ANALYSIS AND DEVELOPMENT OF GRID CONNECTED FRONT-END AC TO DC CONVERTER USING DIRECT POWER CONTROL (DPC) SCHEME

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A report submitted in partial fulfilment of the requirements for the degree of Bachelor of Electrical Engineering

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2018

“I hereby declare that I have read through this report entitled “Analysis and development of grid connected front-end AC to DC converter using Direct Power Control (DPC) scheme.” and found that it complies the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering.”

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Date : ……………………………………………

I declare that this report entitled “Analysis and development of grid connected front-end AC to DC converter using Direct Power Control (DPC) scheme” is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

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To my beloved mother and father.

I would not be here if were not for them.

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ABSTRACT

This project focuses on development of grid connected front-end AC to DC converter using Direct Power Control (DPC) scheme. Nowadays, three-phase AC to DC converters consisting of power electronic switched have been widely used in various industrial applications. However, power electronic switches such as diode and thyristor will generate non-sinusoidal shape of input currents from the main supply. These currents consists of high harmonic components which lead to the increasing of currents total harmonic distortion. The proposed DPC is able to reduce the current harmonics, hence lower the total harmonic distortion of the three-phase input current. DPC is able to control the active and reactive power without any internal current control loop. The optimum switching states for the converter are determined from a switching table. Therefore, the main objective of this project is develop a three-phase AC to DC converter controlled by Direct Power Control (DPC) scheme. Simulation will be done by using MATLAB Simulink. Besides, the three-phase input currents and voltages will be transformed into αβ frame by applying Clarke transformation. The current and voltage in αβ frame are used to estimate the active and reactive power. The power errors (S_p, S_q) and sector signal, θ_n will be used as input parameters to the switching table. Thus, the switching table is responsible to select the optimal rectifier voltage vector and output the corresponding switching state (S_a ,S_b , S_c). After implementing the DPC method, three-phase input currents are almost sinusoidal and current total harmonic distortion is lower. By supplying zero reference reactive power for all sectors, the AC to DC converter operation is maintained at unity power factor. Lastly, the magnitude of DC-link voltage is almost same as the reference DC voltage.

ABSTRAK

Projek ini memberi tumpuan kepada pembangunan grid yang menyambungkan penukar arus ulang alik (AU) kepada arus teurs (AT) dengan menggunakan skim Direct Power Control (DPC). Pada masa kini, penukar tiga fasa AU kepada AT yang mempunyai kuasa elektronik suis telah digunakan secara meluas dalam pelbagai aplikasi perindustrian. Walau bagaimanapun, suis elektronik kuasa seperti diode dan thyristor akan menjana arus masuk yang tidak sinusoidal. Arus yang mempunyai komponen harmonik yang tinggi akan membawa peningkatan arus jumlah herotan harmonik. DPC yang dicadangkan dapat mengurangkan harmonic komponen dan menurunkan jumlah herotan harmonik arus masuk. DPC boleh mengawal kuasa aktif dan kuasa reaktif tanpa gelung kawalan arus dalaman. Status pensuisan yang optimum ditentukan daripada satu jadual pensuisan. Oleh itu, objectif projek ini adalah untuk membangunkan pengawal penukar AU kepada AT dengan mengunakan konsep DPC. Simulasi juga akan dilakukan dengan menggunakan MATLAB Simulink. Selain itu, arus masuk dan voltan masuk tiga fasa akan berubah menjadi paksi $\alpha\beta$ dengan menggunakan transformasi Clarke. Arus dan voltan yang dihasilkan dalam paksi $\alpha\beta$ digunakan untuk menganggarkan kuasa aktif dan kuasa reaktif. Kesalahan kuasa (S_p, S_q) dan isyarat sector, $\theta_n$akan dimasukan ke dalam jadual pensuisan. Oleh itu, jadual pensuisan akan memilih vektor voltan penerus optimum dan status pensuisan penukar arus (Sa, Sb, Sc) akan diberikan. Selepas mengguankan DPC, arus tiga fasa adalah hampir sinusoidal dan jumlah herotan harmonic menjadi lebih rendah. Dengan membekalkan kuasa reaktif rujukan sifar kepada semua sektor, operasi penukar AU kepada AT dikekalkan pada factor daya uniti. Akhir sekali, nilai voltan DC-link hampir sama dengan voltan DC rujukan.

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LIST OF ABBREVIATIONS

AC - Alternating Current
ASDs - Adjustable-speeds Drive
ADC - Analog to Digital Converter
ADCH - Analog to Digital Channel
DC - Direct Current
DPC - Direct Power Control
DAC - Digital to Analog Converter
DACH - Digital to Analog Channel
HVDC - High-voltage Direct Current
HCC - Hysteresis Current Controller
IGBT - Insulated-Gate Bipolar Transistor
PWM - Pulse Width Modulation
PCB - Printed Circuit Board
RTI - Real-Time interface
UPSs - Uninterruptible Power Supplies
VFOC - Virtual-flux Oriented Control
VF-DPC - Virtual-flux-Based Direct Power Control
V-DPC - Voltage-based Direct Power Control

CHAPTER 1

INTRODUCTION

1.1 Motivation

Three-phase AC to DC converter have been frequently used in industrial applications such as high-voltage direct current (HVDC) system, adjustable-speeds drive (ASDs), uninterruptible power supplies (UPSs) and so on. Traditionally, a three-phase diode rectifier or phase-controlled thyristor rectifier are normally used as AC to DC power supply. However, they generate problem of poor power quality in terms of current harmonics being injected back to the main supply, low efficiency, voltage distortion and low power factor [1].

There are various control methods that can be implement on AC to DC converter. The control methods are known such as voltage-oriented control (VOC), Hysteresis current controller (HCC) and Direct Power Control (DPC) [2]. This project will focus on analysis and development of Grid connected Front-End AC to DC converter using Direct Power Control (DPC) scheme.

In energy conversion system, the converter need to be well controlled in order to achieve dynamic performance and satisfactory steady state [3]. DPC scheme is a control method to control the active and reactive power without any internal current control loop and pulse width modulator. By implementing DPC scheme, low harmonic content in line current can be generated which leads to the achievement of almost sinusoidal input current and have almost unity power factor. Meanwhile, the switching states are selected via a switching table. Switching table is used to determine optimum switching state for the converter. There are three signal inputs to the switching table, which are voltage sector position, instantaneous error of active power and reactive power.

1.2 Problem Statement

Nowadays, AC to DC converter has been widely used in industrial applications specifically in power transmission. However, there are a few problems when implementing AC to DC converter into the transmission system. Power diode and thyristor that are commonly used in the AC to DC converter will generate harmonics and reactive currents. The non-sinusoidal shape of input current supply is the main issue that generates significant harmonic components [2]. The currents are distorted and deviate from sinusoidal waveforms. Harmonic currents have significant impacts on the electrical distribution systems and facilities such as lower the system power factor, increase the energy losses, overheating and so on.

To overcome those problems, a three-phase AC to DC converter controlled by DPC scheme is proposed in this project. DPC scheme is able to produce input currents which are close to sinusoidal waveform and have almost unity power factor.

1.3 Objective

The objectives of this project are:

1) To design and run the simulation of three-phase AC to DC converter controlled by Direct Power Control (DPC) scheme by using MATLAB Simulink.
2) To obtain a sinusoidal three-phase input current which have almost unity power factor through simulations
3) To regulate the DC output voltage according to the reference DC value.
4) To develop the hardware of three-phase AC to DC converter controlled by Direct Power Control (DPC) scheme.

1.4 Scope of Research

The scope of this project are:

1) Understand the concept of Direct Power control (DPC) scheme.
2) To transform the three-phase current and voltage into alpha-beta frame by applying Clark transformation.
3) Acquire the instantaneous active and reactive power of three-phase AC to DC converter.
4) Determine the sector position (θ_n) and converter voltage vector (V_n).
5) Determine the switching states of the converter by utilizing the switching table.
6) Development of hardware for DPC and connect with dSpace.
7) Enable gate drivers for implementation of DPC to the three-phase AC to DC converter.

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CHAPTER 2

LITERATURE REVIEW

This chapter is mainly focusing on the research and analysis that have been done by various researchers. In this chapter, the basic concept and theories of Direct Power Control (DPC) on the three-phase AC to DC converter will be emphasised. Related information of previous studies are extracted as references and discussion will be done.

2.1 Topology of three-phase AC to DC converter

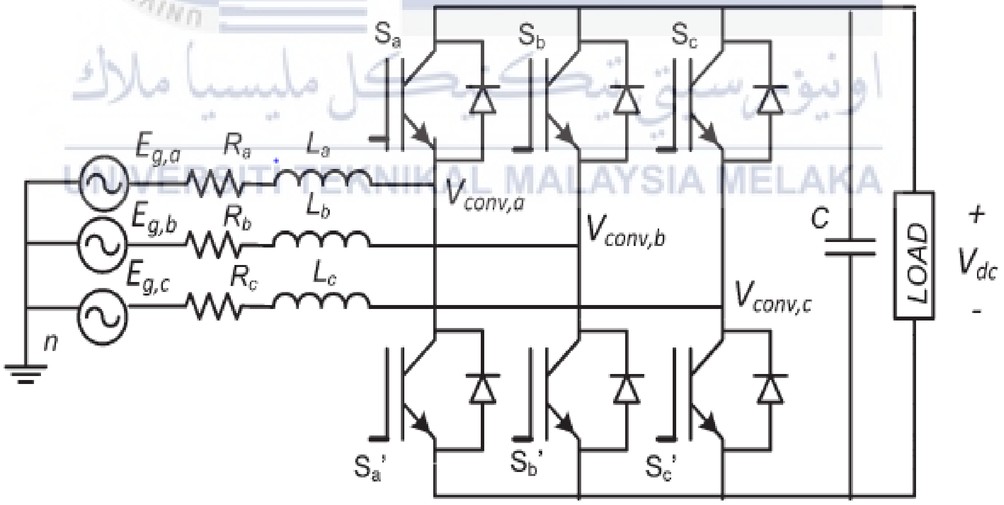


Figure 2.1 Topology of three-phase bidirectional AC-DC converter [4]

The circuit of a three-phase AC to DC converter is shown in Figure 2.1. $E_{a,b,c}$ stand for grid phase voltage and each phase is shifted 120^0 from another phase. The RL branch is connected in between the source and the converter. The present of inductance is to smoothing the current with minimum ripples. Besides, V_{dc} is the DC-link output voltage and $S_{a,b,c}$ is the switching state of the converter [4].

Figure 2.1 clearly shows that six insulated gate bipolar transistors (IGBT) are involved in rectifying the input voltage. IGBT have simple gate drives requirements, high power rating and able to operate in high switching frequency [2]. IGBT have better performance compare to conventional three-phase rectifier. Conventional three-phase rectifier have low power factor, and high harmonic component in input currents. Thus, IGBTs are proposed to be used in this projects.

2.2 Mathematical Model

The equations of the three-phase voltage supply are shown as below. Meanwhile, the E represent the maximum phase voltage and the ω represent the angular frequency of the power source.

$$E_a = E\cos(\omega t) \tag{2.1}$$

$$E_b = E\cos\left(\omega t - \frac{2\pi}{3}\right) \tag{2.2}$$

$$E_c = E\cos\left(\omega t + \frac{2\pi}{3}\right) \tag{2.3}$$

Based on Figure 2.1, $V_{conv,abc}$ is the is the three-phase converter pole voltage. The phase voltage at the poles of the converter can be determine by applying equations below [4, 23].

$$V_{conv,a} = \left(\frac{2S_a - S_b + S_c}{3}\right)V_{dc} \tag{2.4}$$

$$V_{conv,b} = \left(\frac{2S_b - S_a + S_c}{3}\right)V_{dc} \tag{2.5}$$

$$V_{conv,c} = \left(\frac{2S_c - S_a + S_b}{3}\right)V_{dc} \tag{2.6}$$

2.3 Vector Transformation

Vector transformation need to be involved when transform three-phase quantities into two phase quantities and vice versa. Among the various transformation method available, the most common transformation are Clarke transformation, Inverse Clarke transformation, Park transformation, and Inverse Park transformation.

2.3.1 Clarke Transformation

Clarke transformation able to converts balanced three-phase quantities into balanced two-phase quantities. The Clarke transformation for three-phase systems without zero sequence symmetrical components is given by [5]:

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \qquad (2.7)$$

Simplified the equations above and the final equations will be shown as below:

$$X_\alpha = \frac{2}{3}(X_a) - \frac{1}{3}(X_b+X_c) \qquad (2.7)$$

$$X_\beta = \frac{1}{\sqrt{3}}(X_b-X_c) \qquad (2.9)$$

Where X_a, X_b, X_c are three-phase quantities and X_α, X_β are stationary orthogonal reference frame quantities. Equation above is applicable for transformation of both currents and voltage as X represent I and V. Figure 2.2 and Figure 2.3 shows the Clarke transformation from abc-coordinates to αβ-coordinates.

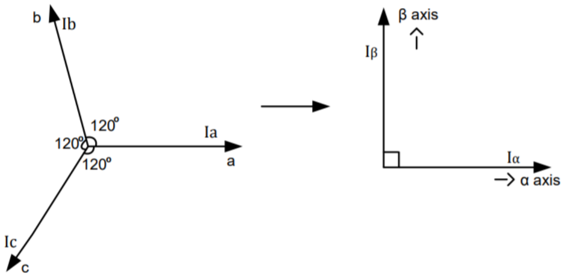


Figure 2.2 abc-coordinates to αβ-coordinates.

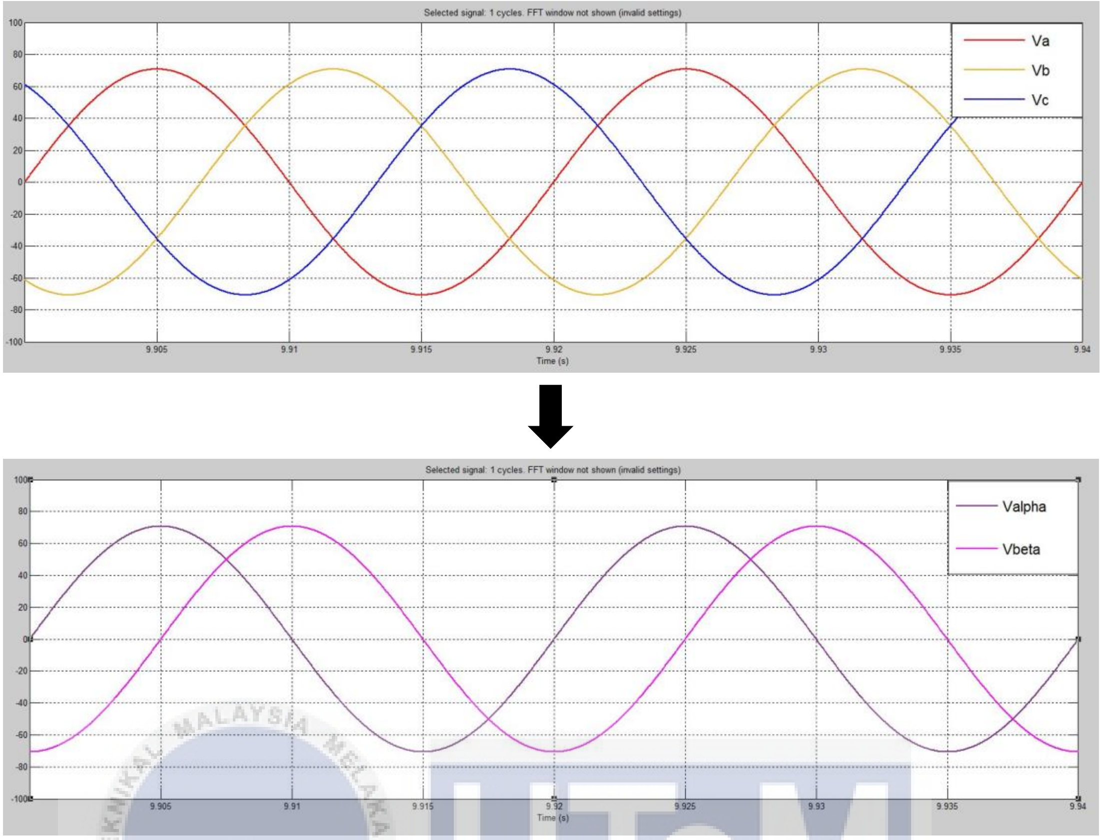


Figure 2.3 Clarke transformation (before and after)

2.3.2 Inverse Clark Transformation

Inverse Clarke transformation able to converts balanced two-phase quantities into balanced three-phase quantities. The Inverse Clark Transformation is expressed by the following equations:

$$\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} = \frac{3}{2} \begin{bmatrix} \frac{2}{3} & 0 \\ -\frac{1}{3} & \frac{1}{\sqrt{3}} \\ -\frac{1}{3} & -\frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} \tag{2.10}$$

Simplified the equations above and the final equations will be shown as below:

$$X_a = X_\alpha \tag{2.11}$$

$$X_b = \frac{1}{2}\left(-X_\alpha + \sqrt{3}\, X_\beta\right) \tag{2.12}$$

$$X_c = \frac{1}{2}\left(-X_\alpha - \sqrt{3}\, X_\beta\right) \tag{2.13}$$

Where X_α, X_β are stationary orthogonal reference frame quantities and X_a, X_b, X_c are three-phase quantities. Equation above is applicable for transformation of both currents and voltage as X represent I and V. Figure 2.4 shows the inverse Clarke transformation from αβ-coordinates to abc-coordinates.

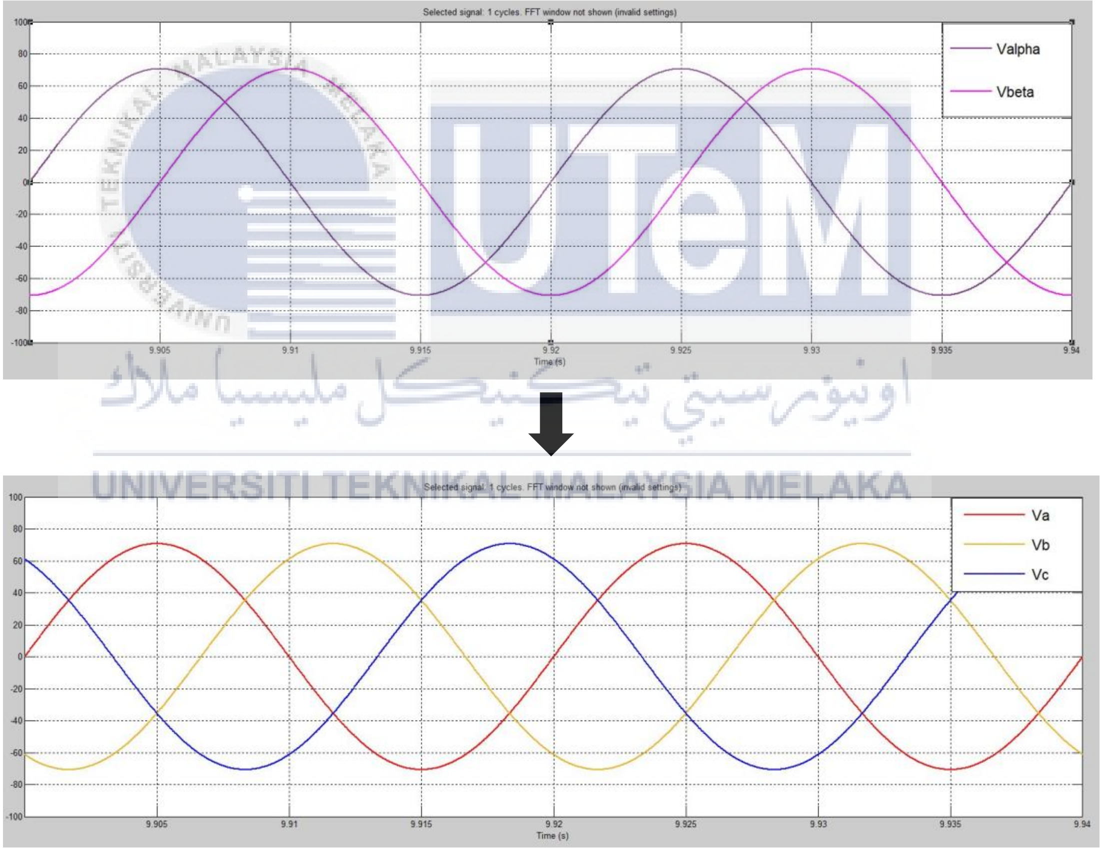


Figure 2.4 Inverse Clarke transformation (before and after)

2.3.3 Park Transformation

From the Figure 2.5, the stationary orthogonal reference frame quantities (X_α and X_β) obtained from Clarke transformation can transform into rotating reference frame quantities (X_d and X_q) using Park Transformation. The Park transformation can be expressed by the following equations [3]:

$$\begin{bmatrix} X_d \\ X_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} X\alpha \\ X_\beta \end{bmatrix} \tag{2.14}$$

Simplified the equations above and the final equations will be shown as below:

$$X_d = X_\alpha\cos\theta + X_\beta\sin\theta \tag{2.15}$$

$$X_q = -X_\alpha\sin\theta + X_\beta\cos\theta \tag{2.16}$$

Equation above is applicable for transformation of both currents and voltage as X represent I and V. The two phases α, β frame representation is fed to a vector rotation block where it is rotated over an angle θ to follow the frame d, q attached to the rotor flux. Park transformation will transform αβ-coordinates to dq-coordinates.

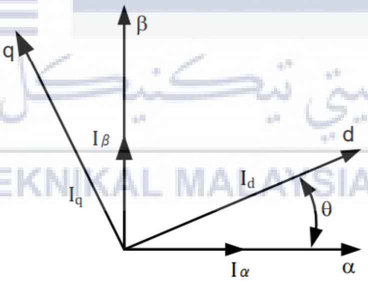


Figure 2.5 Relationship between αβ and dq axis

2.3.4 Inverse Park Transformation

Rotating reference frame quantities (X_d and X_q) can be transformed back to the stationary orthogonal reference frame quantities (X_α and X_β) by using Inverse Park Transformation. The Inverse Park transformation can be expressed by the following equations:

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} X_d \\ X_q \end{bmatrix} \tag{2.15}$$

Simplified the equations above and the final equations will be shown as below:

$$X_\alpha = X_d\cos\theta - X_q\sin\theta \tag{2.16}$$

$$X_\beta = X_d\sin\theta + X_q\cos\theta \tag{2.17}$$

Equation above is applicable for transformation of both currents and voltage as X represent I and V. Inverse Park transformation will transform dq-coordinates to αβ-coordinates.

2.4 Instantaneous active power and reactive power

In electrical system, instantaneous power is defined as the product of instantaneous voltage and instantaneous current. There are two different instantaneous power, which are real power, P and reactive power, Q. In DPC scheme, the instantaneous active and reactive power of three-phase supply can be obtained by applying equation (2.18) [6].

$$\begin{bmatrix} p \\ q \end{bmatrix} = \frac{3}{2}\begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \tag{2.18}$$

Simplified the equations above and the final equations will be shown as below:

$$P_{inst} = \frac{3}{2}\left[V_\alpha I_\alpha + V_\beta I_\beta\right] \tag{2.19}$$

$$Q_{inst} = \frac{3}{2}\left[V_\beta I_\alpha - V_\alpha I_\beta\right] \tag{2.20}$$

2.5 Control Strategies

To achieve proper power flow regulation in the power conversion system, the converter need to be controlled properly. There are several of control methods to control the AC to DC converter. The most common methods are Direct Power Control (DPC), Voltage Oriented Control (VOC), Hysteresis current control, and predictive control [4]. Obtain sinusoidal input current waveforms, improve power factor to unity, and reduce harmonic components are the common objectives that need to be achieved after apply those control methods.

2.5.1 Direct Power Control (DPC)

DPC is a control method that control active and reactive power without any internal current control loop and pulse width modulator. DPC scheme required to be fast and have good accuracy when estimate the active and reactive power to achieve satisfactory performance [7].

In DPC schemes, the converter switching are selected by a switching table according to the instantaneous errors between the commanded and estimated values of reactive power and active power [8]. Figure below shows the block scheme of DPC on switching table. The resistance (R) can be ignored due to relatively small values. Produce a sinusoidal three-phase input currents waveforms with lesser harmonics and almost to unity power factor will be the final aims for this control strategy.

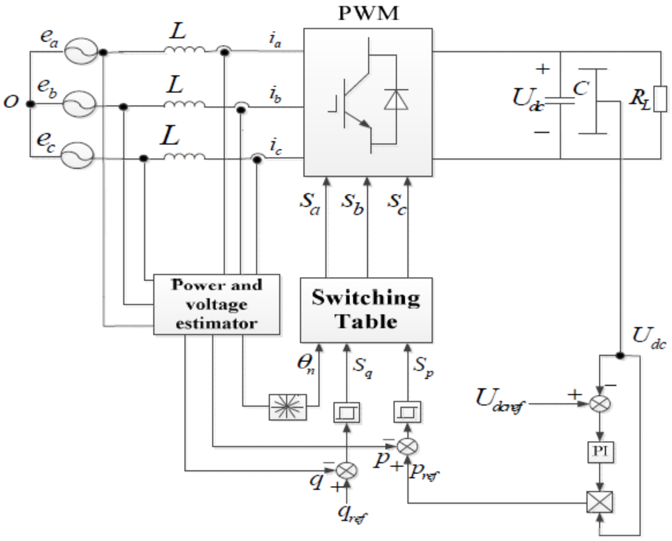


Figure 2.6 Configuration of DPC

Table 2.1 Definitions of units

Units	Definitions
L	Inductance
R	Resistance
R_L	Load resistance
C	Capacitance
e_a, e_b, e_b	Three-phase voltage source
S_a ,S_b, S_c	Switching state of the converter
i_a i_b i_b	Three-phase line current
P	True power
q	Reactive power

The instantaneous errors between the estimated values and commanded of active and reactive power are sent to the hysteresis comparators which then generate two digitalized signals [9]. Active power need to be reduce when active power error status, d_p is equal to 0 and increase the active power when the d_p equal to 1. Besides, same concepts also applicable for reactive power. Reactive power need to be reduce when reactive power error status,d_q equal to 0 and increase the reactive power when the reactive power error is d_q equal to 1.

Table 2.2 Newly developed switching look-up table for DPC [3, 4]

Power error status		Sector position (θ_n) and converter voltage vector (V_n)											
d_P	d_Q	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}	θ_{11}	θ_{12}
0	0	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6
0	1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1
1	0	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5
1	1	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2

The sector selections of DPC can be divided into 12 sectors. Meanwhile, each sectors represents 30^0 and rotates in anticlockwise. For DPC, the sector 1 will be locate in an angle range between 0^0 to 30^0 while the sector 12 will be locate at angle between 0^0 to -30^0 [2]. The two digitalized signals (S_p and S_q) and sector signal, θ_n will send to the switching table. Thus, the switching table responsible to select the optimal rectifier voltage vector and output the corresponding switching state (S_a ,S_b , S_c) [9].

