C O V E N T R Y
U N I V E R S I T Y

Faculty of Engineering and Computing

Department of Aerospace, Electronic and Electrical Engineering

6040CEM Individual Project Realization

# Software-based Control System and Validation Model for Voltage Source Inverter

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Throughout the project, I was able to expose myself to the development of such inverter systems, as well as microgrid configuration. This journey is one of the biggest challenges in my engineering life as microgrid and Field Oriented Control is a very big and complex system, consisting of many subsystems, working in harmony. To learn such a system in a short time is very stressful and difficult as there are not many resources available.

Thank you both for your unwavering support, patience, and belief in my potential. Your mentorship has not only facilitated my academic growth but has also prepared me for future challenges in my professional journey.

# DECLARATION OF ORIGINALITY AND EXCLUSIVENESS

I hereby declare that the dissertation is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Coventry or other institutions.

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# Abstract

This project studies the design and implementation of a development and validation model for an entire voltage source inverter. This research focuses on the operating principles of such systems, as well as a comparison of various control strategies and methods, design procedures, and testing and validation topologies. The initial result of this study is the introduction of the Clarke-Park Transformation, which converts AC signals to two DC variables for more precise control. This study also proposes a control system for a Voltage Source Inverter based on the Synchronous Reference Frame that employs such a transformation. Along with the control system, this project lays the groundwork for a testing and validation methodology. The testing approach also provides information regarding the behaviour of such controllers.

The discussion and analysis reveal significant improvements in the inverter's dynamic response and efficiency. The Synchronous Reference Frame, together with Clarke-Park Transformation, improves accuracy and stability in the control of AC motors and power outputs. Experimental results confirm the theoretical benefits, demonstrating reduced overall harmonic distortion and better handling of variable load situations. This confirms the robustness of the suggested control technique and sets a solid foundation for future improvements.

Future research can focus on real-world applications, including scalability and integration with renewable energy sources and smart grid technology. The research also paves the way for further improvement of control algorithms to optimize energy conversion and management, guaranteeing that the system can effectively adapt to grid disruptions and load variations. The goal is to pave the path for more resilient and efficient power systems, helping to drive the continued growth of smart, sustainable energy solutions.

# Chapter 1: Introduction

For a Photovoltaic (PV) Power Conversion in Consumer Level, Voltage Source Grid Connected Inverter (VSGCI/VSI) Is the most popular type of Power Inverter used. Consumer Level Grid Connected Inverter can be both Single Phase and Three Phase system, exists in several types. Single Phase Microinverter is the one of the most popular forms of such GCI that is used in consumer level for its cost-effectiveness and easy to install.

Below shows the overall system diagram of a Grid Connected Inverter System. The system can be separated into two parts, which are VSI system and AC System. In this Diagram, PCC which is Point of Common Coupling, refers to the location within a power system where a particular source, such as a solar PV system, connects to the larger electrical grid. This point is critical for managing how power from the solar system interacts with the grid. Effective control of the voltage at the PCC is essential for maintaining grid stability and ensuring that the solar system operates efficiently and safely under varying grid conditions.

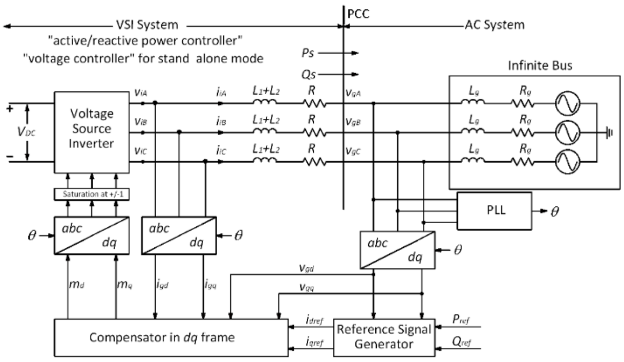



*Figure 1-1 : Overall System Block Diagram of a Grid Connected Inverter*

Voltage Source GCI works by obtaining the grid information using Clarke-Park Transformation, which obtains the direct voltage ($i_d$) and the quadruple voltage ($i_q$) from the grid. This information is then used to regulate and control the output power from the inverter. The compensator will use the information to generate a reference signal from the compensator to switch our Voltage Source Inverter. The output LCL Filter will filter the output current before injecting the current to the PCC. The System is synchronized with the grid using a PLL or Phase Lock Loop.

