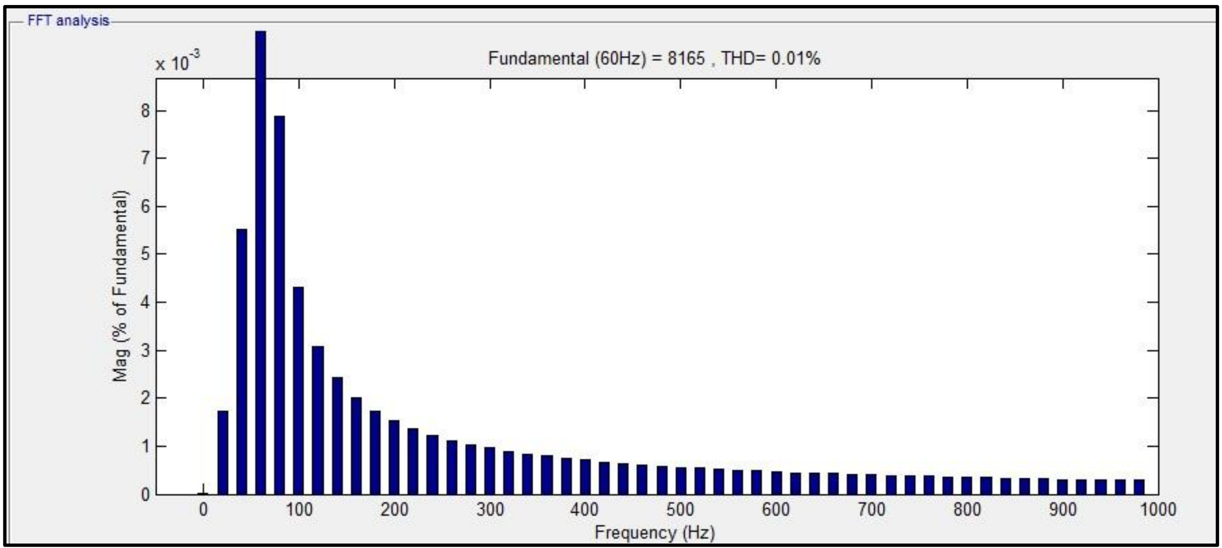


Figure 42: Frequency spectrum of THD at V_c for transient state (voltage)

Figure 43: Frequency spectrum of THD at V_a for steady state (voltage)



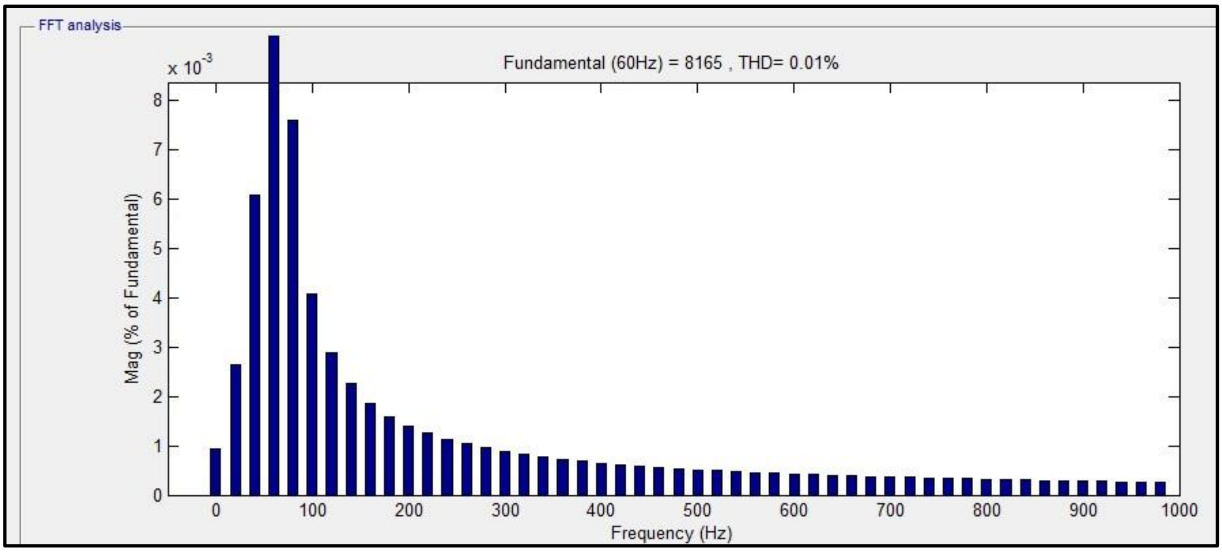


Figure 44: Frequency spectrum of THD at V_b for steady state (voltage)