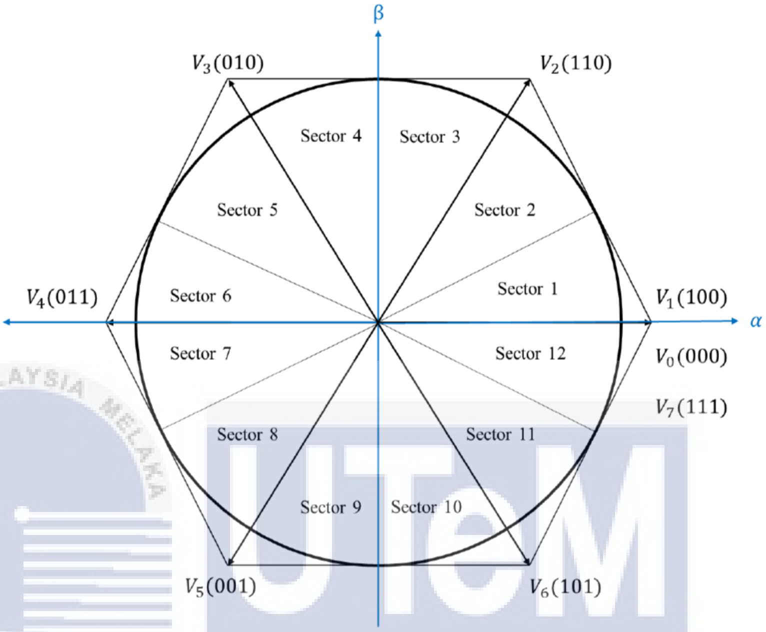


Figure 2.7 Sector selection for DPC

2.5.2 Voltage Oriented Control (VOC)

Figure 2.10 shows the configuration of Voltage Oriented Control (VOC). VOC method is basically about the coordinate's transformation between the fixed coordinates system α-β and synchronous coordinate d-q. VOC method eventually involves Clarke transformation, inverse Clarke transformation, Park transformation, and inverse Park transformation.

For VOC method, the orientation of the current vector should in the same direction with voltage vector by controlling the current vector in the two rotating coordinate d-q. Meanwhile, Phase Locked Loop (PLL) is used in VOC to estimate and filter the angle of the source and the instantaneous amplitude of the equivalent phase of a three-phase system [10]. The implementation of VOC will improves the static performance through the current control loop. Besides, VOC have fixed switching frequency and low sampling frequency [11].

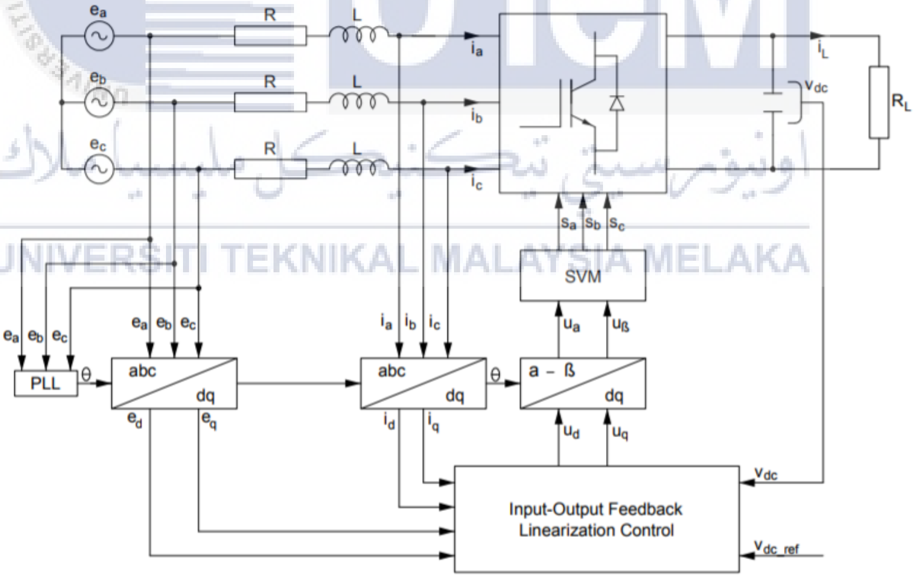


Figure 2.8 Configuration of VOC

2.5.3 Comparison between DPC and VOC

The advantages and disadvantages for VOC and DPC are clearly shown in Table 2.3. According to this table, each control techniques have their own advantages and disadvantages. Hence,

Table 2.3 Advantages and disadvantages for VOC and DPC [11]

Voltage Oriented Control (VOC)
Advantages 1. Fixed switching frequency 2. Good steady state performance 3. Can use advanced PWM strategies
Disadvantages 1. Complex algorithm 2. Involve Clarke transformation, Inverse Clarke transformation, Park transformation, and Inverse Park transformation. 3. Lower input power factor than DPC
Direct Power Control (DPC)
Advantages 1. Simpler and outstanding dynamic performance 2. Without current regulation loops 3. Higher input power factor than VOC 4. Only involve Clarke transformation. 5. Able to regulate the DC output voltage according to the reference DC value
Disadvantages 1. Variable switching frequency 2. High sampling frequency to produce smooth shape of current waveform.

2.6 Pulse Width Modulation

In recent years, Pulse Width Modulation (PWM) has been widely used due many advantages. PMW is a technique to encoding the amplitude of a signal right into a pulse width or duration of another signal, usually a carrier signal, for transmission. The advantages of three-phase pulse width modulation (PMW) rectifier are bidirectional power flow, low harmonic distortion of line current ,unity power factor, and reduced dc filter capacitor size [12].

Generally, the control techniques for PWM rectifier can be classified as virtual-flux based and voltage based. These techniques can separate into 4 category, which are virtual-flux oriented control (VFOC), virtual-flux-based direct power control (VF-DPC), voltage oriented control (VOC), and voltage-based direct power control (V-DPC) [11]. Meanwhile, Hysteresis current control PWM are the commonly used techniques.

2.6.1 Hysteresis-band Controllers PWM

Hysteresis controllers are easy to implement as it uses comparators to switch between the specified hysteresis bandwidth. Hysteresis controllers provides very good dynamic performance as it acts quickly [13]. The common method of hysteresis control is known as two-level hysteresis current control technique. It based on current errors and it is non-linear method. This control method requires defining lower hysteresis band limit and high hysteresis band limit. The lower switch will turn off when it crosses the upper band limit. Besides, the upper switch will turn on when current crosses the lower band limit [14, 15]. Hence, the output current will be forced to follow the current phase reference signal. Therefore, this technique implements modulation and error compensation at the same time. Figure 2.11 shows the operation of hysteresis band.

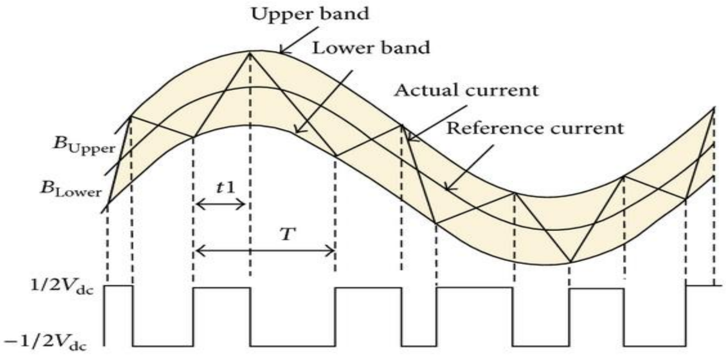


Figure 2.9 The operation of hysteresis band

CHAPTER 3

IMPLEMENTATION OF DIRECT POWER CONTROL (DPC) IN 3-PHASE AC TO DC CONVERTER

This chapter mainly focus on the analysis and development of Direct Power Control (DPC). In this chapter, circuits will be constructed and simulation will be done.

3.1 Software implementation

MATLAB Simulink is the software that implements in this project for simulation purpose. In this project, author will construct a three-phase AC to DC converter with Direct Power Control (DPC) scheme by using MATLAB Simulink. The results obtained from the simulation will be analysed.

3.1.1 Block diagram

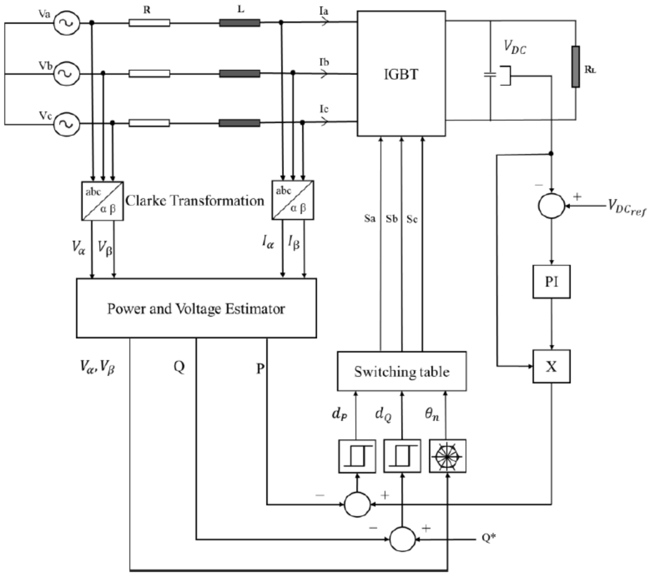


Figure 3.1 Block diagram for Direct Power Control (DPC)

Figure 3.1 shows the block diagram of three-phase AC to DC converter block with DPC scheme. There are several of control methods and DPC is selected for this project. This is due to simple structure and have excellent dynamic response. There are total of seven sensors. Three current sensors are responsible to measure three-phase input currents. Besides, four voltage sensors are responsible to measure three-phase AC input voltage and DC output voltage.

From the block diagram, three-phase inputs voltage and currents will undergo Clarke transformation. The input voltage and currents will transform into αβ frame and fed into “Power and Voltage Estimator” block to obtain the instantaneous active power and reactive power. After that, the instantaneous active power and reactive power will fed into hysteresis comparator to obtain the active and reactive power errors (d_P, d_Q). Meanwhile, the voltage vector angle converter block will generate the angle of αβ frame input voltage (θ_n).

Then, d_P, d_Q, and θ_n will enter switching table. The switching table responsible to generate the suitable switching states of the converter. Besides, the function of PI controller is to regulate the DC output voltage according to the reference DC value.

3.1.2 Development of Simulation Block Scheme

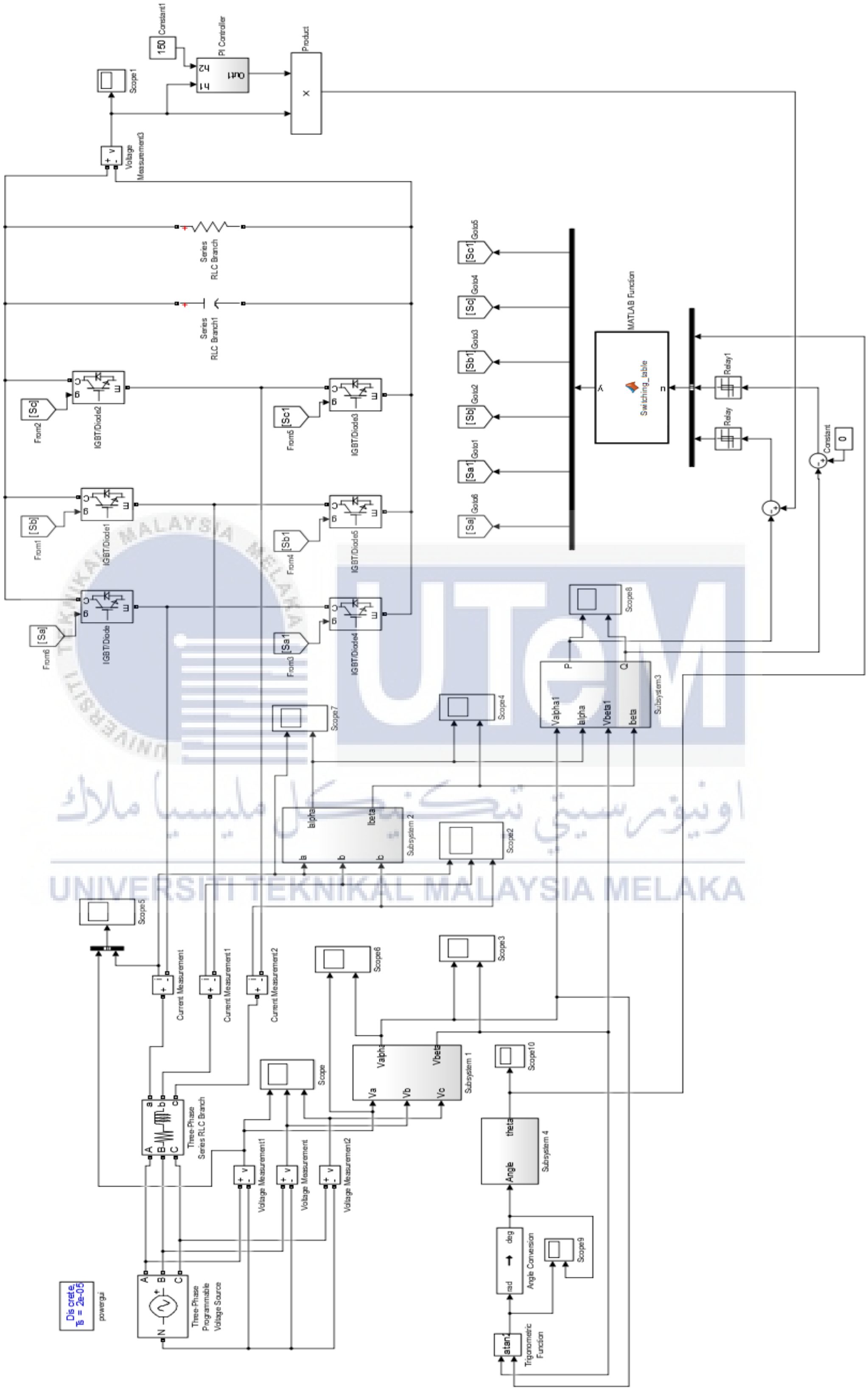


Figure 3.2 Circuit Diagram of DPC (Simulation)

Figure 3.2 shows the circuit diagram of DPC. By using MATLAB Simulink, the circuit diagram is constructed and simulated. The electrical parameters need to be set for simulation purpose. Hence, Table 3.1 shows the settings for each electrical parameters.

Table 3.1 Electrical parameters

Parameters	Value
Sampling time	20μs
Input phase voltage (Peak)	70.71 V
Frequency of source voltage	50 Hz
Resistance ,R	0.2 Ω
Inductance ,L	15mH
DC-link voltage reference, V_{DCref}	150V
DC-link capacitor, C	10.8mF
Load resistance, R_{load}	140Ω

During simulation, time scope need to be implemented in the circuit diagram to observed the input waveform and output waveform. For example, the important waveforms might include three-phase input current, three-phase input voltage, voltage in αβ frame, current in αβ frame, DC output voltage and so on. Besides, the colour of the waveforms also can be change.

3.1.3 Configuration of subsystem

Subsystem 1 and Subsystem 2

Subsystem 1 and subsystem 2 can be found in figure 3.2. Meanwhile, Subsystem 1 represent Clarke transformation for three-phase voltage and subsystem 2 represent Clarke transformation for three-phase current. The block diagrams are constructed according to the formulas of Clarke transformation.

Equation (3.1) and equation (3.2) are the formulas to transform three-phase voltage into αβ frame. Besides, figure 3.3 shows the circuit diagram of Clarke transformation for voltage in subsystem 1.

$$V_\alpha = \frac{2}{3}(V_a) - \frac{1}{3}(V_b + V_c) \tag{3.1}$$

$$V_\beta = \frac{1}{\sqrt{3}}(V_b - V_c) \tag{3.2}$$

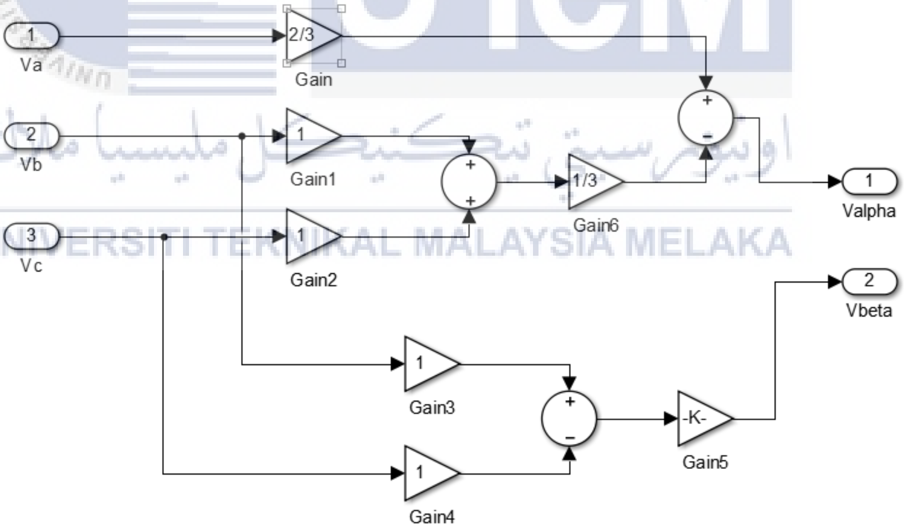


Figure 3.3 Clarke Transformation for voltage (Subsystem 1)

Equation (3.3) and equation (3.4) are the formulas to transform three-phase current into αβ frame. Besides, figure 3.4 shows the circuit diagram of Clarke transformation for current in subsystem 2.

$$I_\alpha = \frac{2}{3}\,(I_a) - \frac{1}{3}\,(I_b+I_c) \tag{3.3}$$

$$I_\beta = \frac{1}{\sqrt{3}}\,(I_b-I_c) \tag{3.4}$$

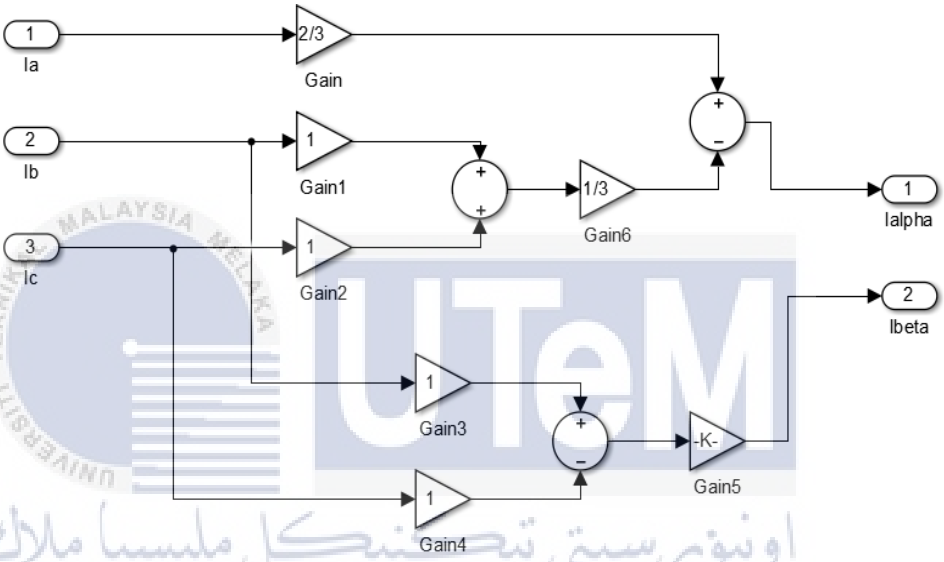


Figure 3.4 Clarke Transformation for current (Subsystem 2)

Subsystem 3

After Clarke transformation, the αβ frame of input voltage (V_α and V_β) and input current (I_α and I_β) are successfully generated. The αβ frame of input voltage and input current are used to determine the instantaneous active power and reactive power. Subsystem 3 is constructed based on equation (3.5) and equation (3.6). Meanwhile, figure 3.5 shows the circuit diagram of subsystem 3.

$$P_{inst} = \frac{3}{2}\left[V_\alpha I_\alpha + V_\beta I_\beta\right] \tag{3.5}$$

$$Q_{inst} = \frac{3}{2}\left[V_\beta I_\alpha - V_\alpha I_\beta\right] \tag{3.6}$$

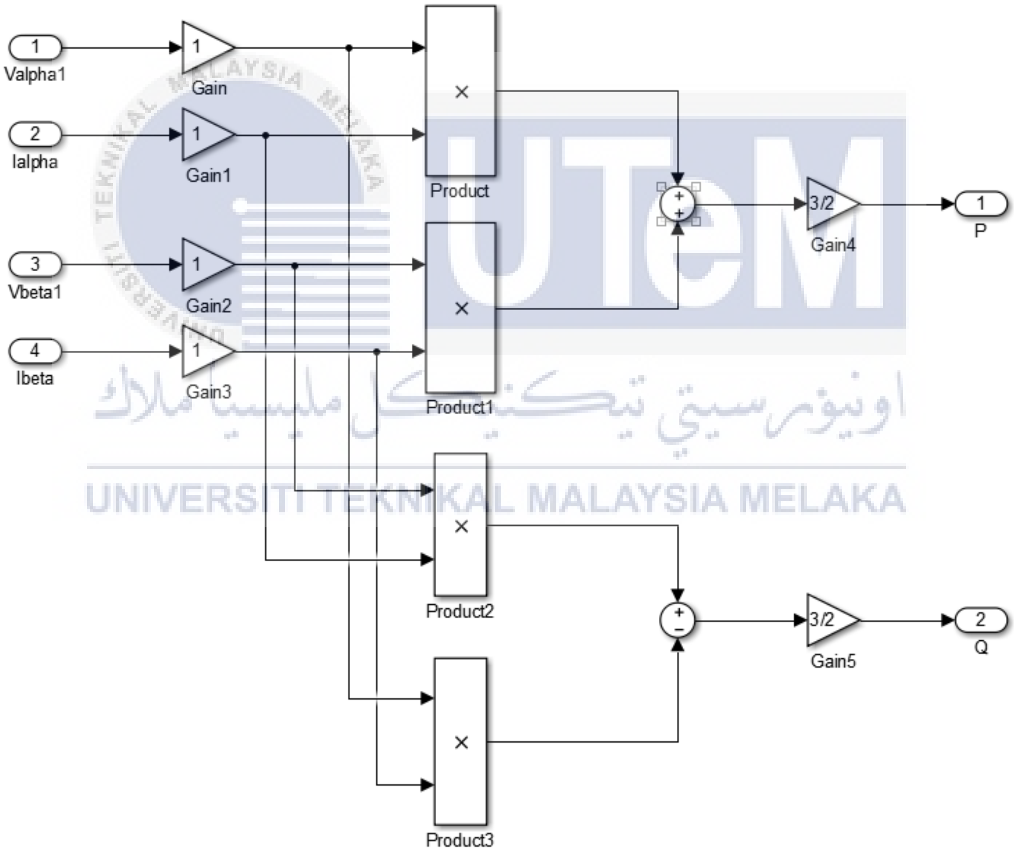


Figure 3.5 Instantaneous active and reactive power (Subsystem 3)

Subsystem 4

Subsystem 4 represent voltage sector selection. The sector selections of DPC can be divided into 12 sectors and each sectors represents 30^0. The inputs of subsystem 4 need to be in degree form. Hence, angle conversion is needed in this system in order to convert the inverse tangent of V_α and V_β from radian form to degree form. Figure 3.6 shows the configuration of voltage sector.

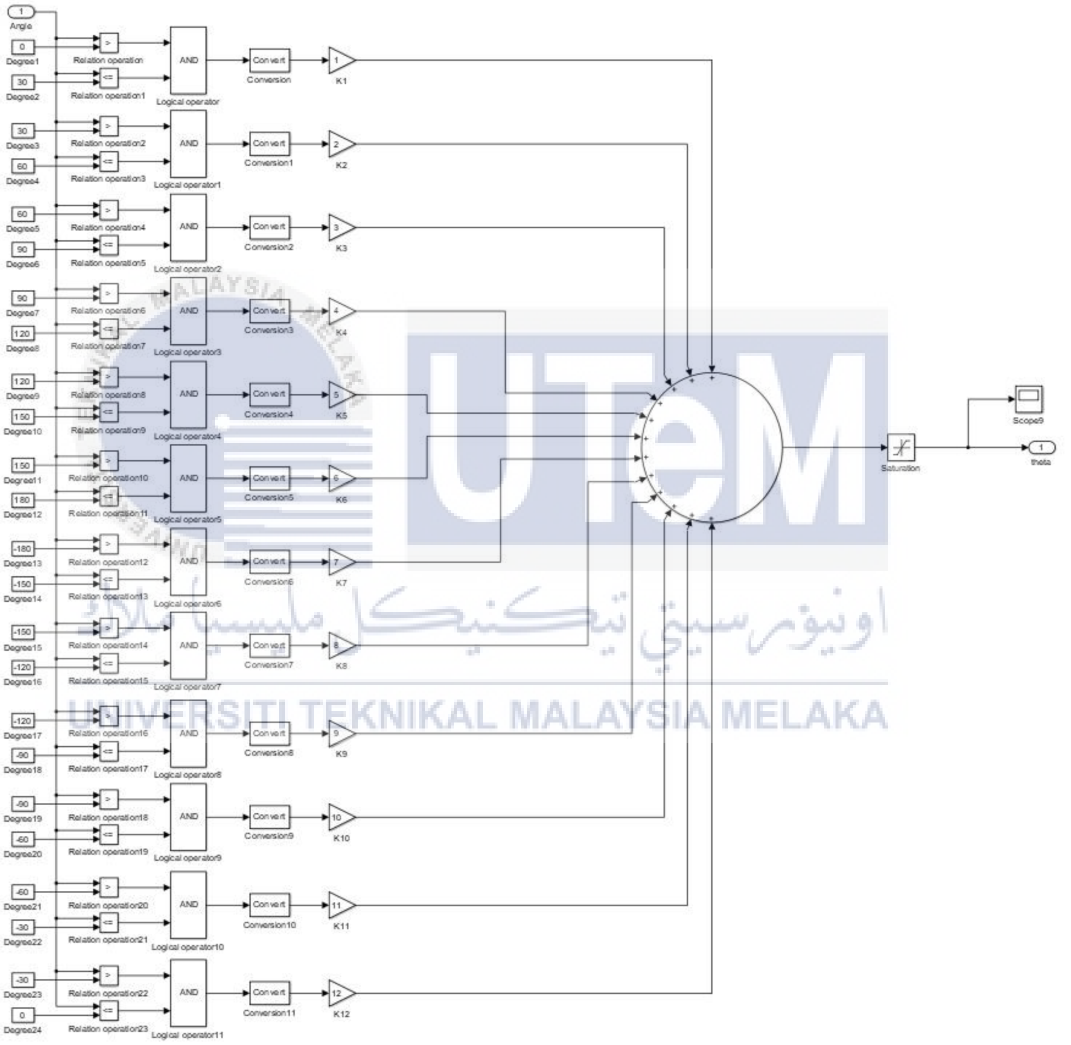


Figure 3.6 Voltage sector selection (Subsystem 4)

Subsystem 5

Figure 3.7 illustrates a simple PI controller. The present of PI controller is to regulate the DC output voltage by controlling the active power. The output of the PI controller will be the reference active power, P_{ref}. Hence, a comparison will be made between the actual instantaneous active power and reference active power to obtain the active power error, P_{err}. The active power error is then send to the switching table. Meanwhile, figure 3.7 indicates that the value of Kp is 5 while the value of Ki is 25. The value of Kp and Ki is set based on trial and error method.