Infinite Bus is the Power Grid that the Inverter Connects to. For most Consumer Grade Inverter, which is mostly installed in residential and semi-commercial application, are connected to microgrid. Microgrid is a local operation of electricity sources and loads that normally operates connected to and synchronous with the traditional centralized electrical grid (macrogrid) but can also disconnect to "island mode" and function autonomously as physical and economic conditions dictate. Microgrids are designed to provide a reliable and secure power supply to a localized area, such as a university campus, hospital complex, business center, or residential neighborhood.

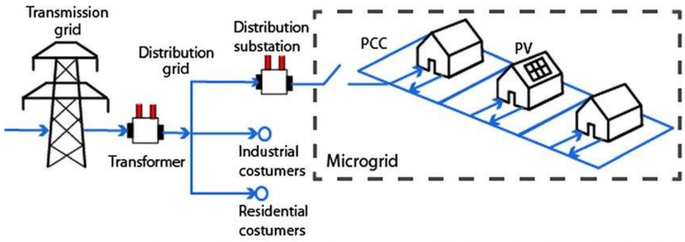



*Figure 1-2: Electrical System and PCC*

In the search for a sustainable energy future, the necessity for innovative and cost-effective solutions is more important than before. As countries around the world work to fulfill this demand, the focus on renewable energy technology has been growing. Malaysia is on the path of a major change in its energy policy and market dynamics, pushed in large part by the government's commitment to promoting renewable energy use. This thesis addresses a significant gap in the Malaysian market: the development of locally produced photovoltaic (PV) power inverters that are complying with national policies and market demands.

Currently, most PV power inverters in Malaysia are imported and not designed to the local environment or market requirements. The gap has become more significant as government policies support the deployment of renewable energy technologies, increasing demand for PV-related power systems. The lack of locally developed solutions creates a unique opportunity for Malaysian businesses to innovate and compete in this rapidly growing sector.

The primary goal of this project is to develop a fundamental framework that allows for rapid development of power conversion systems. This includes motor control and other applications that need AC power control and generation, which are critical for maximizing the efficiency and efficacy of renewable energy systems. The project's technological focus is on developing a software-based control system with digital signal processors (DSP) or microprocessors. This system can also be used as a validation model for the development of voltage source inverters, which are required to convert direct current (DC) from PV panels into usable alternating current (AC).

This thesis will explore the design, development, and testing of this model, emphasizing its potential to be adapted for various applications within the renewable energy sector. By doing so, it aims to not only fill a critical market gap but also contribute to the global effort towards energy sustainability.

## 1.1 Problem Statement:

To achieve a sustainable energy future, innovative and affordable solutions are needed as the current market does not have any available system that is suitable to the local market. With the increased demand and government policy adaptation to promote renewable energy usage, a solution for Malaysia will be a hotcake in the next few years.

## 1.2 Problem Analysis:

Currently Most of the PV Power Inverters are imported and do not have any solution that is developed specifically locally. As the government policy changes will increase the demand of the PV-related Power System solution, this has created a market and opportunity for local companies to develop a solution that is both competitive and innovative with first-class performance.

## 1.3 Project Objective:

This project is aimed to design a MATLAB Simulink Model, which will allow rapid development for Power Conversion System, as well as Motor Control and other applications which apply AC Power Control and Generation.

## 1.4 Technical Objective:

Software-based (DSP/microprocessor) Control System and validation Model for Voltage source Inverters Development:

- Total Harmonic Distortion of the Output Waveform (THD%) < 5%
- Active and Reactive Power Control
- Single Phase Active Power Injection Control with Three Phase Power Exchange Capabilities.