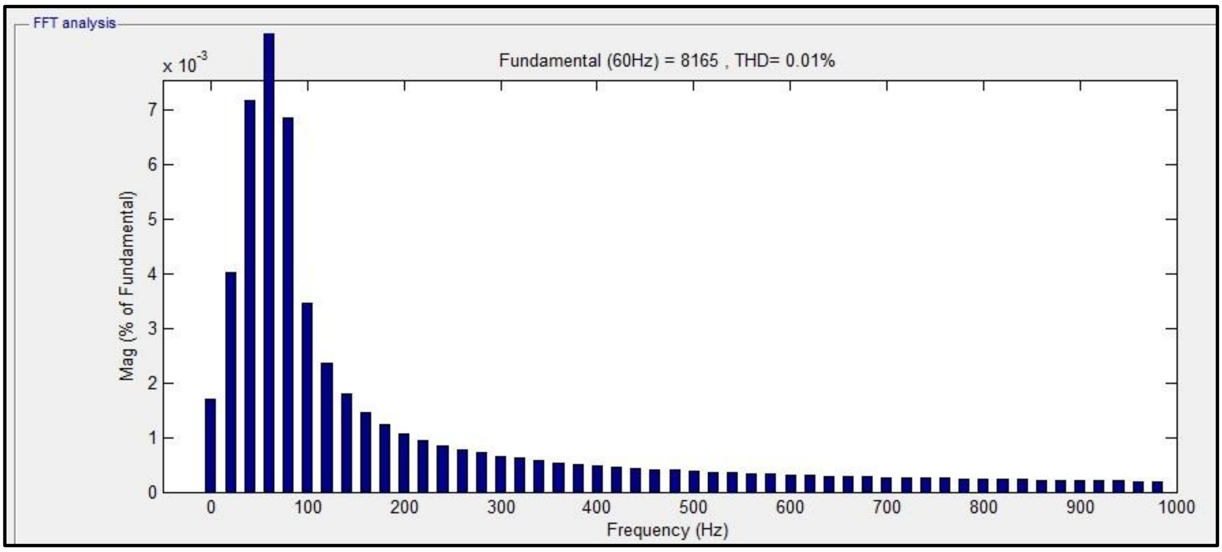


Figure 45: Frequency spectrum of THD at V_c for steady state (voltage)

Figure 40,41 and 42 shows the total harmonic distortion (THD) of voltage at transient state. Eventhough the percentage is low, it still can give impact and affect to the quality of voltage delivered to grid utility in windfarm generation. Because, the simulation that been carry out in this project is theoretically not practically. In real windfarm power plant, there will be a voltage sag and swell that cause the system to malfunction or component to burn.

Figure 43, 44 and 45 shows the steady state of voltage during steady state. The frequency spectrum in figure 43,44 and 45 shows that the order is in fourth harmonic same as steady state of current in figure 36, 37 and 38. This even harmonic can create impact to the converter in windfarm such as overheating in reactor set that being used for harmonic filter associated with inverter three phase system. As being mentioned, THD is almost same with the steady state of current drawn into the grid utility. In addtion, the grid filter that being used is LCL type. As being mentioned from 4.1, this grid filter gives good voltage and current ripples attenuation. Thus from figure 39, the attenuation of voltage ripples inside the waveform is very low. Resulting the voltage of total harmonic distortion is also low.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

Implementation of predictive current control method can be done in windfarm power plant. More simpler and less component in the system is used to feedback the signal into gate of IGBT. This can be seen from results in 4.3 where the component that being used is multi predictive control (MPC) generated the signal that are almost equal to reference value by taking consider the measure disturbance and reference value. As in windfarm power plant the generation of energy from rotating blade to the turbine system will not be same all the times. This reference value can guide the measure output and calculate the value so that the future signal is approximate or almost equal to reference signal. Unfortunately, predictive current control give bad impact during transient state and produce harmonic to the system and as effect the efficiency to the utility grid will be decrease. But in offshore, the changes of wind energy is not so significant. Based on Appendix 1, European offshore wind energy statistics stated that for every year from 2000 until 2014, the installation of fully grid connected to offshore wind turbine is increase gradually. This shows that the percentage of availability of wind energy at offshore is high and always present. The low switching frequency in the three phase inverter is suitable for medium voltage application of windfarm power plant especially for inverter part (IGBT). Compare with MOSFET, the operating switching frequency of IGBT is relatively low. The slow period of the conduction switching during turn-on resulting power loss to be lower than turn-off power loss. Hence, it is suitable to implement low switching frequency in converter. In the other hand, linear PWM can also be implement in three phase inverter of windfarm power plant but the complexity in the calculation is the major drawback that differentiate this method with predictive method. Thus it is better to go with the simpler method that provide good stablity to grid utility and also to downstream.