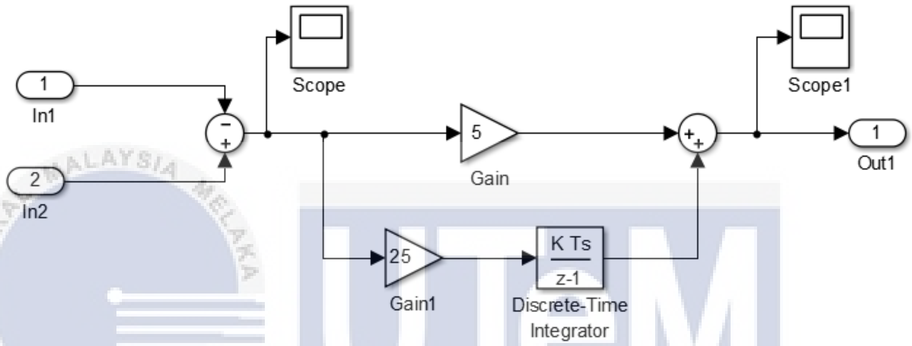


Figure 3.7 PI controller (Subsystem 5)

3.1.4 Switching Table

The switching table responsible to select the optimal rectifier voltage vector and output the corresponding switching state. In MATLAB Simulink, the switching table can be created by adding coding into “MATLAB Function” Block. The coding for the switching table is written based on Table 3.2. Meanwhile, the coding for the switching table can be found in Appendix B.

Table 3.2 DPC Switching table

Power error status		Sector position (θ_n) and converter voltage vector (V_n)											
d_P	d_Q	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	θ_7	θ_8	θ_9	θ_{10}	θ_{11}	θ_{12}
0	0	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6
0	1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1
1	0	V_6	V_6	V_1	V_1	V_2	V_2	V_3	V_3	V_4	V_4	V_5	V_5
1	1	V_3	V_3	V_4	V_4	V_5	V_5	V_6	V_6	V_1	V_1	V_2	V_2

Based on Figure 3.8, the output “y = [S_a S_{a1} S_b S_{b1} S_c S_{c1}] ” stand the commutation state vectors of converter with alternating upper and lower switch on. When the upper switch is on, the lower switch will off. On the contrary, the lower switch is on when the upper switch is off. Hence, the upper switch and lower switch are always complementary to each other.

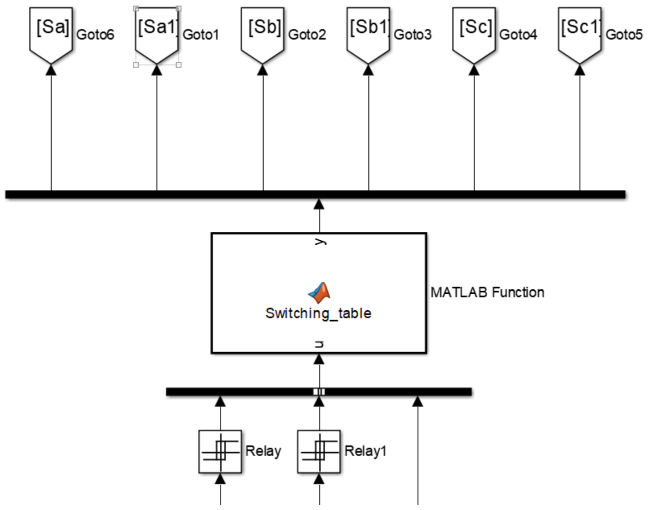


Figure 3.8 Configurations of Switching table

3.2 Hardware Implementation

After complete simulation by using MATLAB Simulink, this project will proceed with hardware implementation. Basically, the flow of hardware implementation are shown in Figure 3.9.

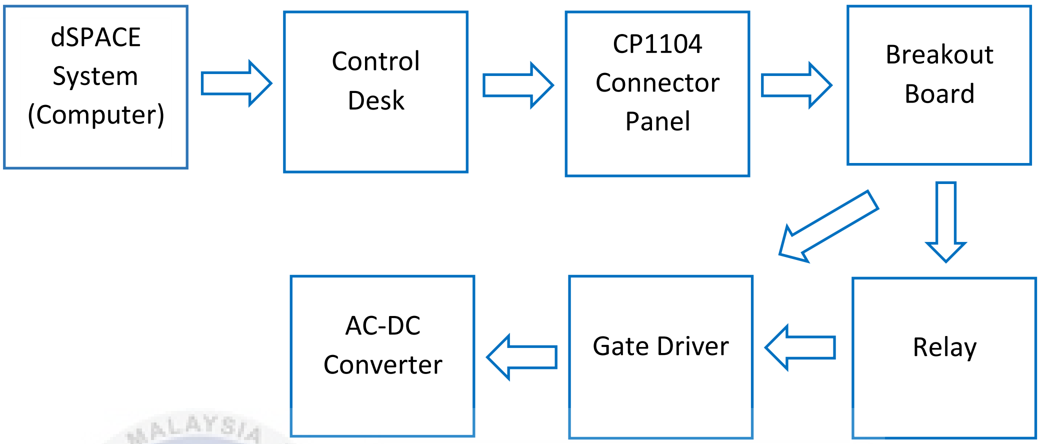


Figure 3.9 Flow of hardware implementation

During hardware implementation, user are required to follow the steps that listed on below. There will be total 7 steps in order to obtain the final results.

1. Build the main circuit board which consist of breakout board, relay, gate driver and AC-DC converter.
2. Use the block from RTI library to construct PWM circuit and DPC scheme in MATLAB Simulink
3. Build the Simulink model and control the circuit model by using ConrtrolDesk.
4. Check the functionally of breakout board, relay, gate driver, and AC-DC converter board.
5. At this state, converter board will run as inverter by supply DC voltage as input. Measure the three phase output form the inverter in order to obtain the waveforms of line-to –line voltage.
6. Then, converter board will run as converter by supply three phase voltage as input. Meanwhile, the inductors will be connected in between three phase voltage supply and the converter board. It will operate as three-phase diode rectifier without gate signals.
7. Implement DPC scheme on the circuit to obtain the final results.

3.2.1 dSPACE

DS1104 R&D Controller Board is the dSPACE system that used in this project. It provide Rapid Control Prototyping (RCP) after installing the board in the computer. Specific connectors comprise of Connector Panel, CP1104, and Connector/LED Combi Panel, CLP1104, which provides an easy and simple way to access all the input and output signals to DS1104. Besides, Simulink model can be build and run on DS1104 by using Real-Time Interface (RTI). User required to connect their model to the CP1104 during real-time applications. Figure 3.10 shows the layout of the Control panel, CP1104.

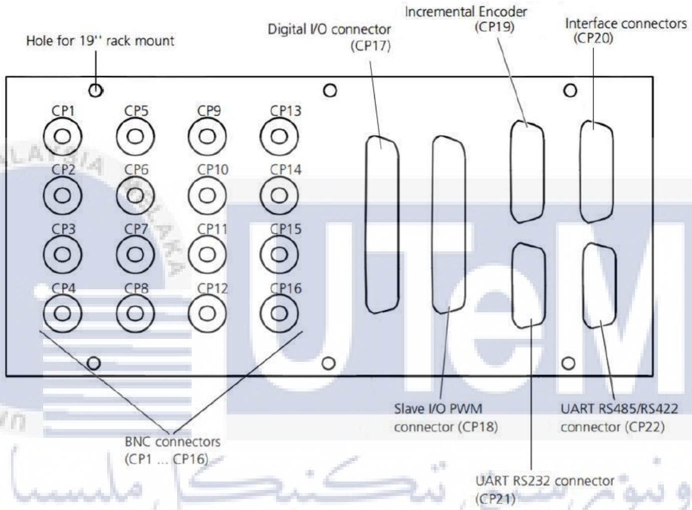


Figure 3.10 Layout of Connector Panel, CP1104

Table 3.3 shows the type of connectors. Each connectors will connect to different components. Hence, users are required to refer to their specific data sheets when using the CP1104.

Table 3.3 Types of connectors

Connectors	Appendix
BNC connectors	Appendix C
Digital I/O connectors	Appendix D
Slave I/O connectors	Appendix E

Other than that, the connector/LED Combi Panel, CLP1104 are responsible to indicate the digital signal states. When the TTL signal is low, the LED will off. On the other hand, the LED will on when the TTL signal is high. Figure 3.11 shows the diagram of CLP1104 connector/LED Combi Panel.

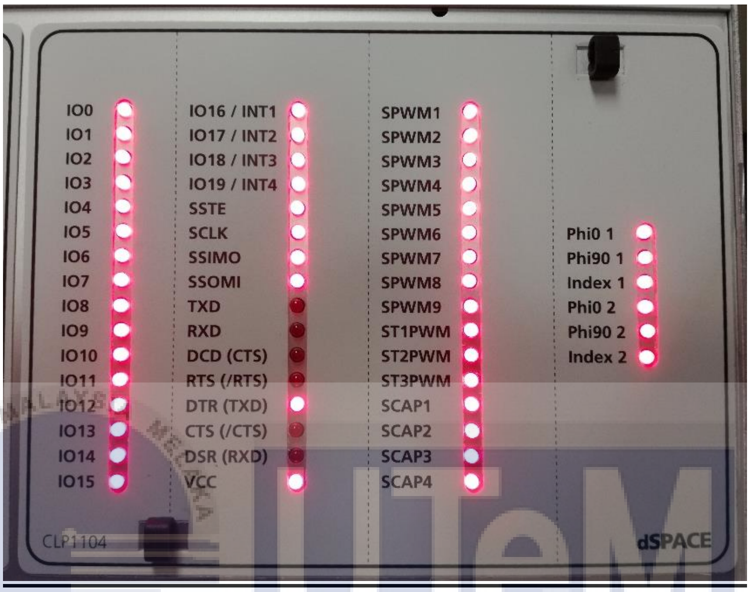


Figure 3.11 CLP1104/LED Combi Panel

For experiment and visualization purpose, dSPACE also have another software knows as ControlDesk. Basically, ControlDesk is the dSPACE experiment software for seamless Electronic Control Unit (ECU) development. It performs all the necessary tasks and gives user a single working environment, from the start of experimentation right to the end. User can build the Simulink model to into ControlDesk. User able to directly modify the controller parameters and settings by using ControlDesk.

3.2.2 Main Circuit Board

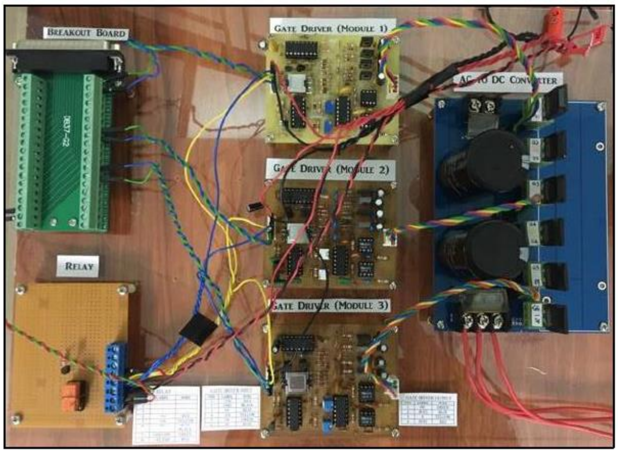


Figure 3.12 Main circuit board

Figure 3.12 shows that the whole circuit board for the three-phase AC to DC converter. There are four main components for this main circuit board, which are breakout board, gate driver modules, relay, and three-phase AC to DC converter. The breakout board is connected with CP1104. Besides, the relay received signals from control desk and responsible to enable or disable the gate driver modules. The gate driver modules is connected with the three-phase AC to DC converter.

3.2.3 Breakout Board

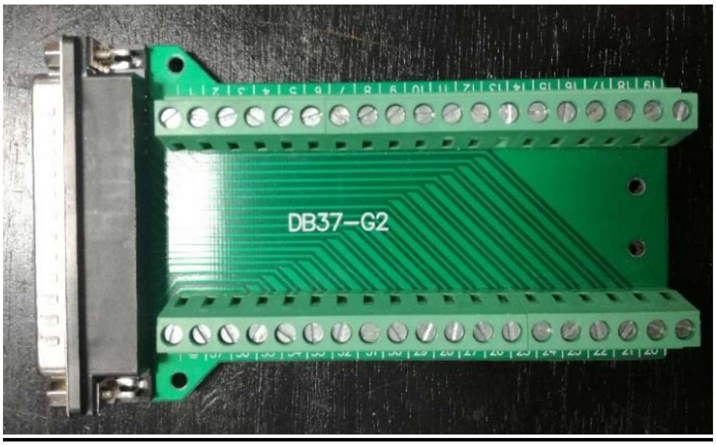


Figure 3.13 Breakout board

Breakout board are shown on Figure 3.13. The model of the breakout board that use in this project is DB37-G2 with Sub-D connector. The breakout board will connect with main circuit board and also control panel, CP1104, of DS11004. With the present of breakout board, Simulink model uploaded to the dSpace memory can be apply to the main circuit. However, user also can modify the system parameters of the model by using ControlDesk. The pinout on the breakout board and its output signal is depends on the type of connectors that connected to the board. Examples for connectors are Digital I/O Connector and Slave I/O PWM Connector.

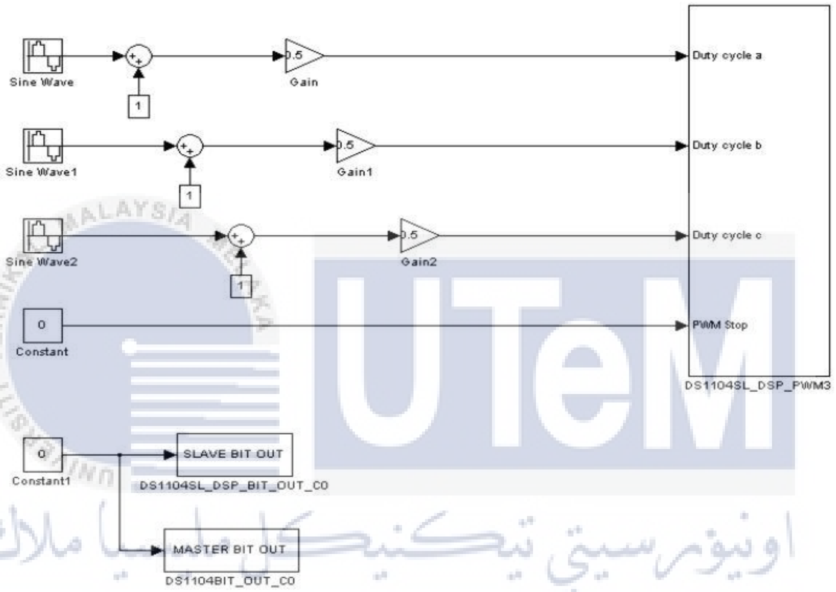


Figure 3.14 Simple circuit for PWM generation

Figure 3.14 shows a circuit model constructed in MATLAB Simulink using the PWM block from RTI library. This circuit is designed to test the functionality of relay and gate driver module. Based on the circuit, the output of “Sine wave” block are fed into the comparator with constant 1. To ensure the output signal limited to the range of 0 to 1, the error will multiplied with gain,K= 0.5. Hence, the PWM block able to generate require PWM signals. Besides, Table 3.4 shows the parameters for “Sine Wave” block.

Table 3.4 Parameters setting for sine wave block

Function Block	Sine wave 1	Sine wave 2	Sine wave 3
Frequency (rad/sec)	100π	100π	100π
Amplitude	0.5	0.5	0.5
Phase (rad)	0	-120 (π/180)	+120 (π/180)

After complete construct the Simulink model by using MATLAB, users are required to build the Simulink model to into ControlDesk by pressing Ctrl+B. Open the ControlDesk and start select the instrument after successfully build the Simulink model. In ControlDesk, Push Button and Multi State LED are selected from Visual Instrument. Meanwhile, user able to modify the parameters and settings by double clicking to the specific instrument. Under “Model Root” category in ControlDesk, it consists of the “P:Variable” which represent the block parameters in Simulink Model. Hence, user required to drag the “P: Variable” to the specific instrument. In this case, user drag the “P:Variable” of “constant” block and assign to the “PWM Enable” push button and the “On/Off” LED which on the left. Meanwhile, the P:Variable” of “constant 1” block will be dragged and assigned to the “DSP Enable” push button and the “On/Off” LED which on the right. Figure 3.15 shows the layout of PWM enable and DSP Enable switch in Control desk.

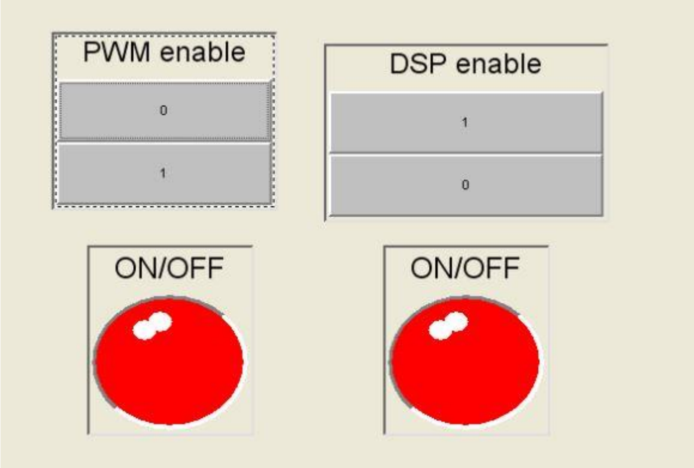


Figure 3.15 Layout of PWM enable and DSP Enable switch

The function of LED is to indicate the state of the switch. Green indicate ON while Red indicate OFF. The initial state of the push button always remain off (0). Hence, user can change the state of the push button to on by clicking “1” in ControlDesk.

When the push button (DSP Enable) is in high state (1), it will supply +5V to the pinout of breakout board. The pinout is then supply the +5V to the relay or the gate driver modules. On the other hand, no voltage supply when the push button is in low state (0). Same concept apply to the push button (PWM Enable). When the push button is in high state (1), it will supply a gate signal to the pinout board and then to gate driver module.

When implement DPC scheme in this circuit, the Digital I/O connector are connected to the breakout board. The gate driver modules will receive gate signal from the breakout board as determine by the Switching table.

3.2.4 Relay

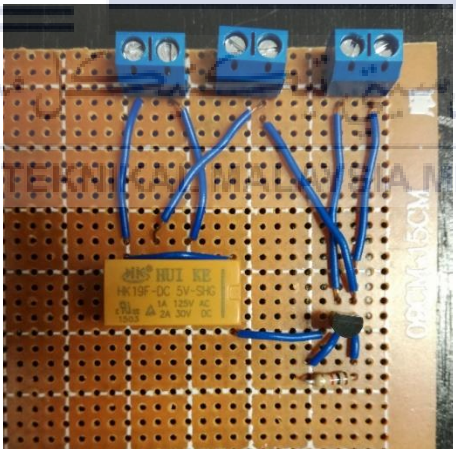


Figure 3.16 Relay used in the hardware implementation

Figure 3.16 shows a complete relay that ready for hardware implementation. Enable and disable the gate driver modules are the main functions of relay. Besides that, relay also act as a protection device for the modules. Meanwhile, switching on and off the relay is controlled by the output from the connector of CP1104. The model of the relay used in this circuit board is HK19F and model of the MOSFET is 2N700. Figure 3.17 shows the connection of the relay circuit board.

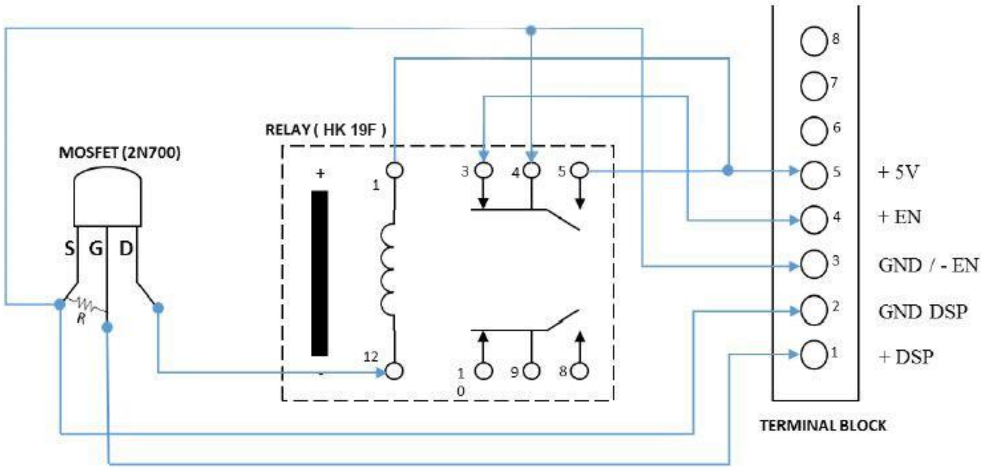


Figure 3.17 Relay circuit connection

Table 3.5 and Table 3.6 shows the detail connection of relay and MOSFET respectively. When the input voltage to the relay is higher than 3V, it will switch on the relay and produce 5V to the + Enable. On the other hand, the relay will remain off mode when input voltage is lesser than 3V.

Table 3.5 Relay connection

Relay	Terminal block Connection
Pin 1	Connected to fixed DC power supply (+ 5V)
Pin 3	Connected to + ENABLE
Pin 4	Connected to GND ENABLE
Pin 5	Connected to fixed DC power supply (+ 5V)
Pin 12	Connected to MOSFET (Pin G)

Table 3.6 MOSFET connection

MOSFET	Connection
Pin S	Connected to GND ENABLE Connected to GND DSP Connected to resistance
Pin G	Connected to +DSP Connected to resistance
Pin D	Connected to relay pin 12

3.2.5 Gate Driver Module

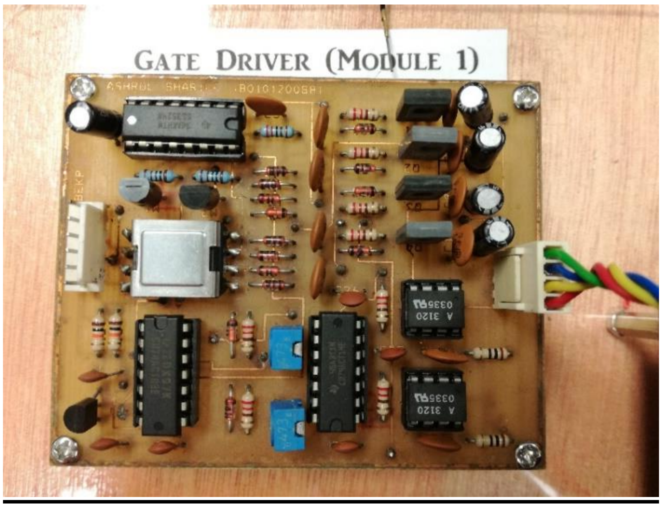


Figure 3.18 Gate Driver module

Figure 3.18 shows the structure of gate driver module. When enable the gate driver, it will produce two gate signals. Those two gate signals are opposite to each other. The two signals are shown in Figure 3.19. Output signal 1 is the gate signal to the upper IGBT while output signal 2 is the gate signal to the lower IGBT. Because of that, the upper IGBT will automatically switch ON when the lower IGBT switch OFF. There will be three gate driver modules that apply in this project. Therefore, three gate drivers will generate 6 gate signals at a single time. Due to the implementation of DPC, switching table will select the optimum switching state for the IGBTs to increase the performance of three phase converter.

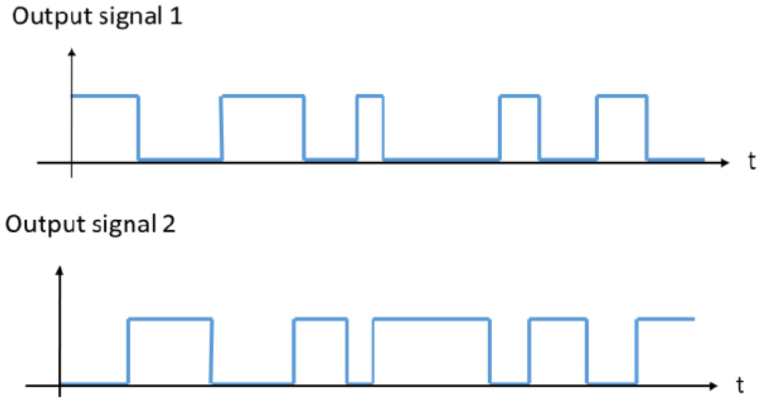


Figure 3.19 Two output signals from Gate driver module

3.2.6 Three-phase AC to DC converter

Figure 3.20 Three phase AC to DC Converter circuit board

Figure 3.20 shows the three phase AC to DC converter circuit board. This board can function as converter or an inverter. When supply DC voltage to the board, the board will operate as inverter by invert the DC voltage to three phase AC voltage output. To check functionality of the board, the waveform of output three phase voltage can be observed by using oscilloscope. On the contrary, the board will operate as converter when supply three phase supply voltage to the board. The board will generate DC voltage as output. The three phase AC power supply used is 50 Vrms (phase to phase). When disable the gate driver modules, the board will operate as full bridge three phase rectifier. However, the board will function as AC to DC converter when enable the gate driver modules.

3.2.7 Simulink Model for Hardware Implementation

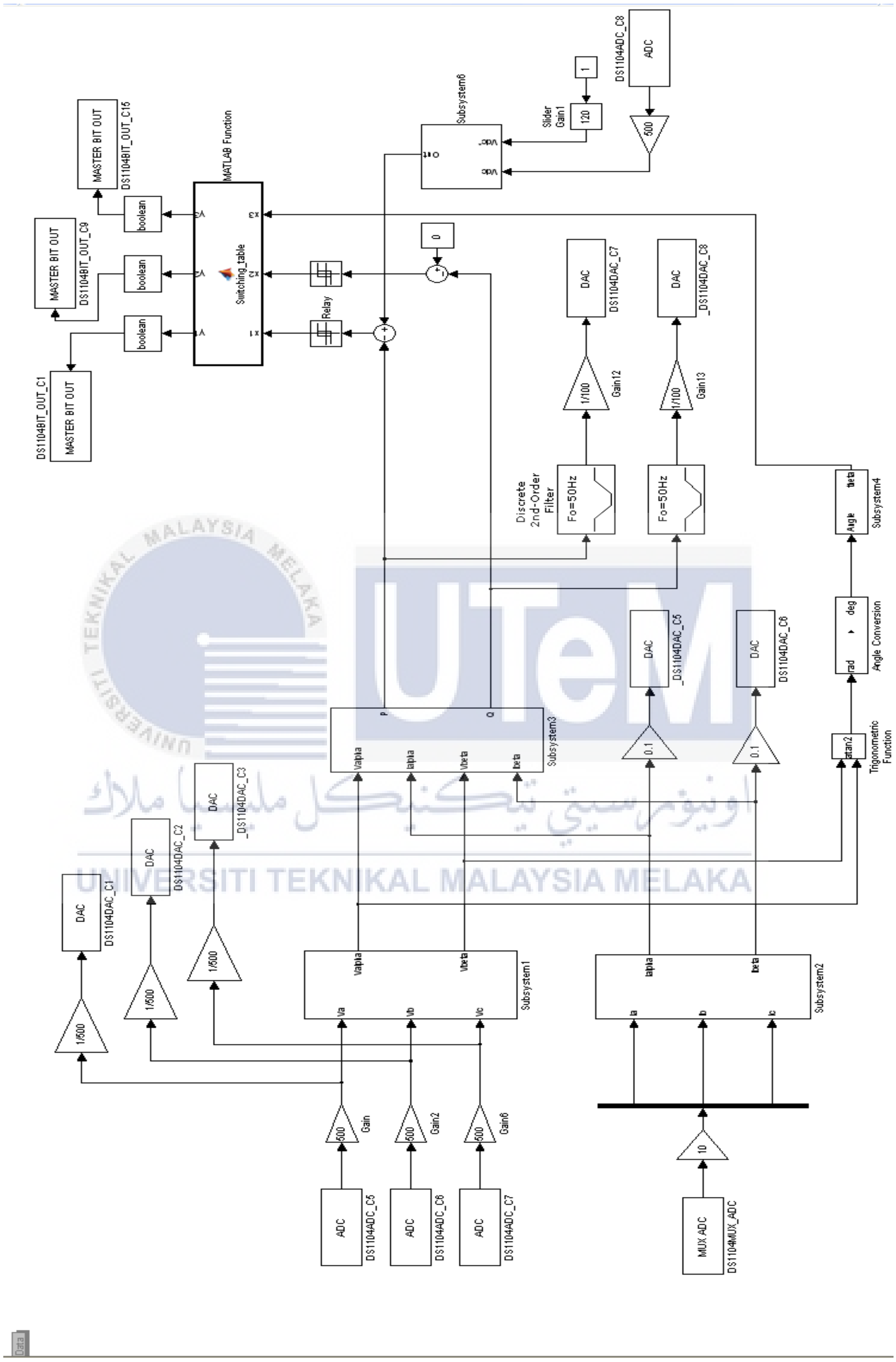


Figure 3.21 Simulation model for overall hardware implementation

Figure 3.21 shows the simulation model for overall hardware implementation. Meanwhile, Table 3.7 show the type of connectors and signal. User can refer to this table when doing the hardware connection.