# Chapter II: Inverter System Working Principle

For a Grid Connected Voltage Source Inverter, it can be divided into several vital parts. Mainly the Bridge Inverter, Control Loop, and the output Filter. All these components together with DC Link Source and PLL (Phase Lock Loop) form a complete inverter system.

For a typical inverter current control loop, there are two main types of it, mainly linear controller, and non-linear controllers. Linear Controller consist of conventional voltage type PWM converters or modulation. Linear controllers' schemes had two separated control actions like compensation against current error and voltage modulation constant. These linear controllers are suitable for maintaining constant switching frequency, optimum switching patterns and for maintaining a better DC Link at the input of the controller. [1]. Common examples of linear controllers are PI (Proportional Integral) controllers and PR (Proportional Resonant) Controllers. Non-Linear Controller works by introducing advanced non-linear control such as hysteresis control and Neural Networks. This method of control gives more freedom and dynamics to the overall system, providing better performance and robustness.

For our case, we are mainly focus on Linear controllers, mainly Synchronous PI controllers as this controller are mature, easy to design, and have great dynamics and modelling capabilities and many methods had been developed for PID control can be implemented. Synchronous PI controller had been widely used in other applications such as Motor Control.

## 2.1 Synchronous Reference Frame based Control.

The Synchronous Reference Frame (SRF), also known as the dq0 transformation, is a mathematical transformation used in control systems for AC electrical devices, including inverters, to simplify the analysis and control of AC power systems. It converts three-phase AC quantities into direct and quadrature components (often with a zero component) in a rotating reference frame. This method is pivotal in the control systems of inverters, particularly when interfacing with AC grids or controlling electric motors. This control method will simplify AC control by decouple the active and reactive power components of the system. This will allow for power control while reducing the computation complexity by converting the AC sinusoidal waveform into a DC quantity. This also gives fast and stable response as the control variable is DC quantity. This control also allows for better versatility and adaptability.

## 2.2 Clarke Park Transformation

The Clarke and Park transformations, named after Edith Clarke and Robert H. Park, are mathematical transformations used extensively in the control of three-phase systems, particularly in electrical engineering for simplifying the analysis and control of three-phase circuits and machines. These transformations are pivotal in converting time-varying three-phase quantities into constant or slowly varying components that are easier to manage, control, and analyse. This is especially useful in applications involving AC motors and power inverters.

**Clarke Transformation (αβ0 Transformation)**

The Clarke transformation converts the three-phase system (usually represented as phases A, B, and C) into a two-phase orthogonal system in the stationary reference frame, along with a zero-sequence component. The Clarke transformation can be expressed mathematically as:

$$\begin{pmatrix} \alpha \\ \beta \\ 0 \end{pmatrix} = \frac{2}{3}\begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix}\begin{pmatrix} i_A \\ i_B \\ i_C \end{pmatrix} \qquad (1)$$

Here, $i_A$, $i_B$, and $i_C$ are the instantaneous currents or voltages of the three-phase system. The outputs $\alpha$ and $\beta$ represent the two-axis orthogonal components in a stationary reference frame, and '0' represents the zero-sequence component, which is relevant in systems where the sum of the three phases does not equal zero (e.g., in unbalanced systems).

**Park Transformation (dq0 Transformation)**

The Park transformation, or dq0 transformation, converts the αβ0 components from the Clarke transformation into a rotating reference frame aligned with one of the phases of the AC system. This transformation essentially aligns the d-axis with the direct component (magnetic axis) of the machine and the q-axis with the quadrature axis, orthogonal to the magnetic axis. This aligns the reference frame to rotate at the same angular velocity as the rotor of the machine or the grid frequency, which simplifies dynamic analysis and control. The Park transformation can be represented as:

$$\begin{pmatrix} d \\ q \\ 0 \end{pmatrix} = -\frac{2}{3}\begin{pmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix}\begin{pmatrix} i_A \\ i_B \\ i_C \end{pmatrix} \quad (2)$$

Here, $\theta$ is the angular position of the rotor or the synchronous angular position of the grid frequency. This transformation results in the d-component, which is aligned with the rotor flux and is typically used to control the torque in motor applications, and the q-component, which is orthogonal to the rotor flux and typically controls the magnetizing flux. Below is a graphical illustration of such transformations.