It is recommend that to implement any of the two methods, especially the predictive current control method, installing protection equipment is compulsary. Because wind energy at offshore have different magnitude of speed as well as direction. The probability of the whole system to experience power trip is also present. Damage, burn or malfunction in the insulation of transmission cable, microprocessor, conductor and many more is the effect of transient problem. To minimize the losses in aspect of money and power, equipments like circuit breaker, relay, current transformer and potential transformer need to install at measuremnt point from upstream to downstream.

REFERENCES

[1] Malesani, L.; Tomasin, P., "*PWM current control techniques of voltage source converters-a survey*," Industrial Electronics, Control, and Instrumentation, 1993. Proceedings of the IECON '93., International Conference on , vol., no., pp.670,675 vol.2, 15-19 Nov 1993.

[2] Mekhilef, S.; Chandrasegaran, D., "*Assessment of off-shore wind farms in Malaysia*," TENCON 2011 - 2011 IEEE Region 10 Conference , vol., no., pp.1351,1355, 21-24 Nov. 2011.

[3] Bianchi, F., "*Power Control of Voltage Source Converter For Distributed Generation*," PHYSCON, vol., no., September 5 2011-September 8 2011.

[4] Devaraj, D.; Jeevajyothi, R., "*Voltage Stability using VSWT with Direct Drive Synchronous Generators*," International Journal of Energy Engineering, vol. 2, no. 5, pp. 259,265, February 5 2012.

[5] Navpreet, T.; Tarun, M.; Amit, B.; Kotturu, J.; Bhupinder, S.; Anant, B.; Gurangel, S., "*Voltage Source Converters as the buiding block of HVDC and FACTS Technology in Power Transmission System: A Simulation based Approach*," Advances in Applied Science Research, vol. 3, no. 5, October 2012.

[6] Radomski, G.; "*Control and modulation methods of voltage source converter*," Bulletin of the Polish Academy of Sciences: Technical Sciences, vol. 7, no. 4, pp. 323,336, December 2009.

[7] Keliang Zhou; Xiaofan Fu; Ming Cheng; Xiaodong Zhu; Wei Wang; Tong Wang, "*Topologies and control of VSC-HVDC systems for grid connection of large-scale off-shore wind farms*," Electrical Machines and Systems, 2008. ICEMS 2008. International Conference on , vol., no., pp.2357,2361, 17-20 Oct. 2008.

[8] Anaya-Lara, O.; Hughes, F.M.; Jenkins, N.; Strbac, G., "*Contribution of DFIG-based wind farms to power system short-term frequency regulation*," Generation, Transmission and Distribution, IEE Proceedings- , vol.153, no.2, pp.164,170, 16 March 2006.

[9] Douangsyla, S.; Indarack, P.; Kanthee, A.; Kando, M.; Kittiratsatcha, S.; Kinnares, V., "*Modeling for PWM voltage source converter controlled power transfer*," Communications and Information Technology, 2004. ISCIT 2004. IEEE International Symposium on , vol.2, no., pp.875,878 vol.2, 26-29 Oct. 2004.

[10] Chaudhary, S.K., "*Control and protection of wind power plants with VSC-HVDC connection*," Aalborg University, 2011.

[11] Madrigal, M.; Acha, E., "*Harmonic modelling of voltage source converters for HVDC stations*," AC-DC Power Transmission, 2001. Seventh International Conference on (Conf. Publ. No. 485) , vol., no., pp.125,131, 28-30 Nov. 2001.

[12] Lehn, P.W., "*Exact modeling of the voltage source converter*," Power Delivery, IEEE Transactions on , vol.17, no.1, pp.217,222, Jan 2002.

[13] Yan Liu; Xiongfei Wang; Zhe Chen, "Cooperative control of VSC-HVDC connected offshore wind farm with Low-Voltage Ride-Through capability," *Power System Technology (POWERCON), 2012 IEEE International Conference on* , vol., no., pp.1,6, Oct. 30 2012-Nov. 2 2012.