Table 3.7 Type of connectors and signal

No.	BNC Connectors	Signal	Connector
1.	DS1104MUX_ADC	ADCH4	CP4
2.	DS1104ADC_C5	ADCH5	CP5
	DS1104ADC_C6	ADCH6	CP6
	DS1104ADC_C7	ADCH7	CP7
3.	DS1104ADC_C8	ADCH8	CP8
4.	DS1104DAC_C1	DACH1	CP9
	DS1104DAC_C2	DACH2	CP10
	DS1104DAC_C3	DACH3	CP11
5.	DS1104DAC_C5	DACH5	CP13
	DS1104DAC_C6	DACH6	CP14
6.	DS1104DAC_C7	DACH7	CP15
	DS1104DAC_C8	DACH8	CP16
	Digital I/O Connector	Signal	PIN
1.	DS1104BIT_OUT_C1	IO1	PIN2
	DS1104BIT_OUT_C9	IO9	PIN8
	DS1104BIT_OUT_C15	IO15	PIN12

“DAC” blocks stands for “Digital to Analog” block. The output status from DACH is either “High” or “Low” only. To ensure the output to DACH is either 1 or 0, the voltage are required to multiply with a gain value, which is K=1/500 before fed into DAC block. Meanwhile, alpha and beta current also required to multiplied with a gain, K= 0.1 before fed into DAC block. This is because the current probe used to measure the current directly form the three phase supply is scaled down by 100mV/A.

“ADC” blocks stands for “Analog to Digital” block. From device to ADCH, the channel input to dSPACE is “Low” when it measures than 10V from the device. On the other hand, the channel input to dSPACE is “High” when it measure more than 10V from the device. The voltage probes used to measure the actual voltage is scaled down by 1/500. Hence, the input three phase voltage from ADC block are required to multiplied with gain, K=500 in order to obtain the actual voltages.

Other than that, the “MASTERBIT OUT” block are responsible to send the switching signal to the breakout board. The coding for the switching table during software simulation (Appendix B) need to be modified. This is because of the incompatible type and size of output from switching table to the RTI block. The new modified coding will be attached at Appendix F.

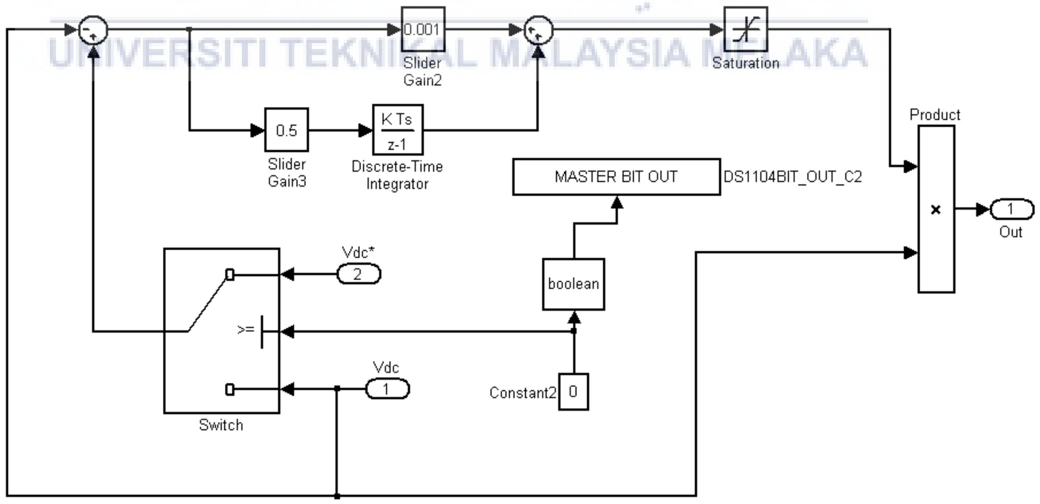
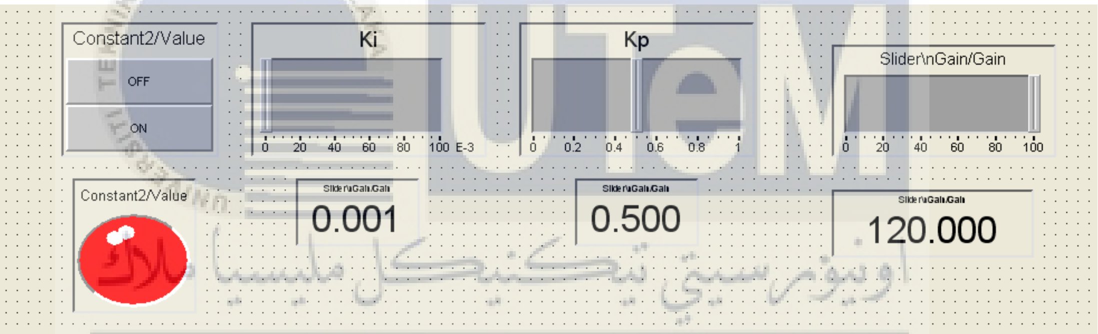


Figure 3.22 Modified version of Subsystem 5

Figure 3.22 shows the subsystem 5 after modified. The initial state of the “Enable gate driver” push button always remain off (0). Hence, the relay will in the off state and there will be no voltage supply to the gate driver. Besides it also rest the PI controller. User can change the state of the push button to on by clicking “1” in ControlDesk.

Meanwhile, the “switch” block is set to “u2>= Threshold” and the value of threshold is 1. When the input to the switch is 1, voltage reference (V_{dc}^{*}) will be the output from the switch. On the other hand, DC Voltage (Vdc) will be the output from the switch when the input to the switch is 0. Other than that, user also can manually tune the PI controller by using the slider gain for Kp and Ki in ControlDesk. The result obtained from the experiment will be discussed in chapter 5. The layout of slider gain for Kp, Ki, V_{ref} and Enable gate driver switch are shown in Figure 3.23



0.001

0.500

120.000

Figure 3.23 Slider gain for Kp, Ki, V_{ref} and Enable gate driver switch

CHAPTER 4

SIMULATION RESULTS AND DISCUSSIONS

This chapter mainly focus on result and discussion. The results can be obtained from simulation by using MATLAB Simulink. The results are then analysed and discussed.

4.1 Simulation of Open Loop Rectifier

Figure 4.1 shows an open loop rectifier circuit diagram which constructed by MATLAB Simulink. When run the simulation, the waveform of three-phase input voltage and input current in abc frame can be captured. After Clarke transformation, the waveform of input voltage and input current in alpha-beta frame also can be obtained. Meanwhile, the waveform of instantaneous active and reactive power can been obtained from the scope. Since the input of voltage sector selection need to be degree form, angle conversion is needed to convert the angle from radian form to degree form. Hence, the waveform of angle in radian form and angle in degree form will be captured. Besides, the voltage sector number waveform also need to be obtained. Further elaboration of each waveform will be done in this chapter.

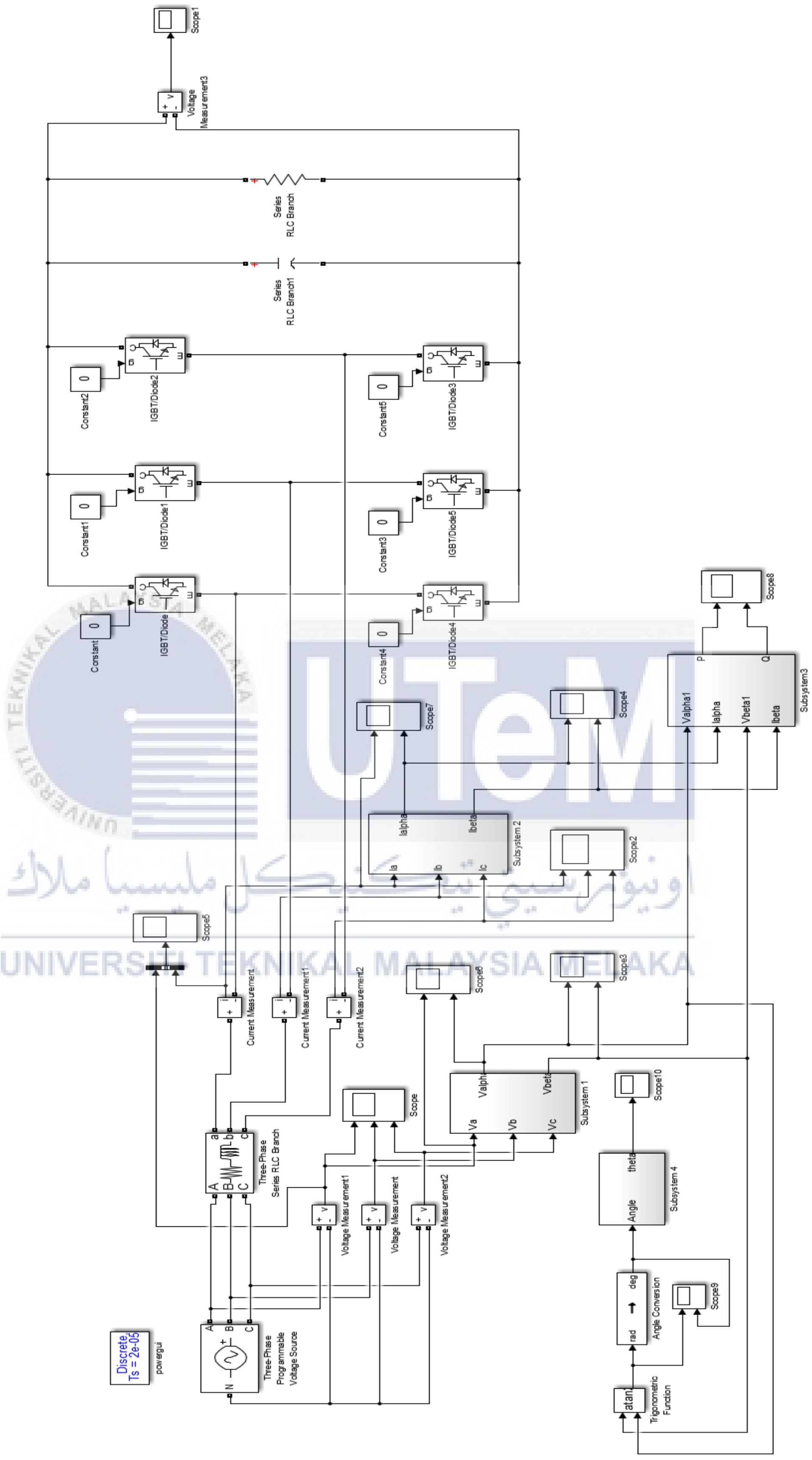


Figure 4.1 Open-loop rectifier circuit

The waveform of three-phase input voltage in a abc frame is shown in Figure 4.2. Meanwhile, Figure 4.3 shows the the waveform of three-phase input current in abc frame. The waveform in red colour represent phase a, the yellow waveform represent phase b, and the blue waveform represent phase c. Based on Figure 4.2 and Figure 4.3, it can be seen that each phase is shifted 120^0 from another. However, the waveform of three-phase input current is non-sinusoidal. The is due to the present of harmonic components in the diode rectifier.

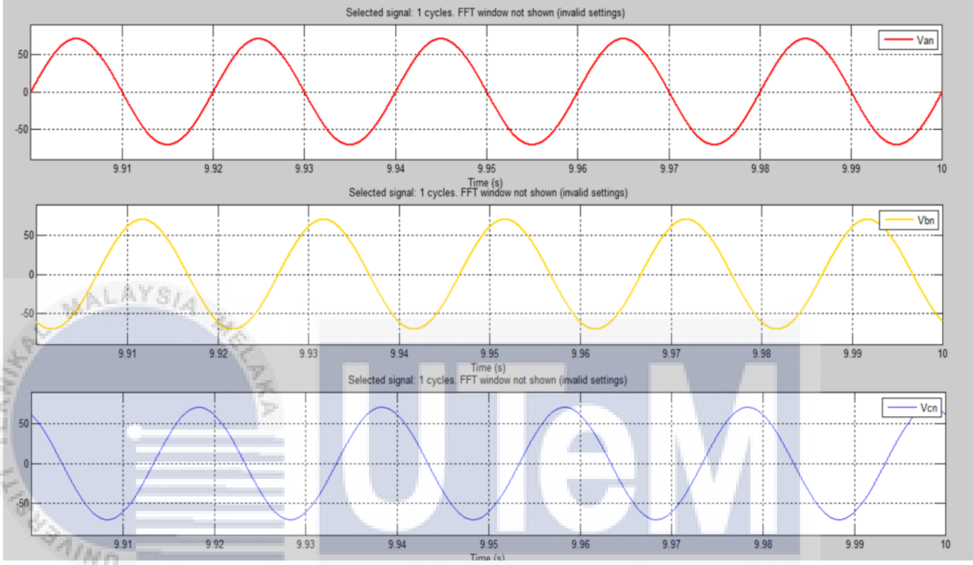


Figure 4.2 Waveform of three phase input voltage in abc frame

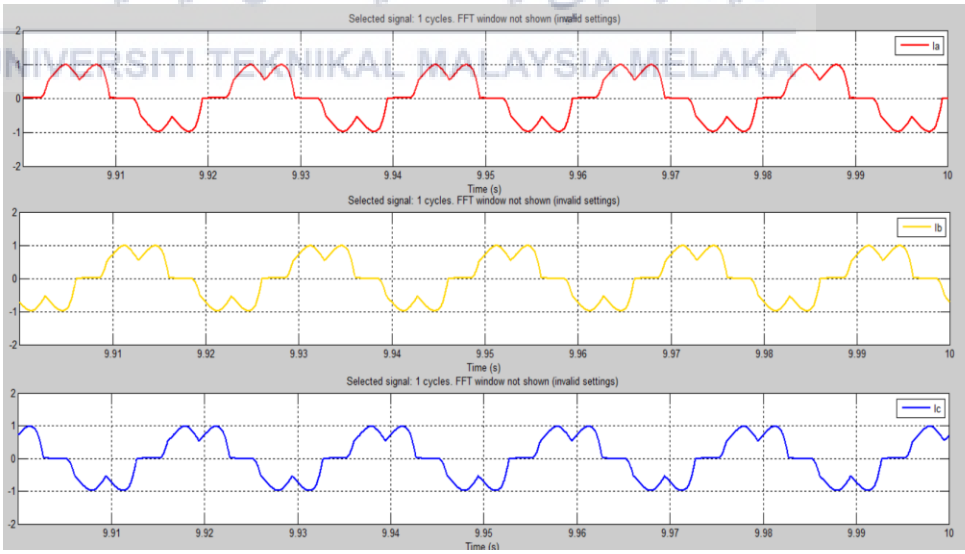


Figure 4.3 Waveform of three phase input current in abc frame

The waveform of three-phase input voltage in a alpha-beta frame is shown in Figure 4.4. Based on Figure 4.4, it can be seen that $V\alpha$ lag V_β by 90^0 . The waveform in green colour represent input voltage in alpha frame and the waveform in pink colour represent input voltage in beta frame.

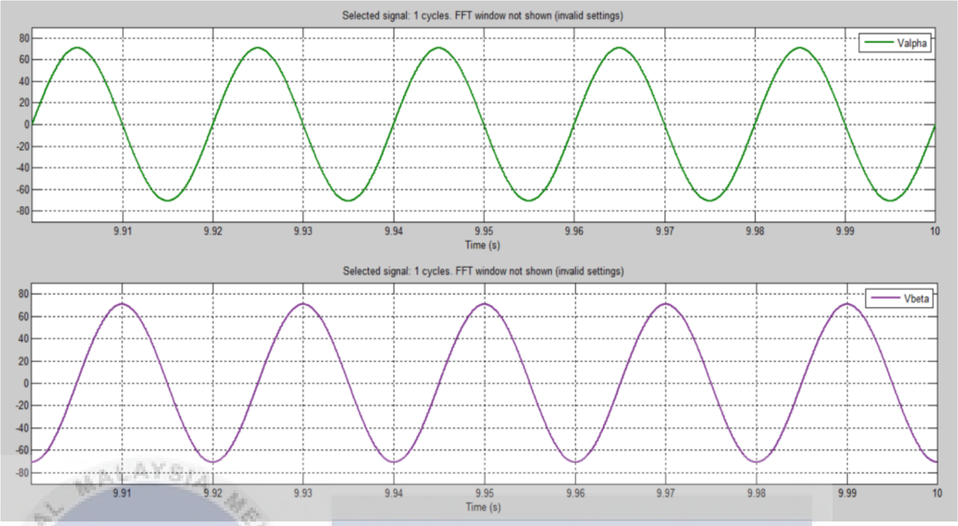


Figure 4.4 Waveform of voltage in alpha-beta frame

The waveform of three-phase input current in a alpha-beta frame is shown in Figure 4.5. The waveform in green colour represent input current in alpha frame and the waveform in pink colour represent input current in beta frame. Based on Figure 4.5, the waveform of input current in alpha-beta frame is non-sinusoidal. This is beacause of the harmonice effect in the input current in abc frame.

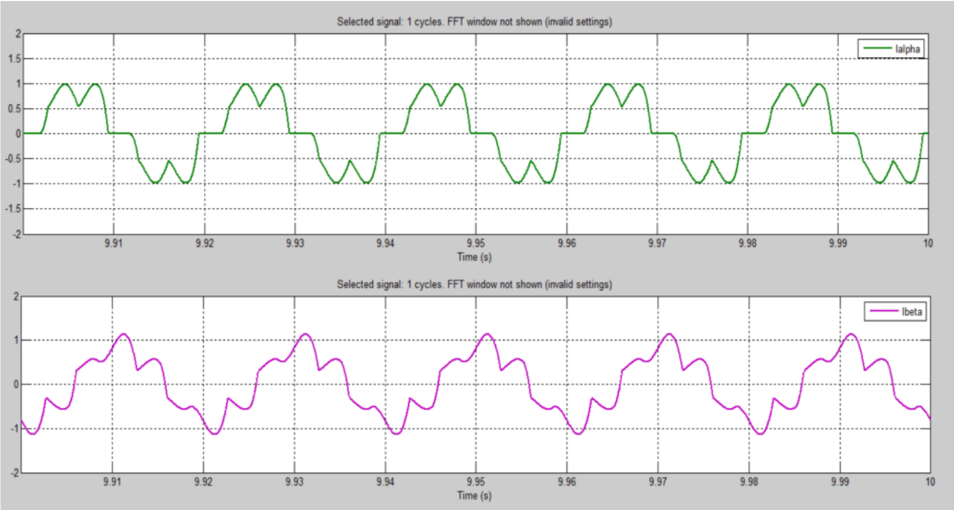


Figure 4.5 Waveform of input current in alpha-beta frame

The waveform of instantaneous active and reactive power is shown in Figure 4.6. The waveform in green colour represent instanstaneous active power and the waveform in pink colour represent instantaneous reactive power. The main reason that cause both waveform have power ripple is due to the harmonic components in the input current.

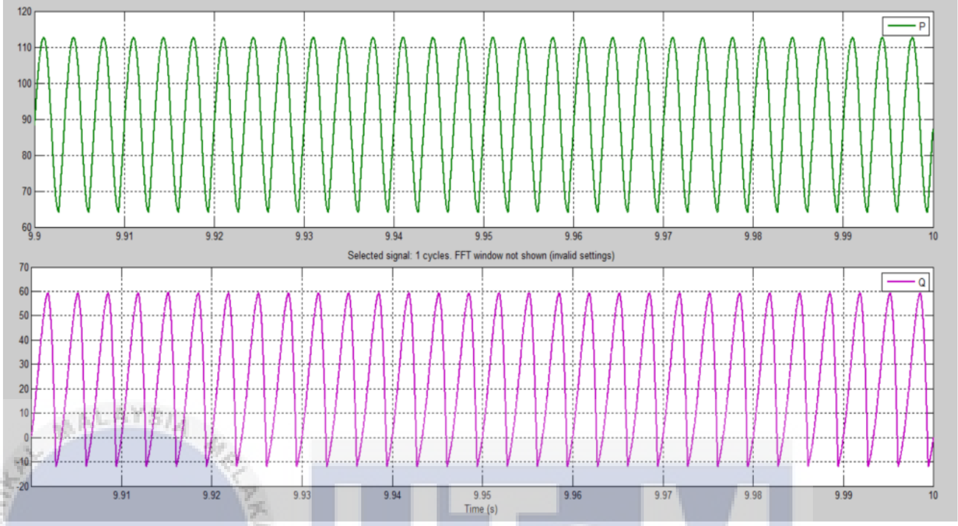


Figure 4.6 Waveform of instantaneous active and reactive power

Figure 4.7 shows the waveform of angle in radian and degree. The waveform in green colour represent angle in radian and the waveform in pink colour represent angle in degree. In MATLAB Simulink, the angle in radian can be convert into degree by using “angle conversion” block.

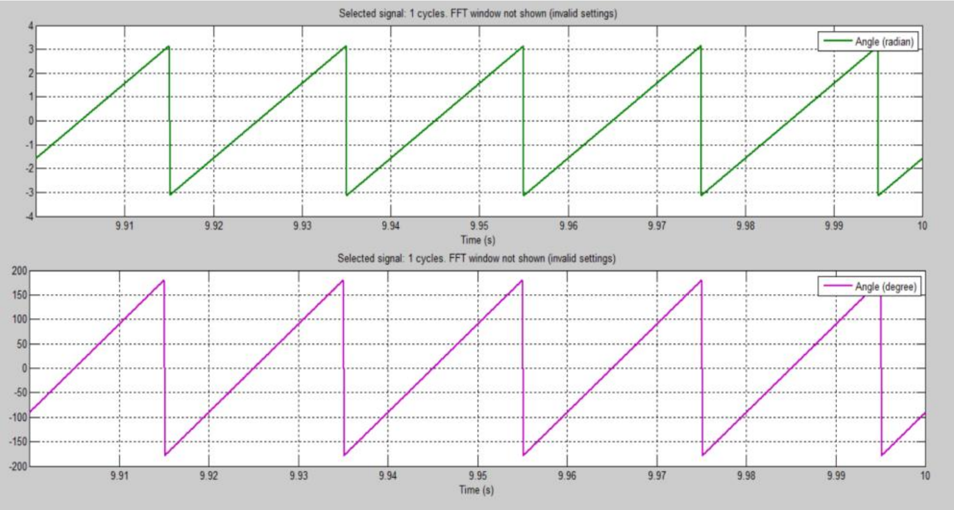


Figure 4.7 Angle in radian and degree

Figure 4.8 shows the output of voltage sector.There are total of 12 sector and each step represent one sector. The waveform of voltage sector is depends on output of $\tan^{-1}(\frac{V_\beta}{V_\alpha})$ in degree form.