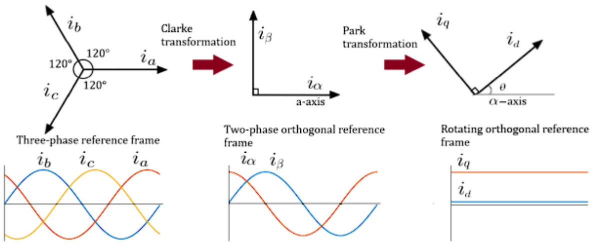



*Figure 2-1 : Clarke-Park Transformation*

The θ is the angular frequency of the grid. This θ can be obtained using PLL which will be implemented along the way of the synchronous frame. Phase Lock Loop is connected to the Quadruple Voltage that is obtained from the outer loop, or the voltage loop of the system.

## 2.3 PLL Operation

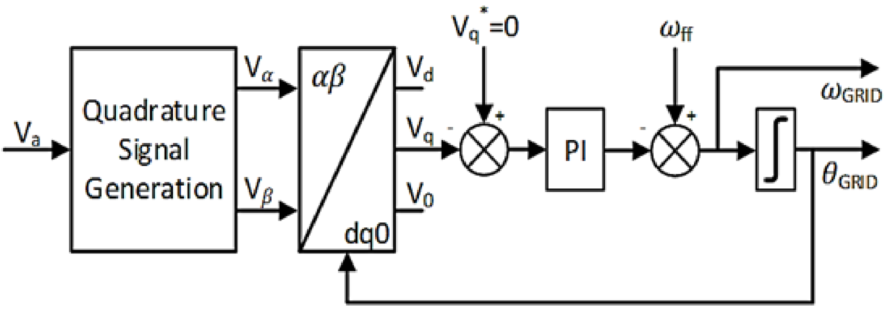



*Figure 2-2: Single Phase PLL Loop*

The basic configuration of the PLL system is shown in Fig. 4. The phase voltages $V_a$ *are* obtained from sampled line *to* line voltages. These stationary reference frame voltages are then transformed to voltages $U_d$, $U_q$, the Clarke-Park Transformation. The angle **θ*** used in the transformations is obtained by integrating a frequency command $\omega^*$. If the frequency command $\omega^*$ is identical to the utility frequency, the voltages and $U_{de}^*$ appear as dc values depending on the angle θ***.** In the given method, a PI regulator is used to obtain that value of $\theta^*$ (or $\omega^*$*)* which drives the feedback voltage $U_{de}$ to a commanded value $U_{de}^*$. In other words, the regulator results in a rotating frame of reference with respect to which the transformed voltage $U_{de}$ has the desired dc value $U_{de}^*$. The frequency of rotation of this reference frame is identical to the frequency of the utility voltage. The Magnitude of the controlled quantity $U_{de}$, determines the phase difference between the utility voltages and sin(θ*) or cos(θ*).

## 2.4 Outer and Inner Loop for Synchronous Reference Frame

There are two loops exist in such Synchronous Reference Frame, which is Outer Loop and Inter Loop. Outer Loop is the Loop that is obtaining and Direct Voltage ($V_D$) and Quadruple Voltage ($V_D$). Inner Loop, in other words, will obtain the Direct Current ($I_D$) and Quadruple

Current ($I_Q$) which represents active and reactive voltage and current. This information which will be injected into the Synchronous controller to generate the control efforts, which will go through the inverse Clarke-Park transformation. This will generate a reference signal then will used to generate PWM signal. This PWM signal will be used to switch the IGBT bridge to allow Power exchanges with the grid. Reference signal is required for such application as this will directly control the injected power into the grid system. Such Reference signal can be generated by using calculations with target power divided by the Direct Voltage of the system.