[14] Miranda, H.; Teodorescu, R.; Rodriguez, P.; Helle, L., "*Model predictive current control for high-power grid-connected converters with output LCL filter*," Industrial Electronics, 2009. IECON '09. 35th Annual Conference of IEEE , vol., no., pp.633,638, 3-5 Nov. 2009.

[15] Rodriguez, J.; Pontt, J; Silva, A.; Correa, P.; Cortes, P., "Predicitve Current Control of a Voltage Source Inverter," Industrial Electronics, 2006, vol. 54, no. 1, pp. 495,503, February 2007.

[16] Blaabjerg, F.; Liserre, M.; Ke Ma, "*Power Electronics Converters for Wind Turbine Systems*," Industry Applications, IEEE Transactions on , vol.48, no.2, pp.708,719, March-April 2012.

[17] *Wind Farm Electrical Systems*. (n.d.). Retrieved from *http://ewh.ieee.org/r3/atlanta/ias/Wind%20Farm%20Electrical%20Systems.pdf*.

[18] Wu, B.; Lang, Y.; Zargari, N.; Kouro, S., *Power Conversion and Control of Wind Energy Systems. Oxford; Piscataway: Wiley-Blackwell ; IEEE, 2011. 88.*

[19] Lettl, J.; Bauer, J.; Linhart, L., "*Comparison of Different Filter Types for Grid Connected Inverter*," PIERS Proceesdings on, pp. 1426,1429, 20-23 March. 2-11.

[20] Inverters in Adjustable Speed Power Energies. (n.d). Retrieved from *http://www.icrepq.com/ICREPQ'09/265-cardona.pdf.*

APPENDICES

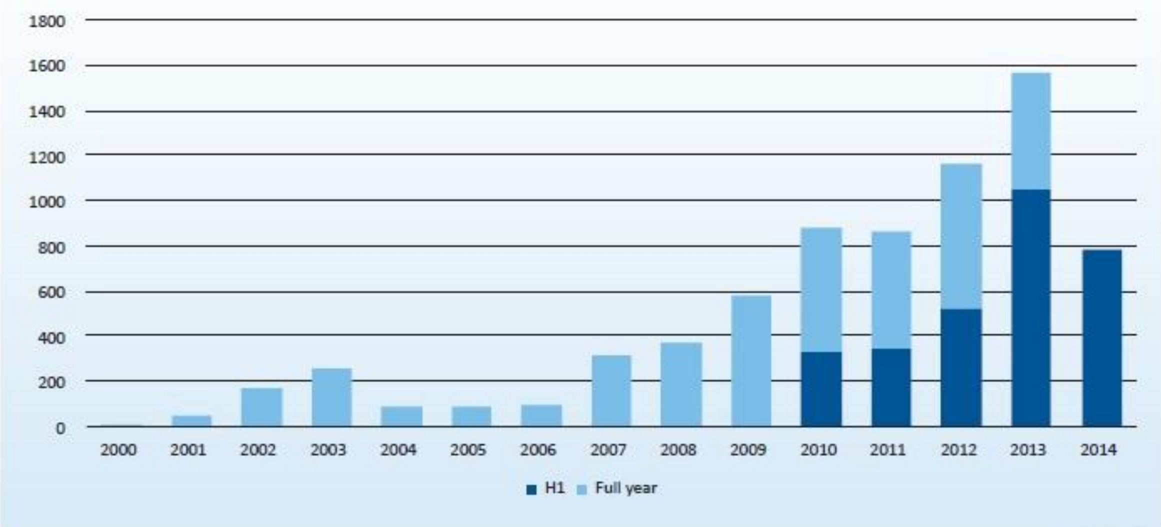
Appendix 1 : The European offshore wind industry – key trends and statistics 1st half 2014

Mid-year European offshore wind energy statistics

In the first six months of 2014, Europe fully grid connected 224 offshore wind turbines in 16 commercial wind farms and one offshore demonstration site with a combined capacity totalling 781 MW. There are 310 wind turbines awaiting grid connection. Once connected, these will add a total capacity of over 1,200 MW. The total capacity of all the wind farms under construction is over 4,900 MW when fully commissioned.

New offshore capacity installations during the first half of 2014 were down 25% compared to the same period the previous year.

FIGURE 1: ANNUAL INSTALLED OFFSHORE WIND CAPACITY IN EUROPE (MW)



Source: EWEA