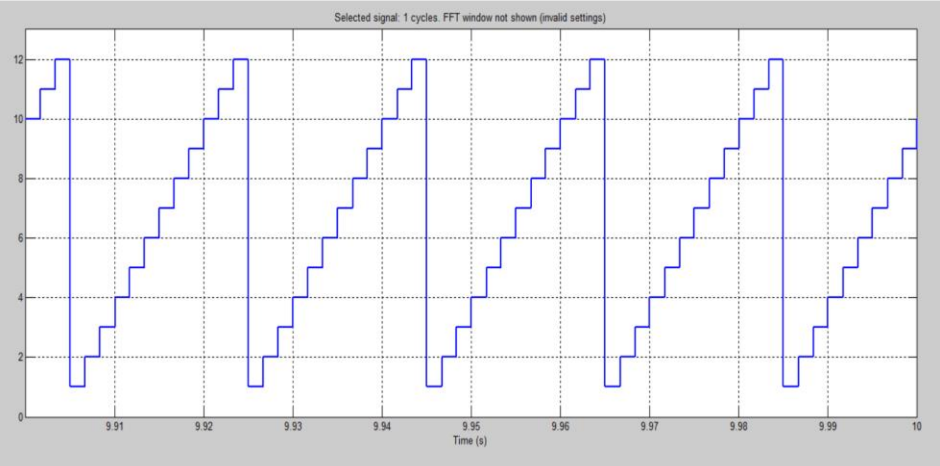


Figure 4.8 Voltage sector number

Figure 4.9 shows the total harmonic distortion (THD) of the line current before implement DPD method. From the figure, the THD is 30.54%

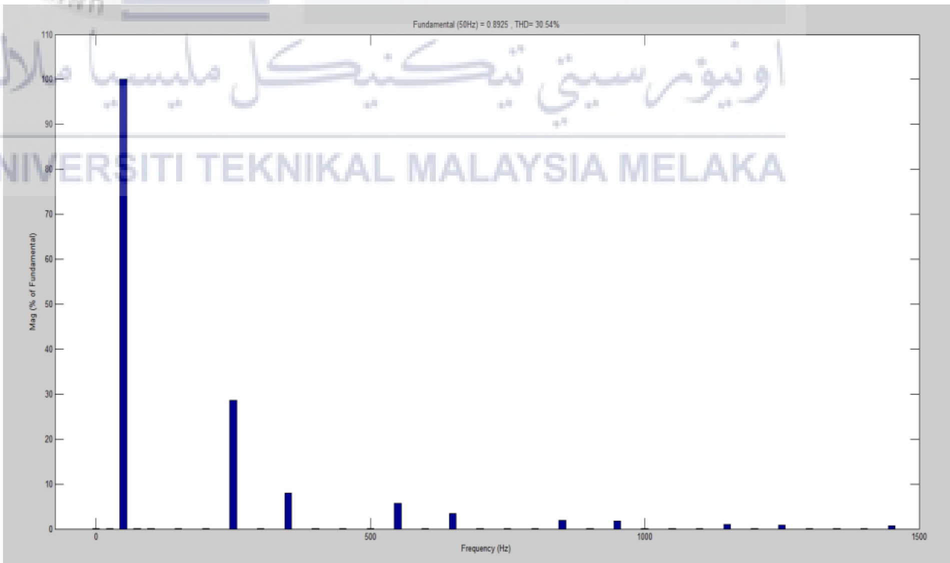


Figure 4.9 Harmonic Spectrum of line current before DPC method

4.2 Simulation of Three-phase Ac to DC Converter using the proposed DPC

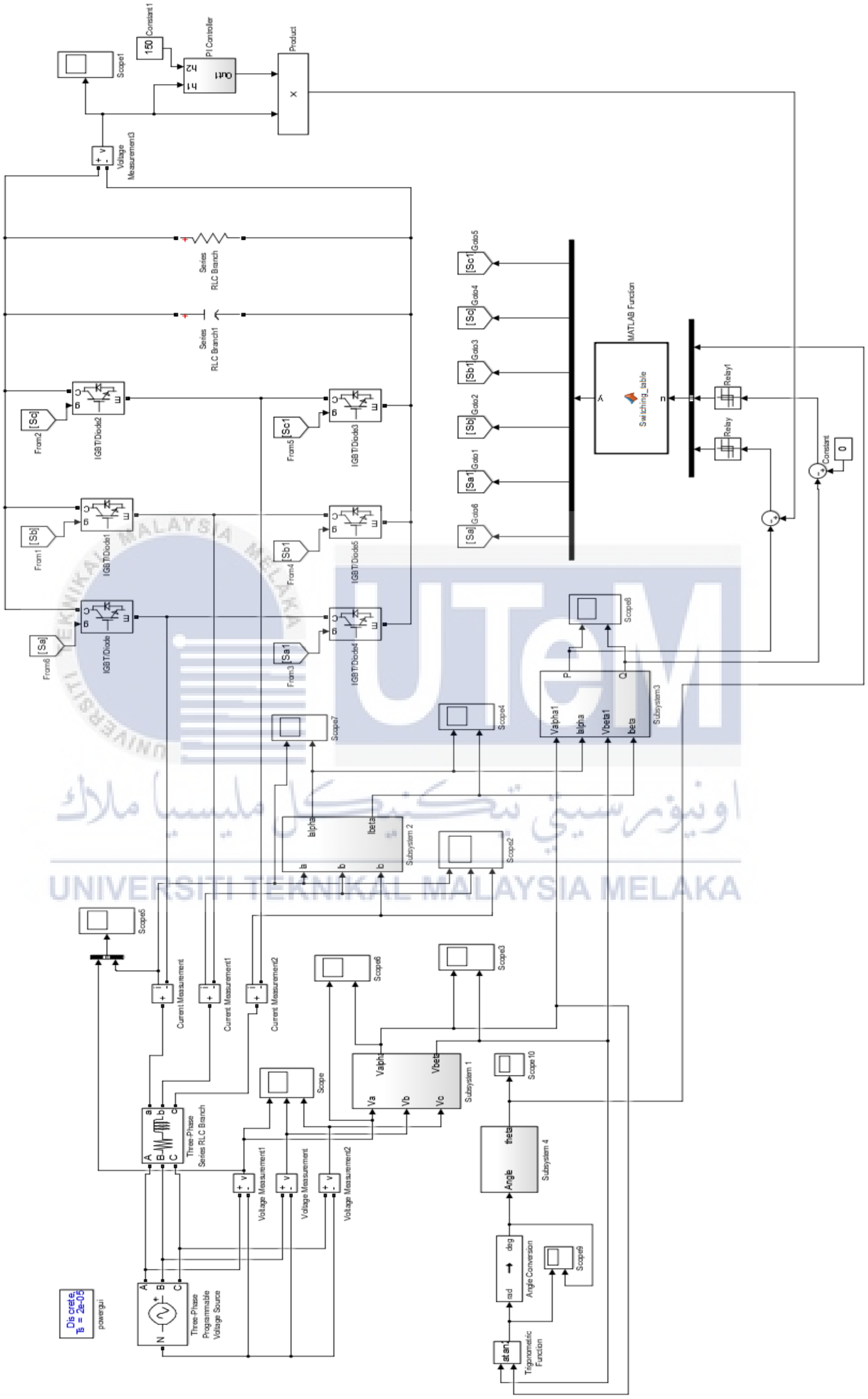


Figure 4.10 Diagram of three-phase AC to DC converter using the DPC

Figure 4.10 shows the simulation model of three-phase AC to DC converter using the DPC method. The output voltage can be obtained after complete run the simulation. The results is shown in Figure 4.11. Based on the graph obtained, it can be seen that there is a sharp increment in rise time and then reach steady state after 1 second. This is because of the tuning of PI controller.

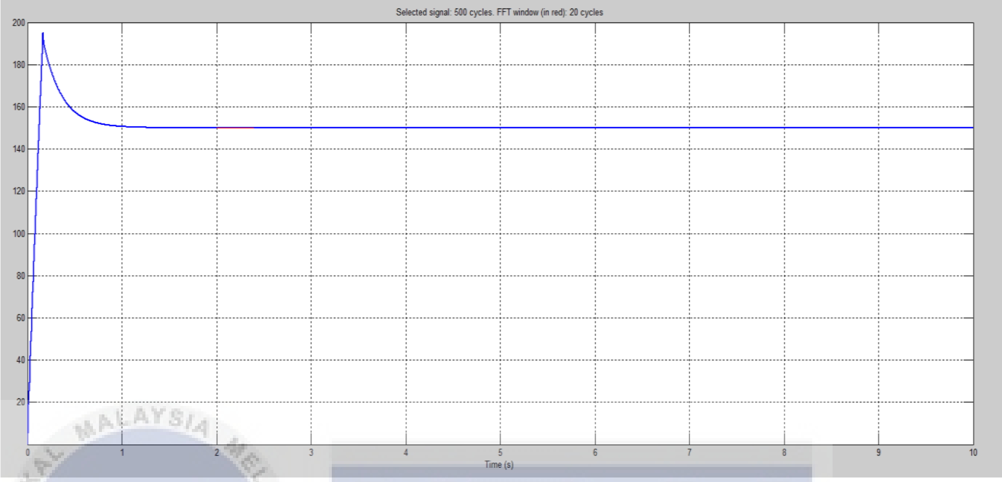


Figure 4.11 Output voltage after apply DPC method

However, the waveforms of input voltage still remains the same after apply DPC method. Figure 4.12 shows the wave of input voltage. But, the three phase input currents waveforms after implement DPC method will become more sinusoidal and less harmonics compare to the input current without DPC. Figure 4.13 shows the waveform of input currents after apply DPC method.

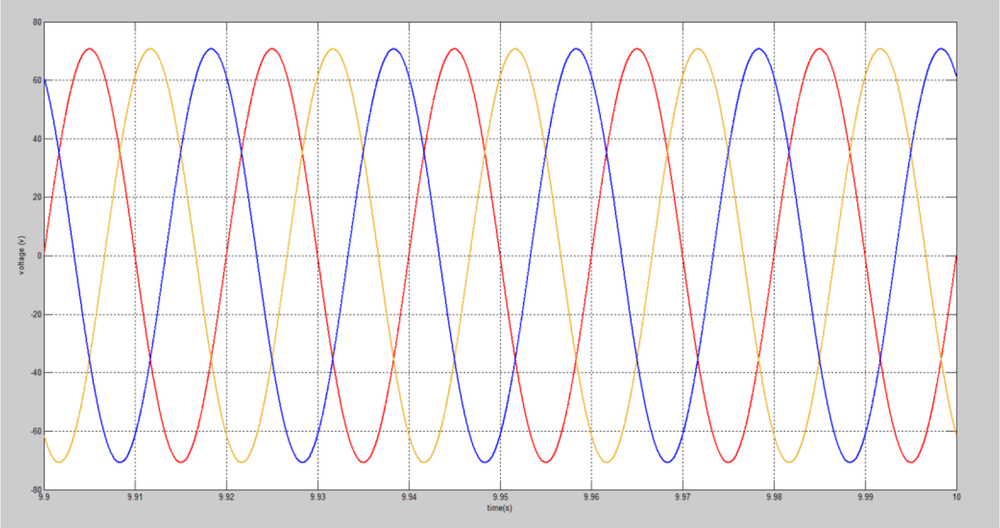


Figure 4.12 Input voltage waveform after apply DPC method

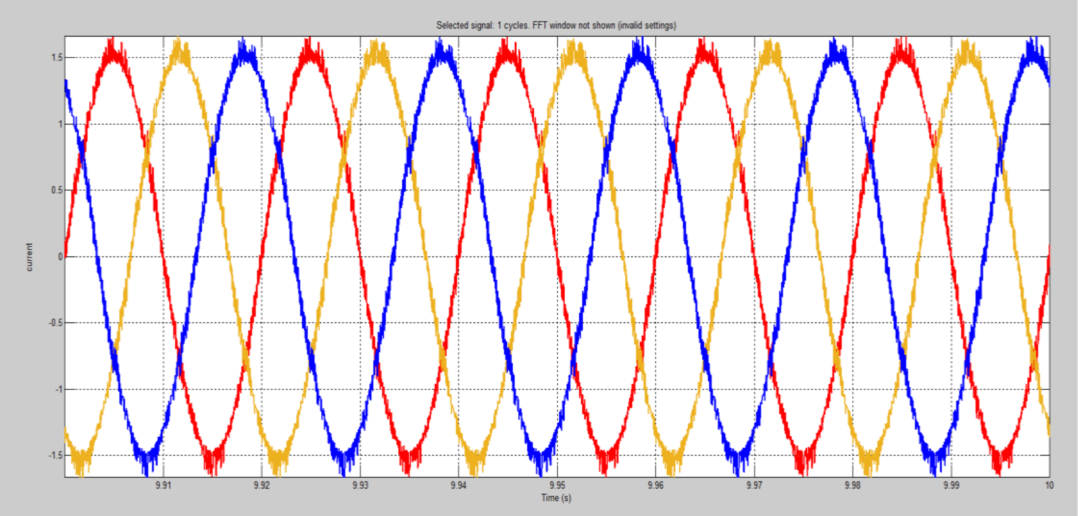


Figure 4.13 Input current waveform after apply DPC method

Based on Figure 4.14, the input voltage and input currents for phase A is in phase. Hence, the reactive power reference, Q_{ref} is set to be zero in order to obtained unity power factor.

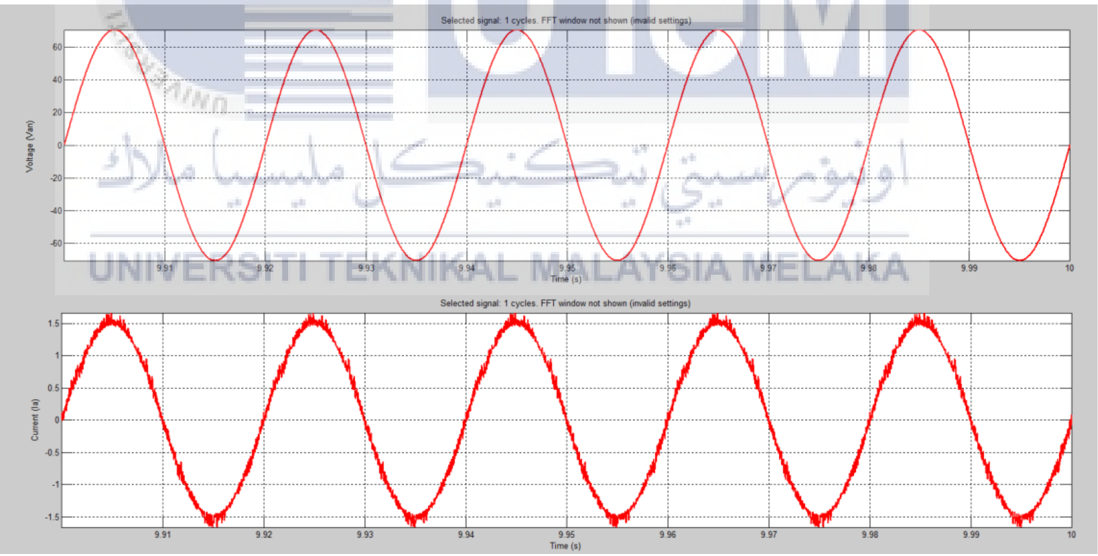


Figure 4.14 Unity power factor between input voltage and input current.

Figure 4.15 shows the total harmonic distortion (THD) of the line current after implement DPC method. From the figure, the reading of THD is 5.32 %. When refer to the Figure 4.9, the reading of THD before implement DPC is 30.54%. Hence, is shows that THD will be reduced approximate 25.22% by implement DPC method on AC to DC converter.

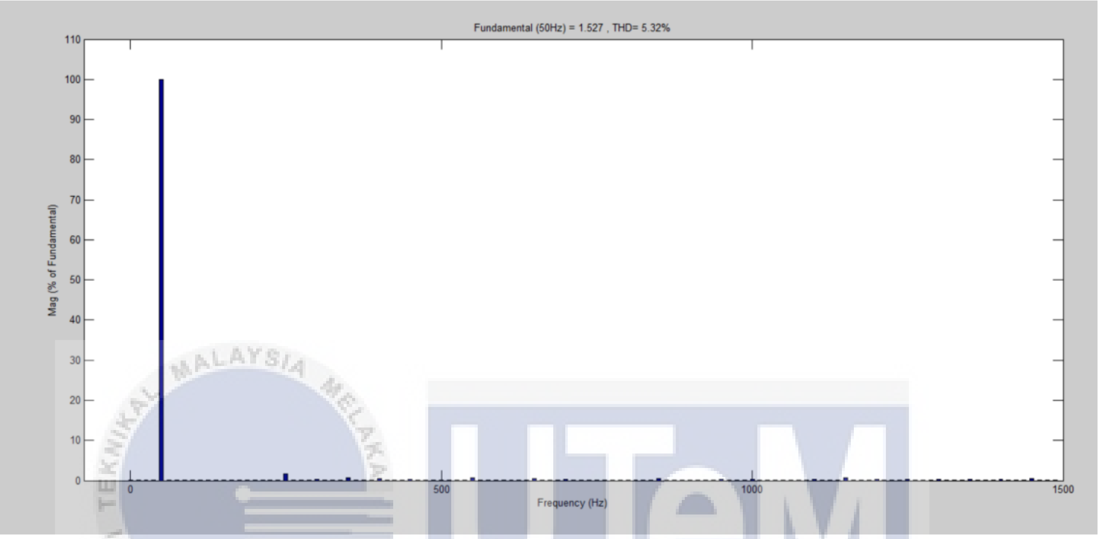


Figure 4.15 Harmonic spectrum of line current with DPC method

4.3 Load Variation

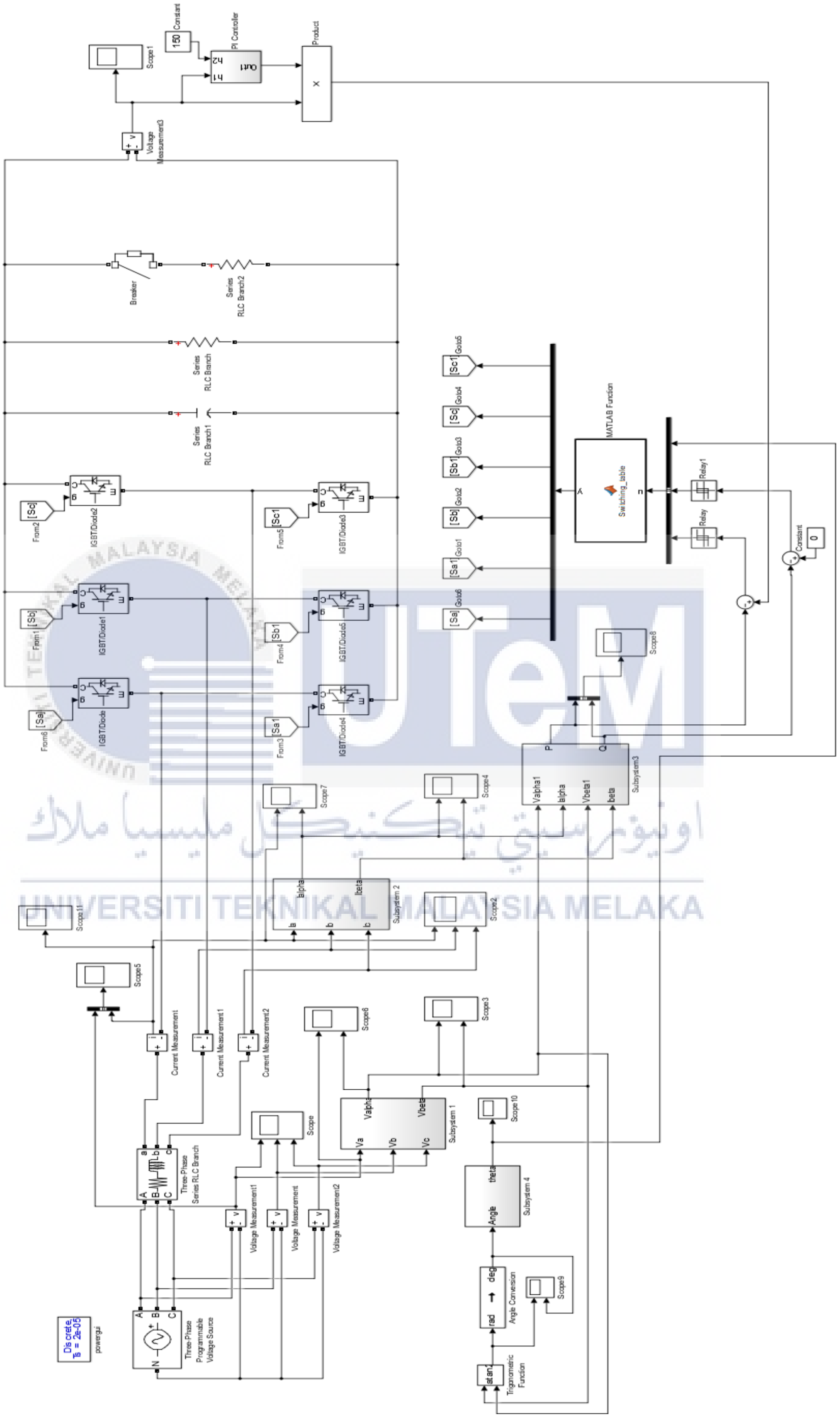


Figure 4.16 Circuit diagram for load variation

Figure 4.16 shows the circuit diagram for load variation. In this part, two different resistor will be used, which are 100Ω and 200Ω. For the first part, the 100Ω resistor and breaker will connect parallel with the existing resistor. The function of breaker is to create a sudden disturbance to the load current at 3s. Hence, the 3second will be the setting time for this breaker. After obtained the results from the simulation, 100Ω resistor will be replace by 200Ω resistor and run the simulation again.

Figure 4.17 shows the dynamic response for the 100Ω load resistor. From the figure, output voltage have a sharp drop at 3s and then bounce back to normal level. This is due to decreasing of load value as resistor are parallel with each other. Meanwhile, the reason output voltage bounce back is because of the PI controller.

Besides, Figure 4.18 shows the waveform of phase "a" current. When the resistance decrease, the current will increase. The value of the resistance has been reduced during 3s. Hence, it explained the behaviour of current waveform that showed in Figure 4.18. Figure 4.19 shows the waveform of active power and reactive power. During 3s, active power increase dramatically due to load disturbance. Meanwhile, there are only slightly changes for reactive power.

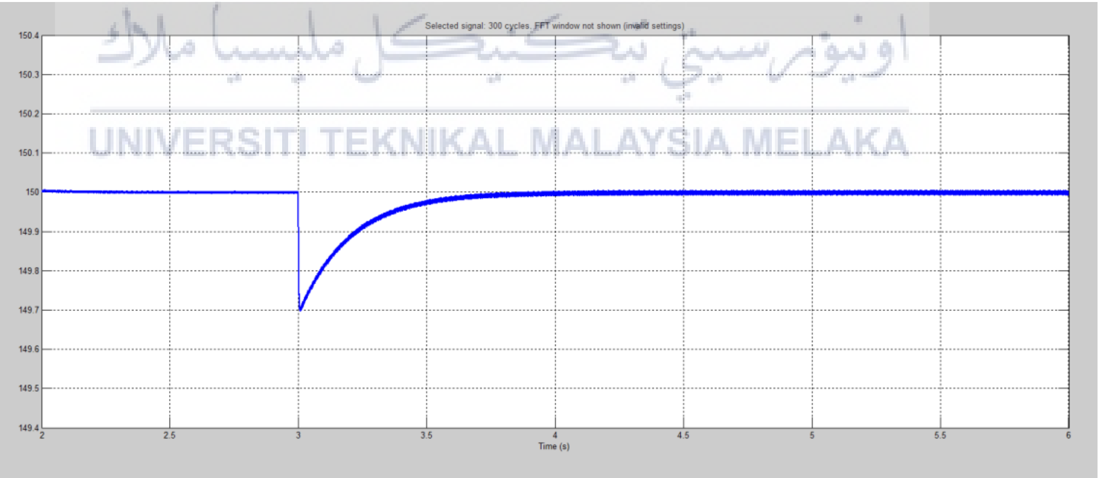


Figure 4.17 Waveform of output voltage for 100Ω load resistor

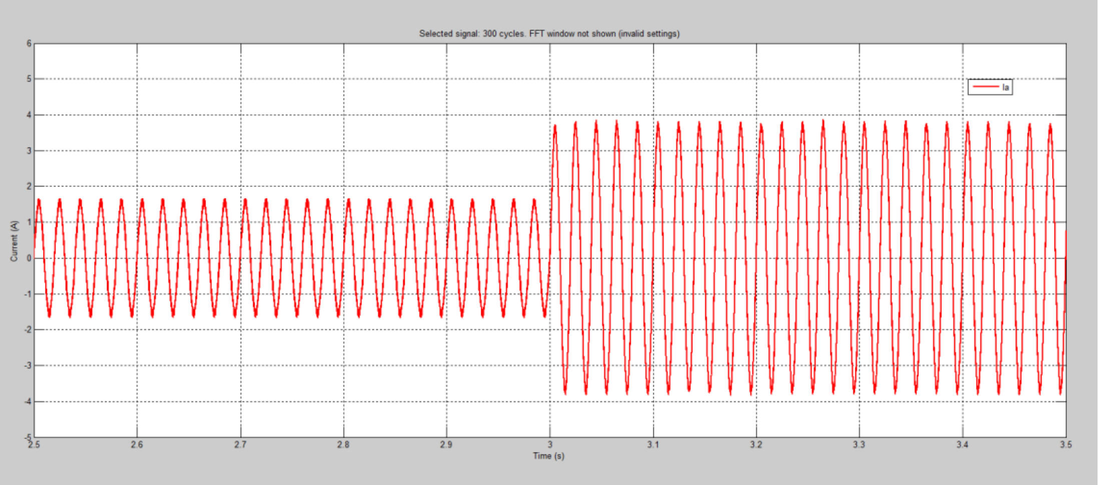


Figure 4.18 Waveform of phase “a” current for 100Ω load resistor

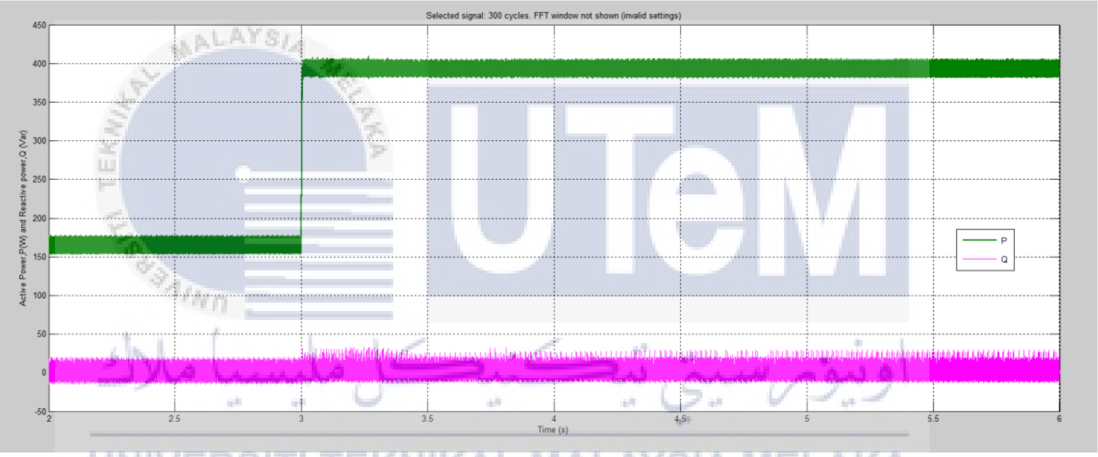


Figure 4.19 Waveform of active power and reactive power for 100Ω load resistor

The whole simulation will be repeated by replacing 100Ω resistor to 200Ω resistor and run the simulation again. Based on Figure 4.20, the output voltage drop at 3s is lesser compare to the Figure 4.17. Other than that, Figure 4.21 also shows that the increment of phase “a” current at 3s are much lesser compare to Figure 4.18. The active power that shown in Figure 4.22 also increase not as much as Figure 4.19. However, the response for Q remains almost same with the load variation of 100Ω.