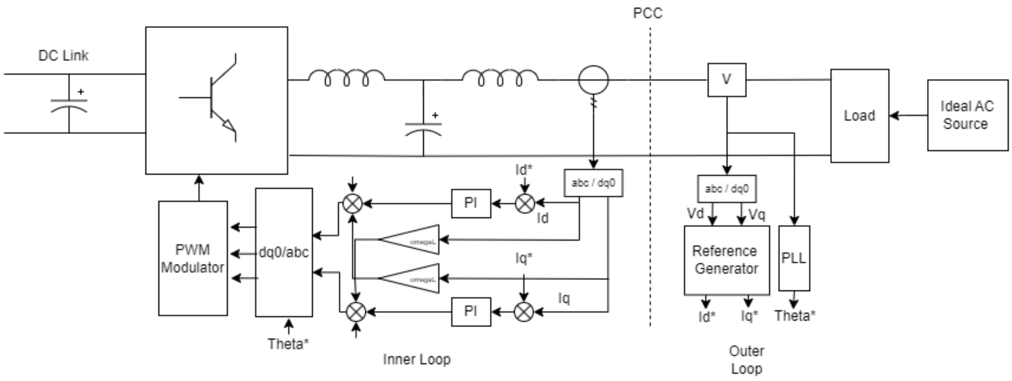



Figure 2-3: Complete Overview of a Single Phase VSI with Outer Loop and Inter Loop

## 2.5 PWM Signal Generation

PWM, or Pulse Width Modulation Signal Generation is critical to the Power Inverter System as it will control the Power Switching Device to control the power flow of the system. For Inverter System, SVPWM (Space Vector Pulse Width Modulation) and SPWM (Sinusoidal Pulse Width Modulation) are two common modulation techniques used to control the output. voltage or current of an inverter. Both techniques aim to approximate a sinusoidal waveform using pulses, but they are different in their approach to generating the control signal. SPWM is a simple modulation technique that directly compares a sinusoidal reference. waveform to a triangular carrier waveform. The output of the comparator is a series of pulses. Whose widths are proportional to the instantaneous amplitude of the reference waveform. The frequency of the carrier waveform determines the switching frequency of the inverter, while the amplitude of the reference waveform determines the output voltage or current amplitude.

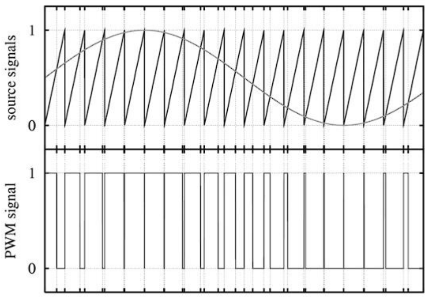



Figure 2-4: Sinusoidal Pulse Width Modulation

Depending on the Current Controller and output requirement Design, SPWM or SVPWM may be used. For Single Phase Usage (Such as Microinverter), SPWM may be enough. because it was optimized to inject single phase power injection. For 3-phase power injection, it will depend on the current controller design and requirements as different current controller. may require different signal input for the output waveform generation.

## 2.6 Control System Development and with MATLAB Simulink

MATLAB Simulink is a graphical programming environment developed by MathWorks for modelling and simulating dynamic systems. It allows users to create block diagrams to represent the components of a system and their interactions. MATLAB Simulink is widely adapted and utilized in the industry due to its versatility and capabilities with different toolbox and blocks. For power systems, PowerGUI Block within Simulink had enabled Powerful discrete and continuous simulation of power system with control system.