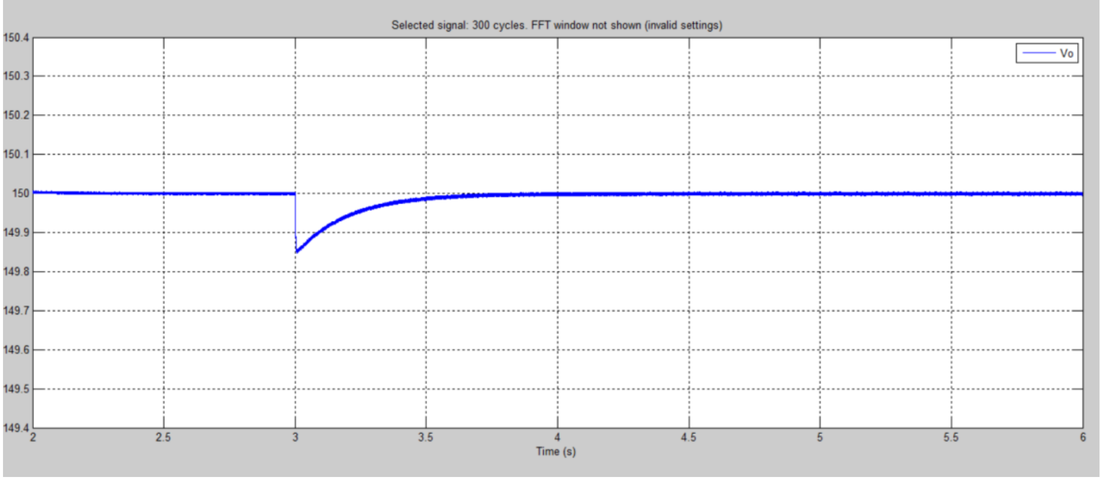


Figure 4.20 Waveform of output voltage for 200Ω load resistor

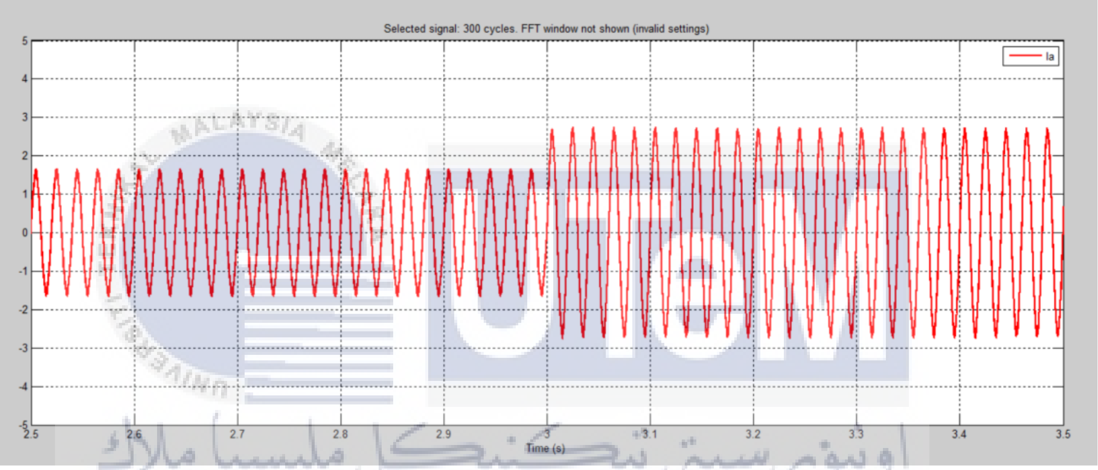


Figure 4.21 Waveform of phase “a” current for 200Ω load resistor

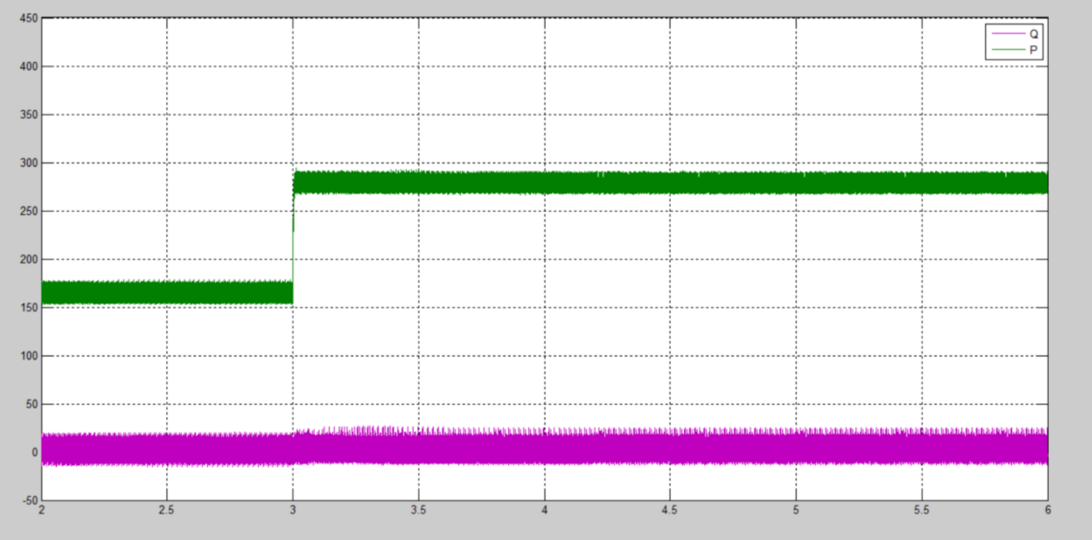


Figure 4.22 Waveform of active power and reactive power for 200Ω load resistor

4.4 DC Voltage Reference Variation

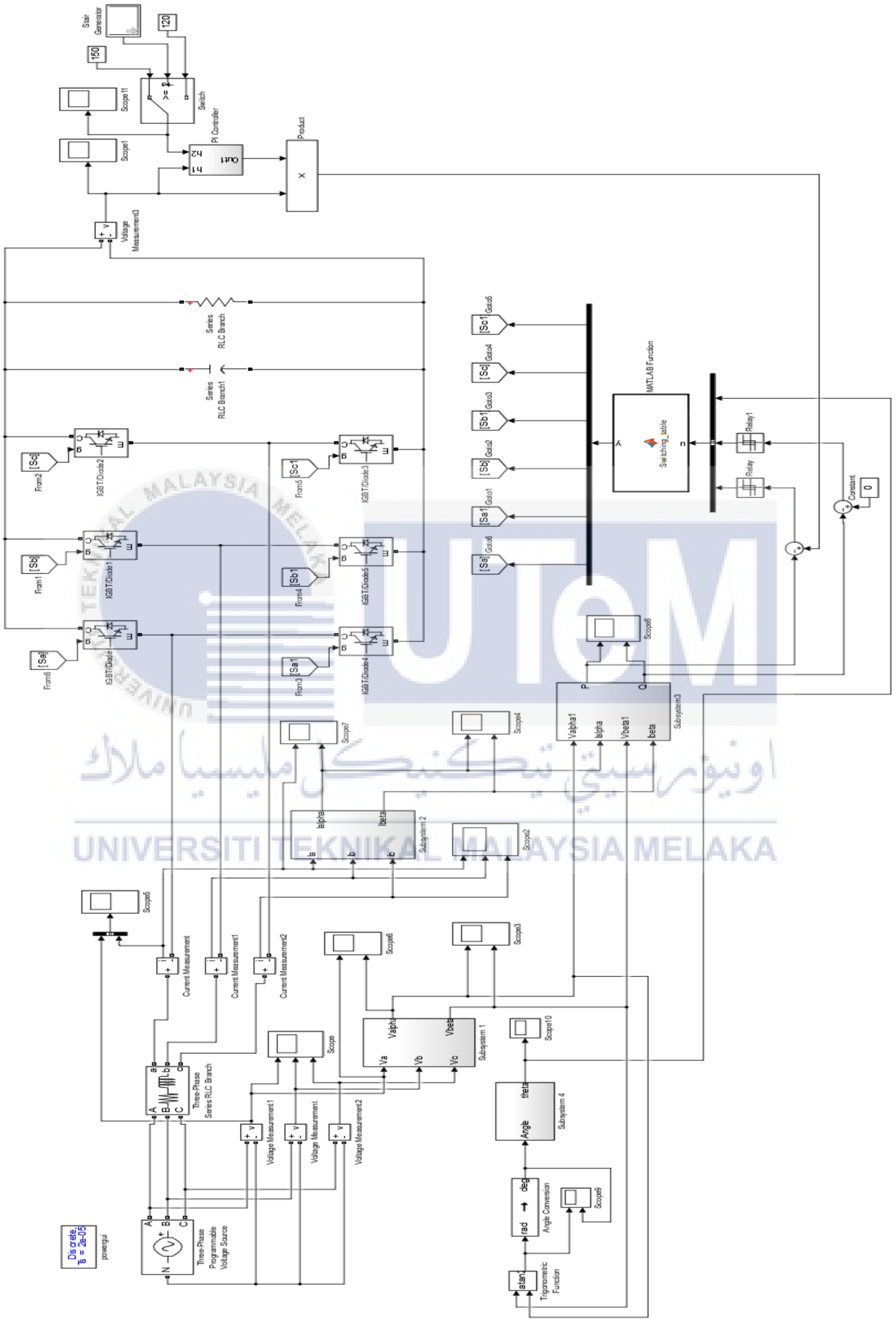


Figure 4.23 Simulation model for DC voltage reference variation

Figure 4.23 shows the simulation model for DC voltage reference variation. For DC voltage reference variation, switch block and generator block will be added in this circuit. In this part, two set of DC voltage variation will be perfomed, which are 150V to 180V and 150V to 120V. Meanwhile, the value of reference voltage will be change immediately at 3s and bounce back to original at 5s.This can be done by changing the setting of stair generator block as shown as below. Meanwhile, the threshold for switch block will be set as 2.

Table 4.1 Setting for stair generator

Parameters	Value
Time	[0,3,5]
Amplitude	[3,1,3]

Figure 4.24 and Figure 4.25 shows the dynamic performances for two different conditions. . Based on Figure 4.24, the output voltage will increase from 150 V to 180 V at 3s and drop back to 150 V at 5s. Besides, Figure 4.25 shows the output voltage drop to 120V at 3s and bounce back to original at 5s. Both simulation results undergo overshoot and undershoot before reaching the steady state when voltage changes. As a conclusion, the implementation of DPC and tuning of PI controller able to produce a good dynamic response.

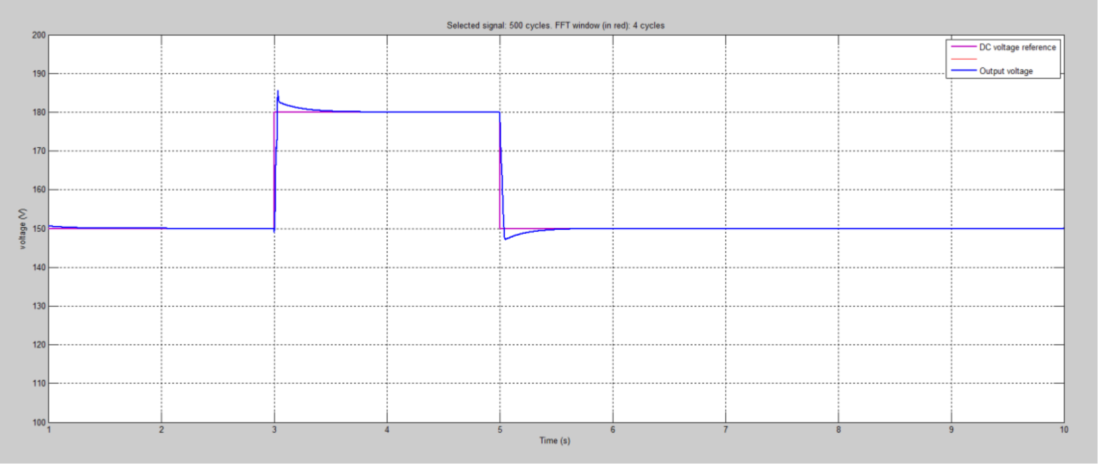


Figure 4.24 Dynamic response when $V_{dc,ref}$ change from 150V to 180V and then 150V

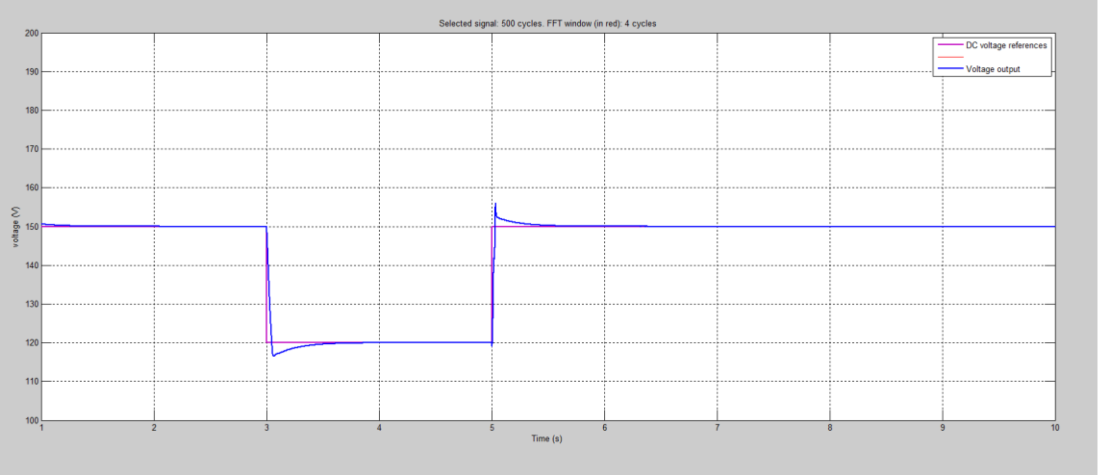


Figure 4.25 Dynamic response when $V_{dc,ref}$ change from 150V to 120V and then 150V

4.5 Power Factor Operation

For the first part, the value of reference reactive power, Q_{ref} will be set as -50Var in order to observe the power factor regulation by the proposed DPC. Figure 4.26 shows the waveform of phase “a” voltage and current while Figure 4.27 shows the waveform of estimated active and reactive power. Results shows that is voltage is leading the current. Hence, it is leading power factor operation.

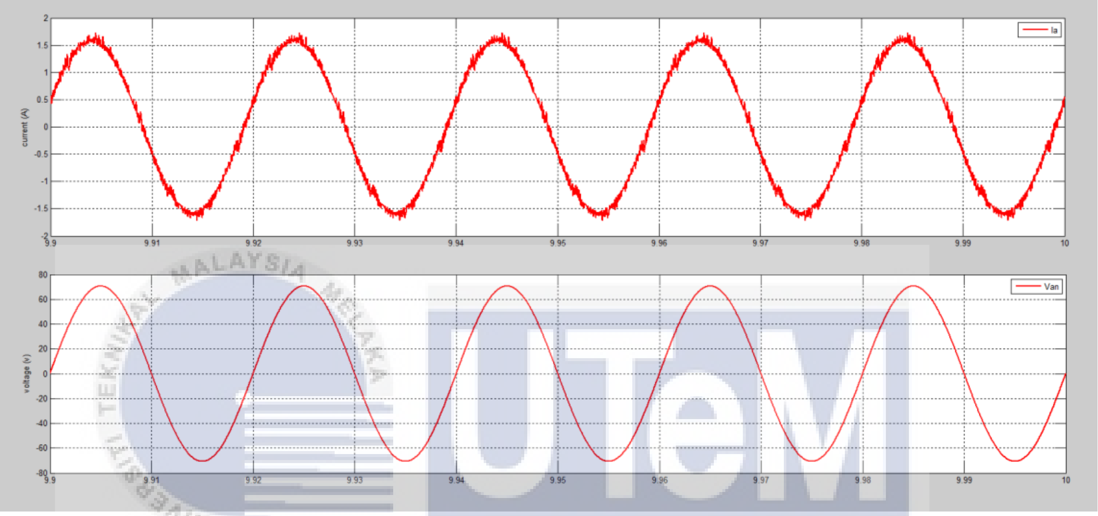


Figure 4.26 Phase “a” voltage and current when Q_{ref} = -50Var

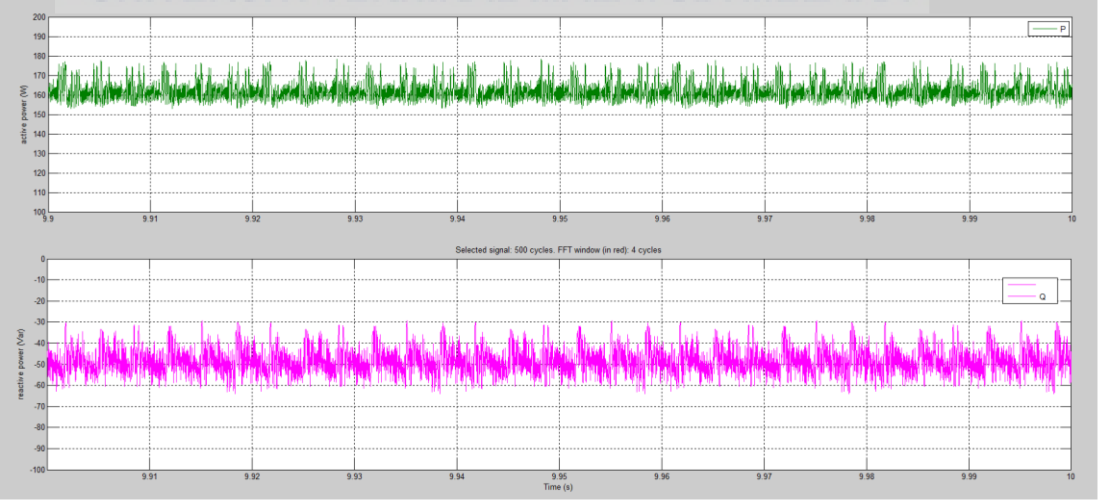


Figure 4.27 Estimated active and reactive power when Q_{ref} = -50Var

For the second part, the value of reference power, Q_{ref} will be set as 50Var in order to observe the power factor regulation by the proposed DPC. Figure 4.28 shows the waveform of phase "a" voltage and current while Figure 4.29 shows the waveform of estimated active and reactive power. Results shows that is voltage is lagging the current. Hence, it is lagging power factor operation.

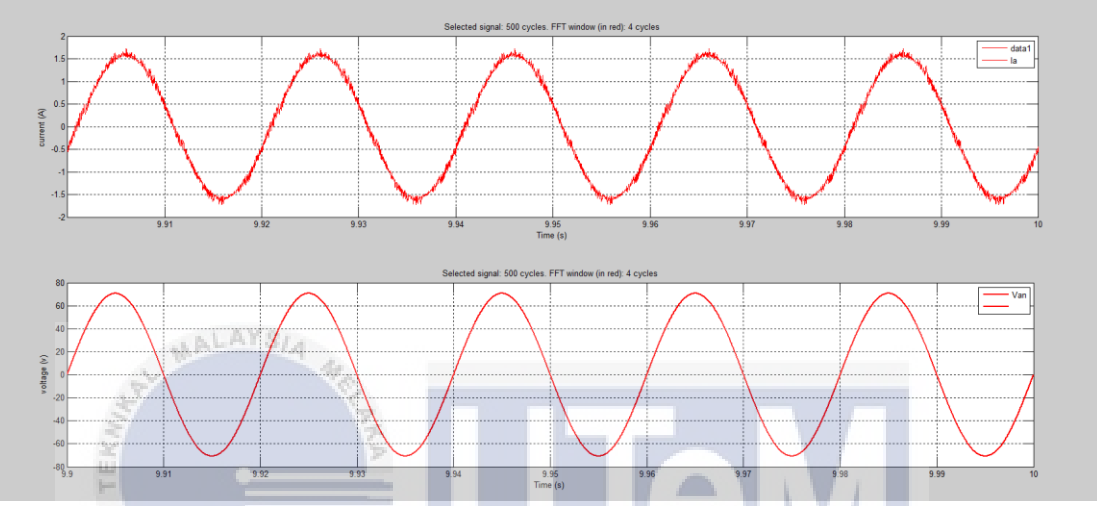


Figure 4.28 Phase "a" voltage and current when Q_{ref} = 50Var

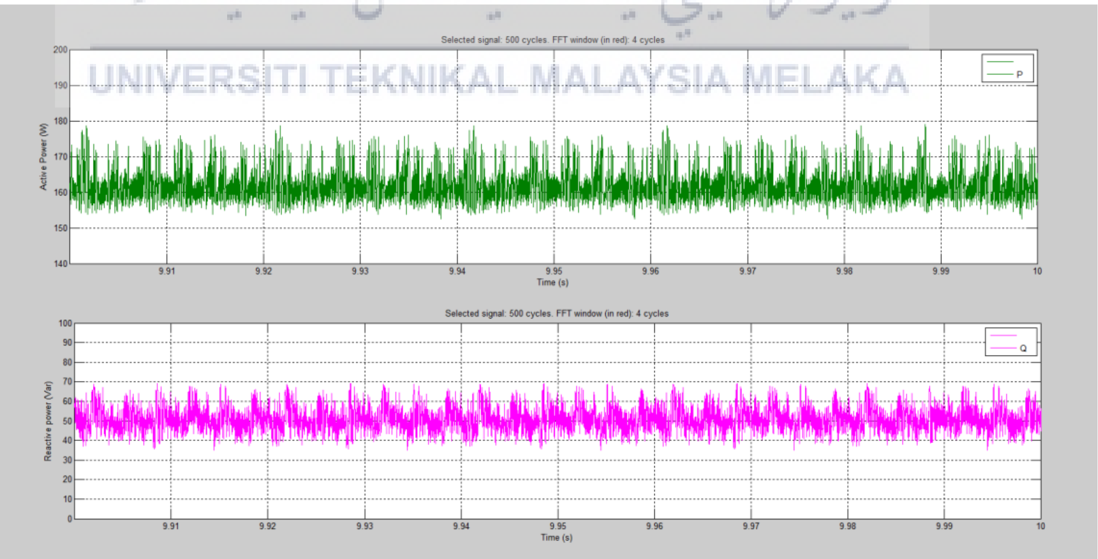


Figure 4.29 Estimated active and reactive power when Q_{ref} = 50Var

4.6 Before and after the implementation of DPC

As a conclusion, implementation of DPC will improve the performance of three-phase AC to DC converter. Based on Table 4.2, the waveform of input line current will become sinusoidal after implement DPC. In addition, DPC scheme is able to produce a regulated output DC voltage with lower harmonics. Based on the simulation results, THD can be reduced from 30.54% to 5.32%. Other than that, DPC able to produce a good dynamic performance during dynamic response analysis. DPC also able to overcome the drawbacks of conventional converters by adjusting the value of reference reactive power. Reference reactive power will directly affect the operation of unity, leading or lagging power factor.

Table 4.2 Before and after the implementation of DPC

	Before implementing DPC	After implementing DPC
Waveform of input line current	Non-sinusoidal	Almost Sinusoidal
Current harmonic	THD = 30.54% Fundamental and higher order harmonics spectrum are visible	THD = 5.32% Only fundamental spectrum is visible.

CHAPTER 5

EXPERIMENT RESULTS AND DISCUSSION

This chapter mainly focus on Experiment result and discussion. The results can be obtained by using oscilloscope during hardware implementation. The results are then analysed and discussed.

5.1 Enable and disable the relay

When user disable the relay, the output of the relay will be zero voltage which same as the Figure 5.1. This result can be obtained by using oscilloscope. However, user also can switch on the relay by supply +5V to the "+DSP" pin of the relay. A "click" sound can be heard when the relay is on. Figure 5.2 show the output of relay during enable state. A +5V will be generate from the "+EN" pin of relay to the gate driver.

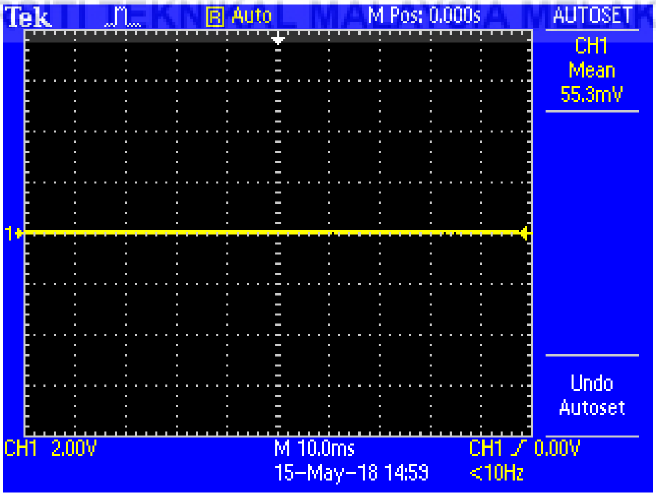


Figure 5.1 The output of relay during disable state.

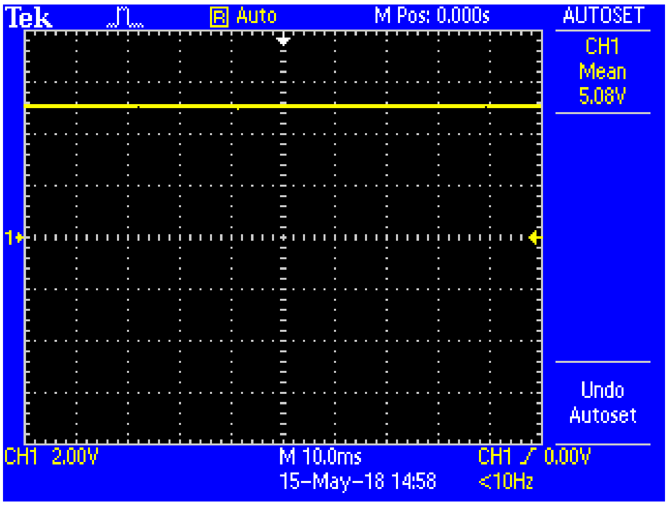


Figure 5.2 The output of relay during enable state.

5.2 Gate signals from Gate Driver Modules.

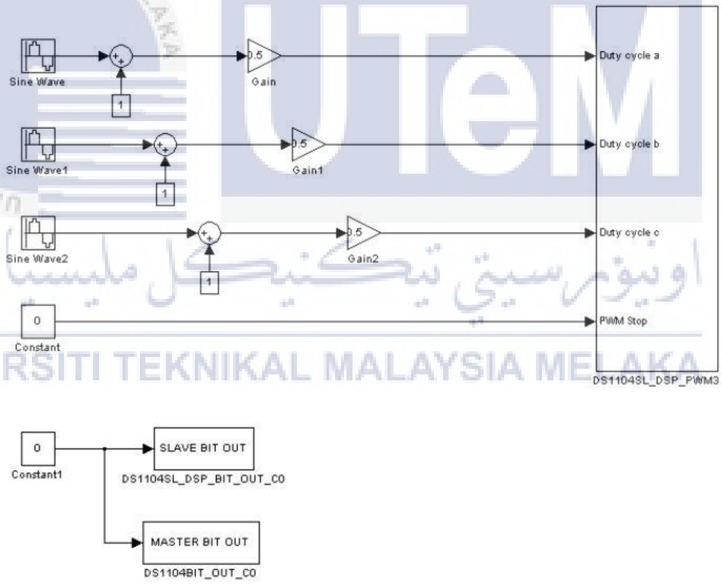
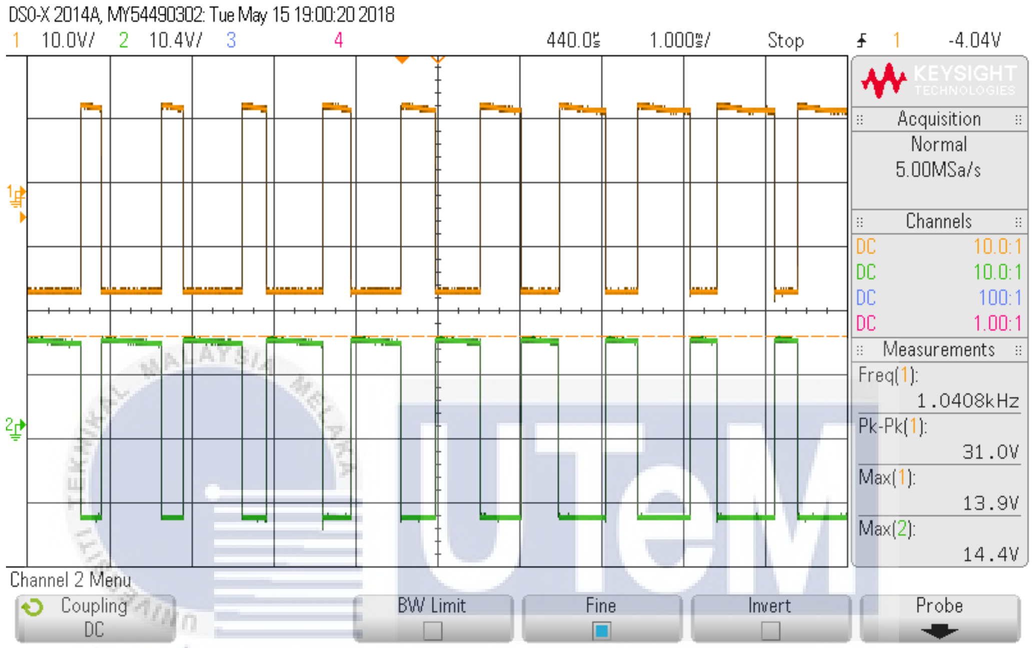


Figure 5.3 Generation of PWM signals using RTI library

Figure 5.3 shows a simple circuit that constructed in MATLAB Simulink using the PWM block from RTI library. The purpose of this circuit is to verify the functionality of relay and gate driver modules. Meanwhile, the state of relay and PWM signal can be control through the “PWM enable” switch and “DSP Enable” switch at ControlDesk.

When enable the relay and PWM signals. PWM signals will fed into 3 gate drive modules. Each modules will eventually produce two output signal. The two gate signals will always opposite of each other and fed into the power switches, IGBTs.Figure 5.4, Figure 5.5 and Figure 5.6 show the output signals from the gate drive module 1, gate driver module 2, and gate driver module 3 respectively.


DSO-X 2014A, MY54490302: Tue May 15 19:00:20 2018

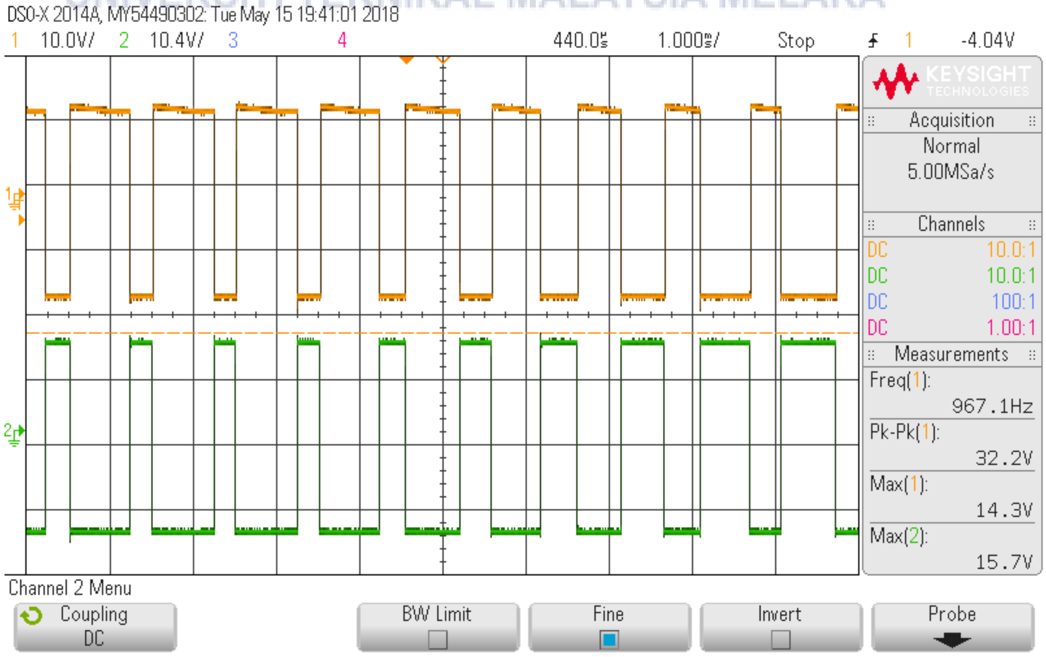
1 10.0V/ 2 10.4V/ 3 4 440.0s 1.000s/ Stop 1 -4.04V

Acquisition: Normal, 5.00MSa/s

Channels: DC 10.0:1, DC 10.0:1, DC 100:1, DC 1.00:1

Measurements:
Freq(1): 1.0408kHz
Pk-Pk(1): 31.0V
Max(1): 13.9V
Max(2): 14.4V

Figure 5.4 Output 1 and output 2 signal of Gate Driver module 1


DSO-X 2014A, MY54490302: Tue May 15 19:41:01 2018

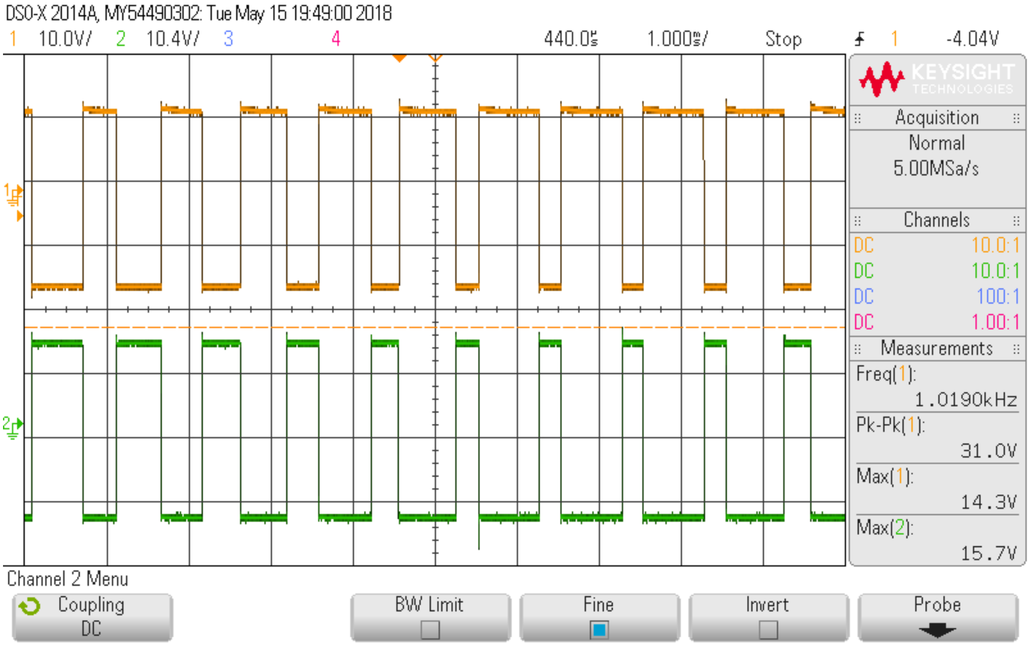
1 10.0V/ 2 10.4V/ 3 4 440.0s 1.000s/ Stop 1 -4.04V

Acquisition: Normal, 5.00MSa/s

Channels: DC 10.0:1, DC 10.0:1, DC 100:1, DC 1.00:1

Measurements:
Freq(1): 967.1Hz
Pk-Pk(1): 32.2V
Max(1): 14.3V
Max(2): 15.7V

Figure 5.5 Output 1 and output 2 signal of Gate Driver module 2



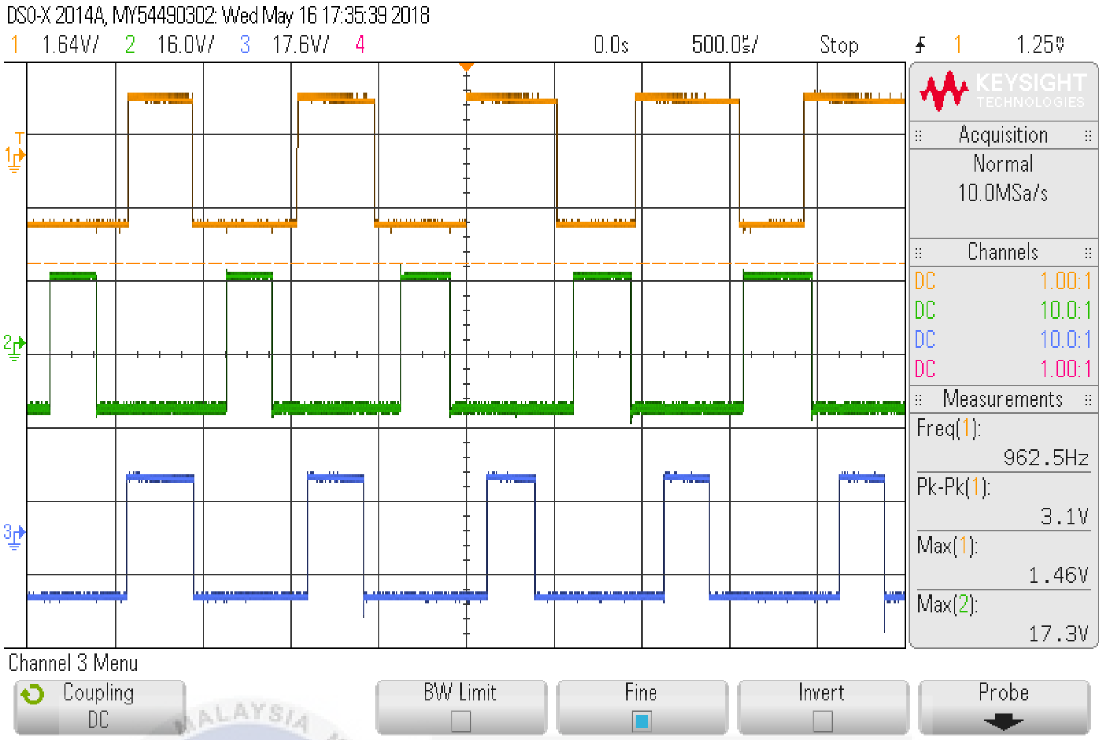
DSO-X 2014A, MY54490302: Tue May 15 19:49:00 2018
1 10.0V/ 2 10.4V/ 3 4 440.0µs 1.000ms/ Stop 1 -4.04V
Acquisition
Normal
5.00MSa/s
Channels
DC 10.0:1
DC 10.0:1
DC 100:1
DC 1.00:1
Measurements
Freq(1):
1.0190kHz
Pk-Pk(1):
31.0V
Max(1):
14.3V
Max(2):
15.7V
Channel 2 Menu
Coupling DC
BW Limit ☐
Fine ☑
Invert ☐
Probe

Figure 5.6 Output 1 and output 2 signal of Gate Driver module 3

5.3 Gate signals from IGBTs

The output of gate driver module 1 will be connect to the IGBT 1 (upper switch) and IGBT 2 (lower switch) while output of gate driver module 2 is connect to the IGBT 3 (upper switch) and IGBT 4 (lower switch). Besides, output of gate driver 3 will connect to the IGBT 5 (upper switch) and IGBT6 (lower switch).

Since the input signals of IGBTs are directly from the gate drivers, the gate signal obtained from IGBTs are similar with the gate signal from gate driver module. Figure 5.7 shows the gate signals obtained from IGBT1, IGBT 3, and IGBT 5. Based on this figure, the phase shift for each waveforms are 120^0. By using the probe from oscilloscope to touch IGBTs gate and source terminals, the waveforms of gate signals can be obtained.



DSO-X 2014A, MY54490302: Wed May 16 17:35:39 2018

1 1.64V/ 2 16.0V/ 3 17.6V/ 4 0.0s 500.0us/ Stop 1 1.25V

Acquisition
Normal
10.0MSa/s

Channels
DC 1.00:1
DC 10.0:1
DC 10.0:1
DC 1.00:1

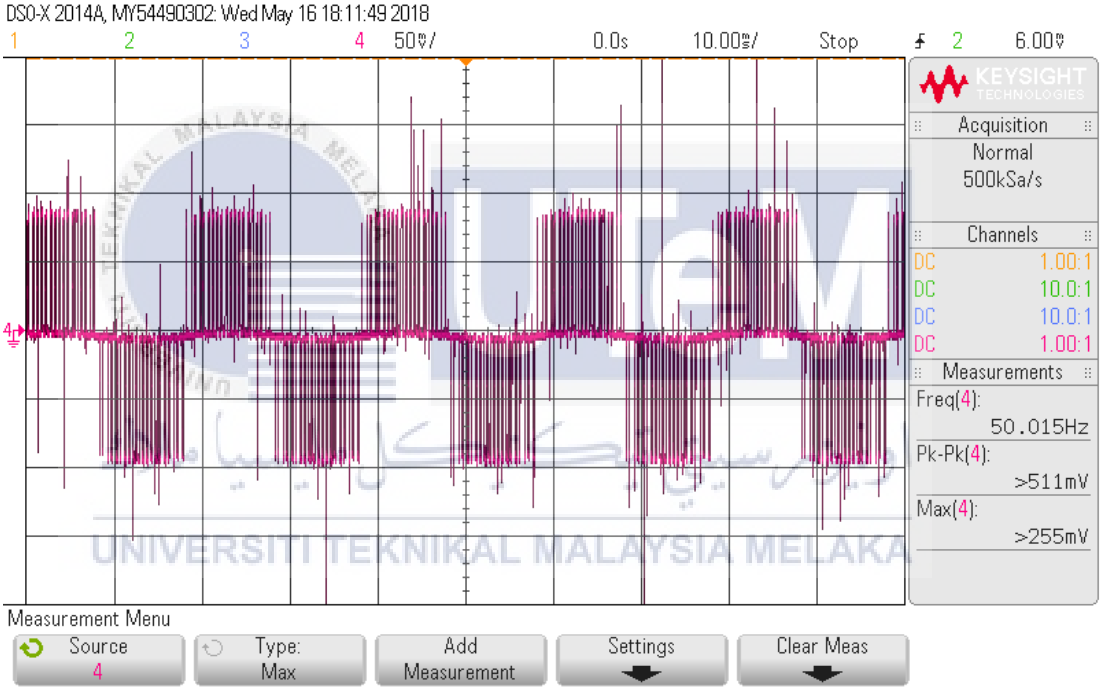
Measurements
Freq(1): 962.5Hz
Pk-Pk(1): 3.1V
Max(1): 1.46V
Max(2): 17.3V

Channel 3 Menu
Coupling DC

Figure 5.7 Gate Signal obtained from IGBT1, IGBT 3, and IGBT 5

5.4 Three-Phase Line-to-Line Voltage when operation as Inverter

Basically, converter PCB can be use as AC to DC converter or DC to AC inverter. In this part, this board will run as inverter because it is easier to check the functionality of PCB board and determine the AC line-to-line voltage waveforms. 20V will be supplied to the inverter. Use the probe of oscilloscope to connect on the output of inverter in order to obtain the waveforms of line-to-line voltage. Figure 5.8 shows the line-to-line voltage for V_{ab} and Figure 5.9 shows the line-to-line voltage for V_{bc}. Besides, user also can refer Figure 5.10 for line-to-line voltage for V_{ca}


DSO-X 2014A, MY54490302: Wed May 16 18:11:49 2018

1 2 3 4 50mV/ 0.0s 10.00ms/ Stop 2 6.00V

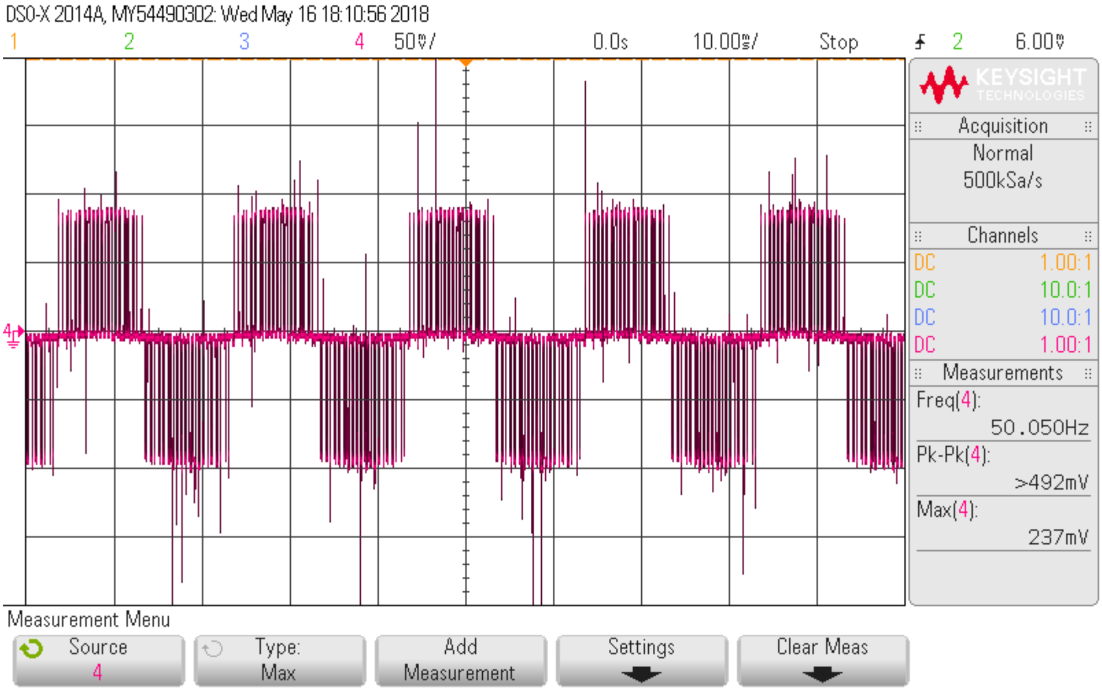
Acquisition
Normal
500kSa/s

Channels
DC 1.00:1
DC 10.0:1
DC 10.0:1
DC 1.00:1

Measurements
Freq(4): 50.015Hz
Pk-Pk(4): >511mV
Max(4): >255mV

Measurement Menu

Figure 5.8 Line-to-line voltage for V_{ab} when circuit operate as inverter



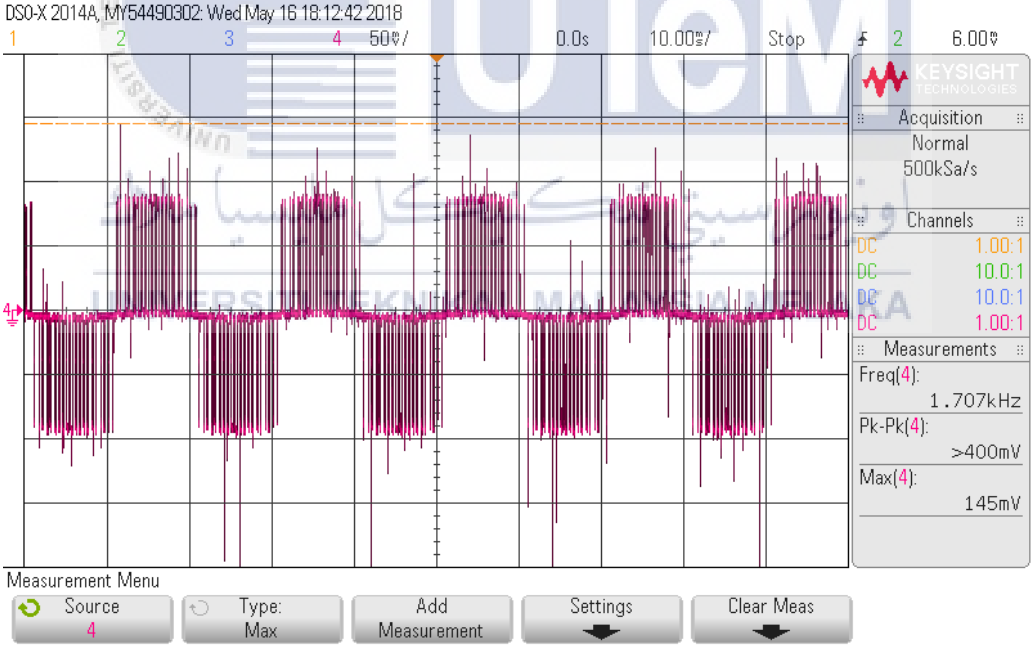
DSO-X 2014A, MY54490302: Wed May 16 18:10:56 2018

Acquisition
Normal
500kSa/s

Channels
DC 1.00:1
DC 10.0:1
DC 10.0:1
DC 1.00:1

Measurements
Freq(4): 50.050Hz
Pk-Pk(4): >492mV
Max(4): 237mV

Figure 5.9 Line-to-line voltage for V_{bc} when circuit operate as inverter



DSO-X 2014A, MY54490302: Wed May 16 18:12:42 2018

Acquisition
Normal
500kSa/s

Channels
DC 1.00:1
DC 10.0:1
DC 10.0:1
DC 1.00:1

Measurements
Freq(4): 1.707kHz
Pk-Pk(4): >400mV
Max(4): 145mV

Figure 5.10 Line-to-line voltage for V_{ca} when circuit operate as inverter

5.5 There-Phase Diode Rectifier

Since already the waveform of line-to-line voltage, now the board will operate as converter by supplying three phase voltage supply. Disable the relay and gate signal and this board will act as three-phase diode rectifier. The three phase supply is turn on and increase slowly to avoid damage to the board. At this moment, the waveform of the three phase supply will be obtained. The voltage sensor ratio is set to be 1/500. Figure 5.11 show the waveform of input three phase voltage for the diode rectifier

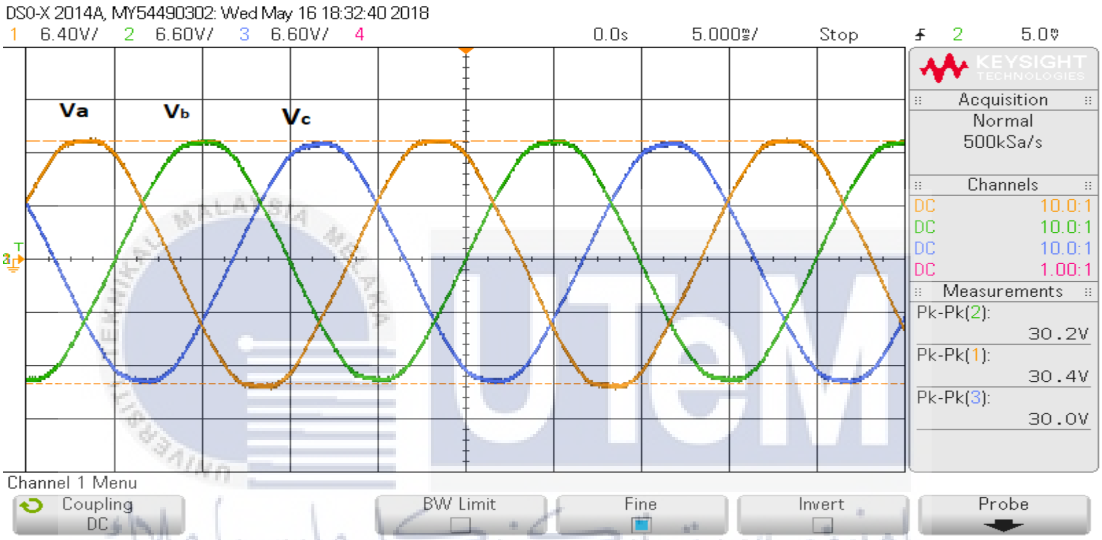


Figure 5.11 Waveform of input three phase voltage for the diode rectifier

Meanwhile, user can refer to Figure 5.12 for constructing a simple circuit in MATLAB Simulink in order to obtain the waveform of V_α and V_β. In this part, three phase voltage supply will be connect to CP5, CP6, and CP7 of CP1104 connector panel. Then, the output from CP1, CP2 and CP3 of CP1104 connector panel directly connected to the oscilloscope. The wave form of of V_α and V_β and V_a are shown in Figure 5.13.

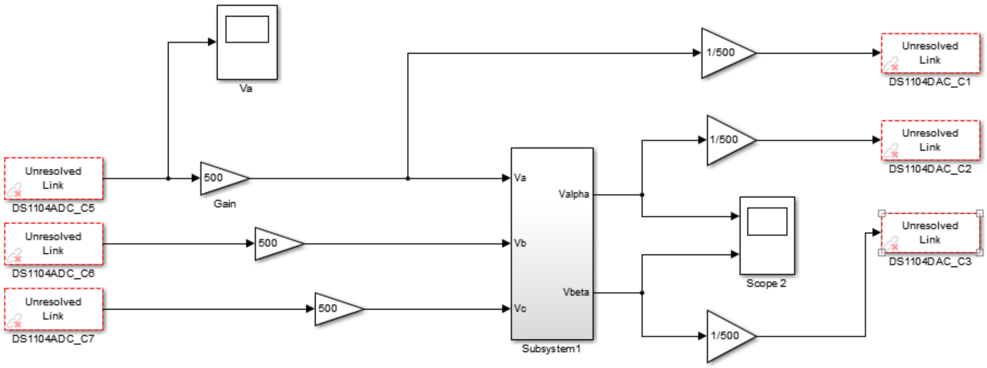


Figure 5.12 Simple circuit to obtained waveform of V_α and V_β

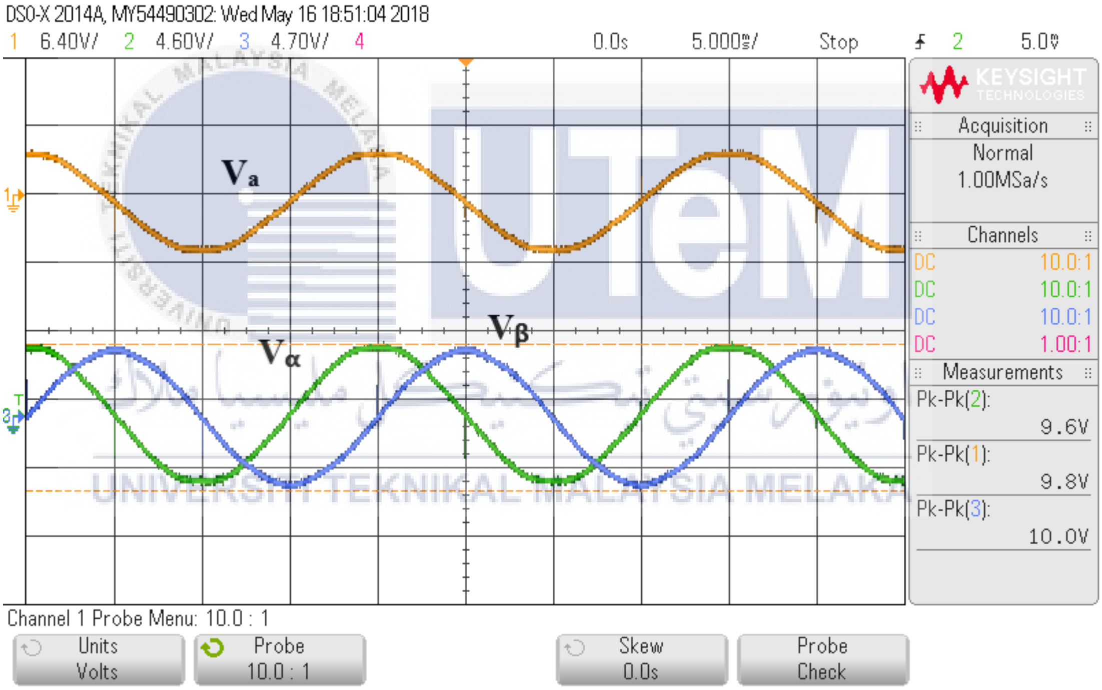


Figure 5.13 Waveform of V_α and V_β for the diode rectifier

5.6 Discussion about the interference of hardware implementation for further progress

This part highlights the interference of the hardware implementation for further continuation of the project to obtain the desired final result. The final results should include the current harmonic spectrum and the waveform of three phase input current after the implementation of DPC. However, certain circumstances have impede the progression. Therefore, obtaining the waveforms of V_α and V_β for the diode rectifier will be the last result of the hardware implementation.

When this project is trying to obtain the waveform of input current for the diode rectifier, a problem occurred. For the first try, a three phase voltage supply is directly connected to the converter board and the DC output is directly connected to the 300Ω resistor. Current sensors are used to observe the three phase input current waveforms.

The voltage supply is turned on and increase gradually. When the voltage is increased to a certain value, the expected waveform of the input currents have been obtained. However, the IGBTs on the converter board turned hot quickly at the same time. Although the IGBTs are installed to the heatsink, the IGBTs are still unable to withstand the high heat in a short time.

Unfortunately, one of the IGBTs get damaged after being exposed to the high temperature for a long time. After troubleshooting the problems, the possible reason that caused the damage of IGBT is because of the low resistance. According to the formula V=IR, the voltage is directly proportional to current. Therefore any increase in voltage will directly increase the current which will generate a high amount of heat. Hence, the IGBT turned hot when it received high current.

Anyway, the damaged IGBT is replaced with a new IGBT. For the second try, a three phase voltage supply is fed into an inductor before connected to the converter board. Besides, the DC output is directly connected to the 1kΩ resistor. This step is taken to protect the IGBT from getting damage again due to high heat. Meanwhile, the relay is disabled while the output of gate driver is connected to the converter board. This could eventually turn on all the IGBTs. After that, current sensors is connected to the phase “a” voltage which is same as first trial. Then, the voltage supply is turned on and increased slowly from time to time.

When the voltage supply is increased up to approximate 5V, a hissing sound can be heard from the voltage supply that may be caused by short circuit. There might be an issue such as short circuit during the supply of 3 phase voltage to the converter board. The voltage supply is turn off immediately to protect the hardware from exposing to possible malfunction. However, the system is still unable to generate current waveform smoothly using this implementation.

A few tests have been carried out to recheck the functionality of every components. The gate driver, relay, and breakout board are well functioning. The troubleshoot process consume a lot of time due to complex circuit connections. The time limitation and unknown issues that occur becomes a barrier for further testing to obtain the final results that can be generated by the hardware.

For the unknown issues, there might be a few factors that caused this errors to happen. One of the factor might be the ill-maintenance of variable resistors. The variable resistors is not well maintained and the performance is not stable as the value of resistors will keep fluctuating. Besides that, the second factor is the condition of three-phase voltage. The three phase voltage may be faulty at the internal part and will cause a short circuit in the system. The third factor is due limitation of instruments. There is no extra instruments to replace the current instruments.

If the issue above can be solved, there is no doubt to obtain the final results. By referring to the methodology, the development of the hardware implementation will continue until the final result is obtained. Based on Figure 3.19 on chapter 3, the Simulink model for overall hardware implementation was done. The modified coding for switching table and PI controller also able to functioning well. Although the hardware is unable to prove that THD of the currents drop after implementing DPC scheme, but the simulation results are already proven.

CHAPTER 6

CONCLUSION

This chapter will summarize all the topic that have been done in the previous chapter. The recommendation also has been included.

6.1 Conclusion

Input currents which are close to sinusoidal waveform and have almost unity power factor can be generated by implements Direct Power Control (DPC) scheme on three-phase AC to DC converter. The details of this project was clearly shown in this paper.

First, an open loop rectifier circuit diagram is constructed and simulated by MATLAB Simulink. Based on the simulation of open-loop rectifier, the waveform of three-phase input currents are non-sinusoidal. The is due to the present of harmonic components in the diode rectifier. Hence, this issue can be solve by implement DPC scheme.

After that, a three phase AC to DC converter with DPC scheme is constructed by using MATLAB Simulink. The circuit of DPC contains 5 subsystem, which are Clarke transformation for voltage, Clarke transformation for currents, instantaneous active power and reactive power, voltage sector selection and PI controller. The switching table for DPC also can be created by adding coding into “MATLAB Function” Block. From the simulation results, the three phase input currents waveforms after implement DPC method will become more sinusoidal and less harmonics compare to the input current without DPC. Besides, the total harmonic distortion (THD) of the line current after implement DPC method will be reduced.

The next step is study dynamic performance in simulation for load variation and DC voltage reference. It can be observed that output voltage could rise back to the reference voltage in a short time after a sudden disturbance. This is because of proper tuning of PI controller. The PI controller will reduce the errors between the reference voltage and the output voltage. For power factor operation, the value of reference of reactive power will determine the power factor for this system. When the reference of reactive power is negative value, it operate as leading power factor. On the other hand, it operate as lagging power factor when the reference of reactive power is positive value.

During hardware implementation, the experiment proceeded until the waveform of Vα and Vβ for the diode rectifier were obtained. However, the experiment was unable to progress further to find the current harmonic spectrum and the input current waveform as there are some problems that occured to the components or instruments. There are several factors that impede the progress of hardware implementation. A full explanation will be described in chapter 5 which is results and discussion. As a conclusion, the project has achieved the objectives of this project,

6.2 Recommendation

Reducing the size of the hardware is one of the factors that needs to be considered to improve the functionality of the hardware to be implemented in this project. The current hardware consists of three separate gate driver modules where each gate driver modules have 6 inputs and 4 outputs. Hence, there will be a lot of cable connections on the circuit that will make the circuit looks untidy. To overcome this problem, user can develop an integrated gate driver PCB that can be used to combine all the 3 gate drivers into a single board. The circuit design printed on the PCB board is able to reduce the possibility for error and short circuit to occur due to incorrect wiring connection. Besides that, combining all gate drivers into a single board makes it easier for user to troubleshoot problems when errors occur at the gate driver. As a safety precaution, every component installed need to be tested carefully for defects or malfunctions before they can be used to run the hardware

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APPENDIX A

Gantt Chart

Project Activity	2017																2018													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Development of study stool	▨					▨										▨									▨					
Topic Selection	▨	🟩				▨										▨									▨					
Discussion with supervisor	▨	🟩	🟩	🟩	🟩	▨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	🟩	🟩	🟩	🟩	🟩
Litretaure Review	▨					▨	🟩	🟩	🟩	🟩						▨									▨					
Prepare Proposal	▨	🟩	🟩	🟩		▨										▨									▨					
Submit Proposal	▨				🟩	▨										▨									▨					
Data Collection	▨					▨										▨									▨					
Selection of subject to test	▨					▨	🟩	🟩	🟩	🟩						▨									▨					
Research briefing	▨					▨	🟩	🟩	🟩	🟩						▨									▨					
Baseline Study	▨	🟩	🟩	🟩	🟩	▨	🟩	🟩	🟩	🟩	🟩					▨									▨					
Data Collection	▨					▨				🟩	🟩	🟩	🟩	🟩	🟩	▨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨					
Data Processing & analysis	▨					▨										▨									▨					
Data entering & Pre-post anlysis	▨					▨				🟩	🟩	🟩	🟩	🟩	🟩	▨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	🟩	🟩	🟩	🟩	
Final report 1 & Final report 2	▨					▨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▨	🟩	🟩	🟩	🟩	🟩
Project presentation	▨					▨					🟩					▨									▨					
Submit Project	▨					▨								🟩		▨									▨					🟩

APPENDIX B

The coding for “MATLAB Function” block

```
function y = Switching_table(u)
% u(1)= Power error; u(2)=Reactive power error; u(3)=sector angle

if u(1)==1 %dp=1

  %this code section is for dp=1 and dq=1
  if u(2)==1
     if u(3)==1                                     %sector 1
         y=[0 1 1 0 0 1];   %V3=010

     elseif u(3)==2                                 %sector 2
         y=[0 1 1 0 0 1];   %V3=010

     elseif u(3)==3                                 %sector 3
         y=[0 1 1 0 1 0];   %V4=011

     elseif u(3)==4                                 %sector 4
         y=[0 1 1 0 1 0];   %V4=011

     elseif u(3)==5                                 %sector 5
         y=[0 1 0 1 1 0];   %V5=001

     elseif u(3)==6                                 %sector 6
         y=[0 1 0 1 1 0];   %V5=001

     elseif u(3)==7                                 %sector 7
         y=[1 0 0 1 1 0];   %V6=101

     elseif u(3)==8                                 %sector 8
         y=[1 0 0 1 1 0];   %V6=101

     elseif u(3)==9                                 %sector 9
         y=[1 0 0 1 0 1];   %V1=100

     elseif u(3)==10                                %sector 10
         y=[1 0 0 1 0 1];   %V1=100

     elseif u(3)==11                                %sector 11
         y=[1 0 1 0 0 1];   %V2=110

     else %x(3)==12                                 %sector 12
         y=[1 0 1 0 0 1];   %V2=110
```

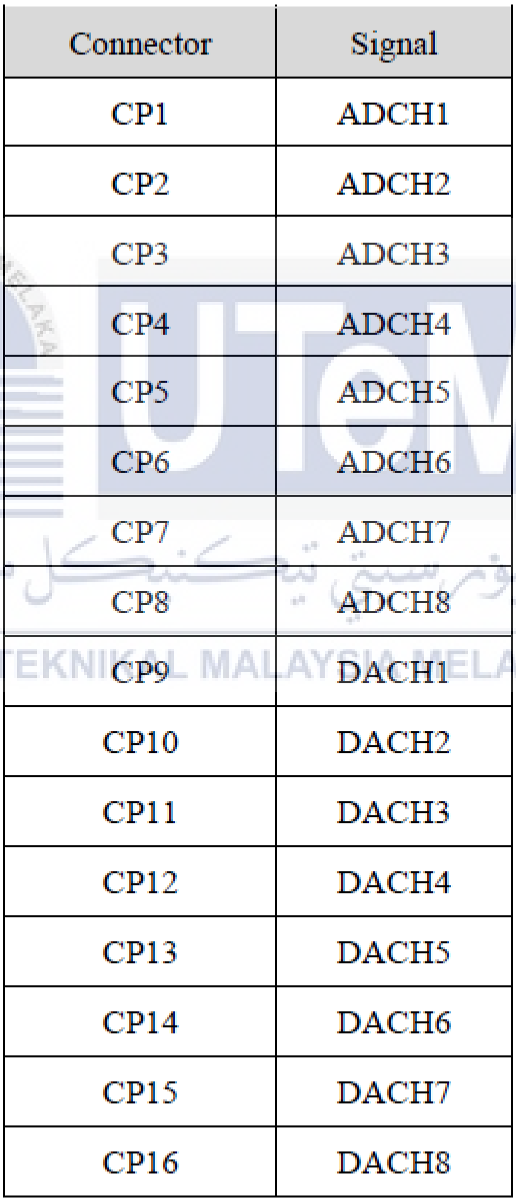
```
     end

 %this code section is for dp=1 and dq=0
 else %x(2)==0
      if u(3)==1                                    %sector 1
         y=[1 0 0 1 1 0];   %V6=101

     elseif u(3)==2                                 %sector 2
         y=[1 0 0 1 1 0];   %V6=101

     elseif u(3)==3                                 %sector 3
         y=[1 0 0 1 0 1];   %V1=100

     elseif u(3)==4                                 %sector 4
         y=[1 0 0 1 0 1];   %V1=100

     elseif u(3)==5                                 %sector 5
         y=[1 0 1 0 0 1];   %V2=110

     elseif u(3)==6                                 %sector 6
         y=[1 0 1 0 0 1];   %V2=110

     elseif u(3)==7                                 %sector 7
         y=[0 1 1 0 0 1];   %V3=010

     elseif u(3)==8                                 %sector 8
         y=[0 1 1 0 0 1];   %V3=010

     elseif u(3)==9                                 %sector 9
         y=[0 1 1 0 1 0];   %V4=011

     elseif u(3)==10                                %sector 10
         y=[0 1 1 0 1 0];   %V4=011

     elseif u(3)==11                                %sector 11
         y=[0 1 0 1 1 0];   %V5=001

     else %x(3)==12                                 %sector 12
         y=[0 1 0 1 1 0];   %V5=001
     end
  end %end for if x(1)==1



else %x(1)==0 ,dp=0

   %this code section is for dp=0 and dq=1
   if u(2)==1
     if u(3)==1                                     %sector 1
         y=[1 0 1 0 0 1];   %V2=110

     elseif u(3)==2                                 %sector 2
         y=[1 0 1 0 0 1];   %V2=110

     elseif u(3)==3                                 %sector 3
         y=[0 1 1 0 0 1];   %V3=010

     elseif u(3)==4                                 %sector 4
```

```
     y=[0 1 1 0 0 1];   %V3=010

 elseif u(3)==5                                 %sector 5
     y=[0 1 1 0 1 0];   %V4=011

 elseif u(3)==6                                 %sector 6
     y=[0 1 1 0 1 0];   %V4=011

 elseif u(3)==7                                 %sector 7
     y=[0 1 0 1 1 0];   %V5=001

 elseif u(3)==8                                 %sector 8
     y=[0 1 0 1 1 0];   %V5=001

 elseif u(3)==9                                 %sector 9
     y=[1 0 0 1 1 0];   %V6=101

 elseif u(3)==10                                %sector 10
     y=[1 0 0 1 1 0];   %V6=101

 elseif u(3)==11                                %sector 11
     y=[1 0 0 1 0 1 ];   %V1=100

 else %x(3)==12                                 %sector 12
     y=[1 0 0 1 0 1];   %V1=100
 end


%this code section is for dp=0 and dq=0
else % x(2) ==0
 if u(3)==1                                     %sector 1
     y=[1 0 0 1 0 1];   %V1=100

 elseif u(3)==2                                 %sector 2
     y=[1 0 0 1 0 1];   %V1=100

 elseif u(3)==3                                 %sector 3
     y=[1 0 1 0 0 1];   %V2=110

 elseif u(3)==4                                 %sector 4
     y=[1 0 1 0 0 1];   %V2=110

 elseif u(3)==5                                 %sector 5
     y=[0 1 1 0 0 1];   %V3=010

 elseif u(3)==6                                 %sector 6
     y=[0 1 1 0 0 1];   %V3=010

 elseif u(3)==7                                 %sector 7
     y=[0 1 1 0 1 0];   %V4=011

 elseif u(3)==8                                 %sector 8
     y=[0 1 1 0 1 0];   %V4=011

 elseif u(3)==9                                 %sector 9
     y=[0 1 0 1 1 0];   %V5=001

 elseif u(3)==10                                %sector 10
```

```
         y=[0 1 0 1 1 0];   %V5=001

     elseif u(3)==11                                %sector 11
         y=[1 0 0 1 1 0 ];  %V6=101

     else %x(3)==12                                 %sector 12
         y=[1 0 0 1 1 0];   %V6=101
    end
   end %end for if x(1)==1

end %end of coding for switching table
```

APPENDIX C

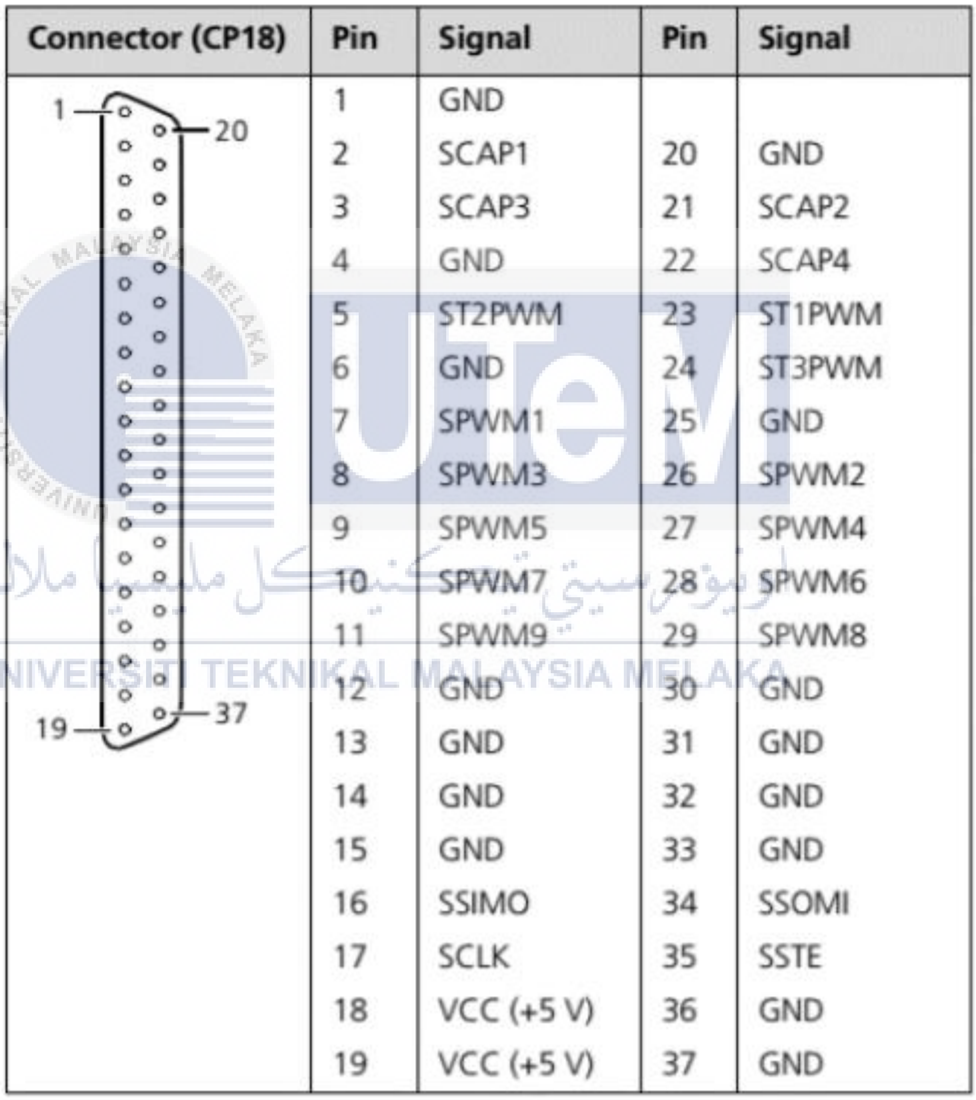
BNC Connectors (CP1…CP16)



Connector	Signal
CP1	ADCH1
CP2	ADCH2
CP3	ADCH3
CP4	ADCH4
CP5	ADCH5
CP6	ADCH6
CP7	ADCH7
CP8	ADCH8
CP9	DACH1
CP10	DACH2
CP11	DACH3
CP12	DACH4
CP13	DACH5
CP14	DACH6
CP15	DACH7
CP16	DACH8

APPENDIX D

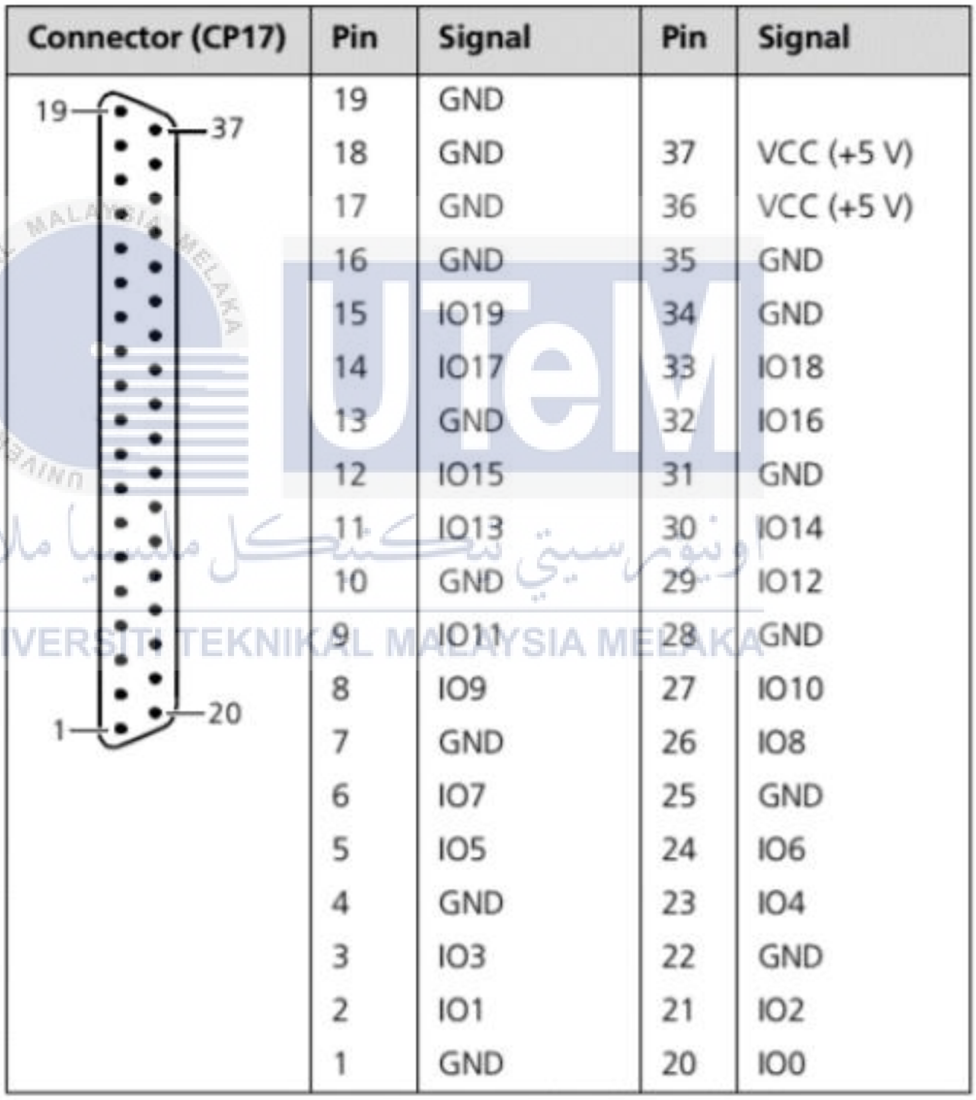
Slave I/O PWM Connector



Connector (CP18)	Pin	Signal	Pin	Signal
	1	GND		
	2	SCAP1	20	GND
	3	SCAP3	21	SCAP2
	4	GND	22	SCAP4
	5	ST2PWM	23	ST1PWM
	6	GND	24	ST3PWM
	7	SPWM1	25	GND
	8	SPWM3	26	SPWM2
	9	SPWM5	27	SPWM4
	10	SPWM7	28	SPWM6
	11	SPWM9	29	SPWM8
	12	GND	30	GND
	13	GND	31	GND
	14	GND	32	GND
	15	GND	33	GND
	16	SSIMO	34	SSOMI
	17	SCLK	35	SSTE
	18	VCC (+5 V)	36	GND
	19	VCC (+5 V)	37	GND

APPENDIX E

Digital I/O Connectors



Connector (CP17)	Pin	Signal	Pin	Signal
	19	GND		
	18	GND	37	VCC (+5 V)
	17	GND	36	VCC (+5 V)
	16	GND	35	GND
	15	IO19	34	GND
	14	IO17	33	IO18
	13	GND	32	IO16
	12	IO15	31	GND
	11	IO13	30	IO14
	10	GND	29	IO12
	9	IO11	28	GND
	8	IO9	27	IO10
	7	GND	26	IO8
	6	IO7	25	GND
	5	IO5	24	IO6
	4	GND	23	IO4
	3	IO3	22	GND
	2	IO1	21	IO2
	1	GND	20	IO0

APPENDIX F

Coding for modified switching table

```
function [y1,y2,y3]= Switching_table(x1,x2,x3)
% y denotes upper switches, y1=Sa, y2=Sb and y3=Sc
% x1= Power error, x2=Reactive power error and x3=sector number

if x1==1 %dp=1

  %this code section is for dp=1 and dq=1
  if x2==1
     if x3==1                                     %sector 1
                y1=0;
                y2=1;
                y3=0;   %V3=010


     elseif x3==2                                 %sector 2
                y1=0;
                y2=1;
                y3=0;    %V3=010


     elseif x3==3                                 %sector 3
                y1=0;
                y2=1;
                y3=1;   %V4=011

     elseif x3==4                                 %sector 4
                y1=0;
                y2=1;
                y3=1;   %V4=011

     elseif x3==5                                 %sector 5
                y1=0;
                y2=0;
                y3=1;   %V5=001

     elseif x3==6                                 %sector 6
                y1=0;
                y2=0;
                y3=1;   %V5=001

     elseif x3==7                                 %sector 7
                y1=1;
                y2=0;
                y3=1;   %V6=101
```

```
    elseif x3==8                                 %sector 8
               y1=1;
               y2=0;
               y3=1;   %V6=101

    elseif x3==9                                 %sector 9
               y1=1;
               y2=0;
               y3=0;   %V1=100

    elseif x3==10                                %sector 10
               y1=1;
               y2=0;
               y3=0;   %V1=100

    elseif x3==11                                %sector 11
               y1=1;
               y2=1;
               y3=0;   %V2=110


    else %x3==12                                 %sector 12
               y1=1;
               y2=1;
               y3=0;   %V2=110
    end

%this code section is for dp=1 and dq=0
else %x2==0
     if x3==1                                    %sector 1
               y1=1;
               y2=0;
               y3=1;   %V6=101

    elseif x3==2                                 %sector 2
               y1=1;
               y2=0;
               y3=1;   %V6=101

     elseif x3==3                                 %sector 3
               y1=1;
               y2=0;
               y3=0;   %V1=100

    elseif x3==4                                 %sector 4
               y1=1;
               y2=0;
               y3=0;   %V1=100

    elseif x3==5                                 %sector 5
               y1=1;
               y2=1;
               y3=0;   %V2=110

    elseif x3==6                                 %sector 6
               y1=1;
               y2=1;
               y3=0;   %V2=110
```

```
     elseif x3==7                                 %sector 7
                y1=0;
                y2=1;
                y3=0;   %V3=010

     elseif x3==8                                 %sector 8
                y1=0;
                y2=1;
                y3=0;   %V3=010

     elseif x3==9                                 %sector 9
                y1=0;
                y2=1;
                y3=1;   %V4=011

     elseif x3==10                                %sector 10
                y1=0;
                y2=1;
                y3=1;   %V4=011

     elseif x3==11                                %sector 11
                y1=0;
                y2=0;
                y3=1;   %V5=001


     else %x3==12                                 %sector 12
                y1=0;
                y2=0;
                y3=1;     %V5=001
     end
  end %end for if x3==1


else %x(1)==0 ,dp=0

   %this code section is for dp=0 and dq=1
   if x2==1
     if x3==1                                     %sector 1
                y1=1;
                y2=1;
                y3=0;     %V2=110

     elseif x3==2                                 %sector 2
                y1=1;
                y2=1;
                y3=0;   %V2=110

     elseif x3==3                                 %sector 3
                y1=0;
                y2=1;
                y3=0;   %V3=010

     elseif x3==4                                 %sector 4
                y1=0;
                y2=1;
                y3=0;   %V3=010
```

```
 elseif x3==5                                 %sector 5
            y1=0;
            y2=1;
            y3=1;  %V4=011

 elseif x3==6                                 %sector 6
            y1=0;
            y2=1;
            y3=1;   %V4=011

 elseif x3==7                                 %sector 7
            y1=0;
            y2=0;
            y3=1;   %V5=001

 elseif x3==8                                 %sector 8
            y1=0;
            y2=0;
            y3=1;   %V5=001

 elseif x3==9                                 %sector 9
            y1=1;
            y2=0;
            y3=1;   %V6=101

 elseif x3==10                                %sector 10
            y1=1;
            y2=0;
            y3=1;   %V6=101

 elseif x3==11                                %sector 11
            y1=1;
            y2=0;
            y3=0;   %V1=100

 else %x3==12                                 %sector 12
            y1=1;
            y2=0;
            y3=0;   %V1=100
 end


%this code section is for dp=0 and dq=0
else % x(2) ==0
 if x3==1                                     %sector 1
            y1=1;
            y2=0;
            y3=0;   %V1=100

 elseif x3==2                                 %sector 2
            y1=1;
            y2=0;
            y3=0;   %V1=100

 elseif x3==3                                 %sector 3
            y1=1;
            y2=1;
            y3=0;   %V2=110
```

```
        elseif x3==4                                        %sector 4
                   y1=1;
                   y2=1;
                   y3=0;     %V2=110

        elseif x3==5                                        %sector 5
                   y1=0;
                   y2=1;
                   y3=0;     %V3=010

        elseif x3==6                                        %sector 6
                   y1=0;
                   y2=1;
                   y3=0;    %V3=010

        elseif x3==7                                        %sector 7
                   y1=0;
                   y2=1;
                   y3=1;    %V4=011

        elseif x3==8                                        %sector 8
                   y1=0;
                   y2=1;
                   y3=1;    %V4=011

        elseif x3==9                                        %sector 9
                   y1=0;
                   y2=0;
                   y3=1;    %V5=001

        elseif x3==10                                       %sector 10
                   y1=0;
                   y2=0;
                   y3=1;     %V5=001

        elseif x3==11                                       %sector 11
                   y1=1;
                   y2=0;
                   y3=1;    %V6=101

        else %x(3)==12                                        %sector 12
                   y1=1;
                   y2=0;
                   y3=1;    %V6=101
       end
      end %end for if x(1)==1

   end %end of coding for switching table
```