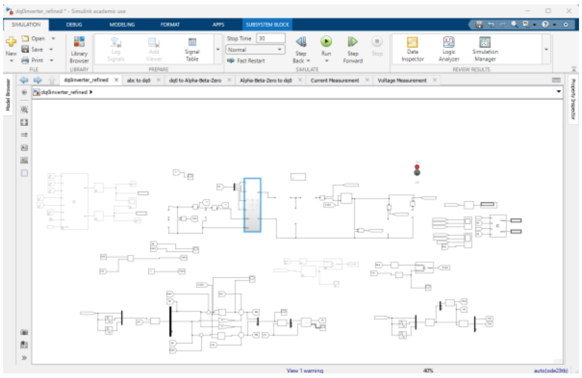


*Figure 2-5: MATLAB Simulink*

PowerGUI block serves as an interface for configuring and solving simulations of electrical. power systems. It enables users to select from three solver methods: continuous using a variable-step solver, discretization for fixed time steps, or a choice between continuous and discrete phasor solutions. The block provides analysis of steady-state and dynamic responses, while providing access to tools for simulation results analysis and advanced parameter design.

# Chapter III: System Methodology

## 3.1 Synchronous Reference Frame for a Single-Phase System Model

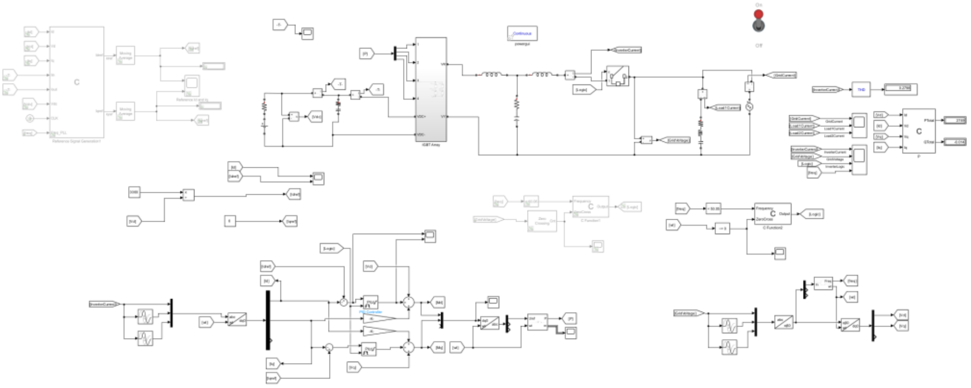


*Figure 3-1: Complete Single Phase Inverter System*

**Synchronous d-q-0 Reference Frame For single phase.**

**Inner Loop / Current Control Loop:**

The synchronous current loop will obtain the current information of the grid information which will be used for current control for the system. The current information of the inverter will be obtain using a current measurement device which will be passed thru a Clarke-park transformation block to obtain the $I_d$ and $I_q$. This information will be used to generate $\Delta I$ or the System Error. This error will be injected to the PI controller to obtain the control effort ($V_{d(ERROR)}$). The signal will be injected with $-I_q$ with the Gain of $\omega L_f$ and $V_d$ of the system. This signal is the reference signal for the inverse Clarke-Park transformation block to recover the reference signal for the inverter.

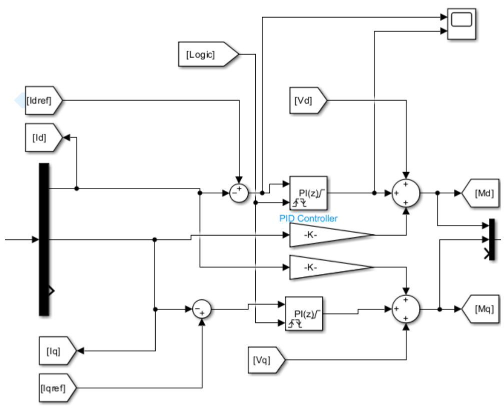



*Figure 3-2: Current Control Loop*

### Outer Loop /Voltage Loop

Outer Loop, or the Voltage d-q-0 loop is placed after the grid side inductor. This loop is used for obtaining the grid phasor and frequency based. The PLL loop will be implemented at the Va of the Voltage SRF. A single Phase PLL is applicable in this case. The output frequency will be used for power injection point control and validation purposes, while the angular frequency (θ) is used for the inverse Clarke-park transformation to generate reference signal for the PWM signal.

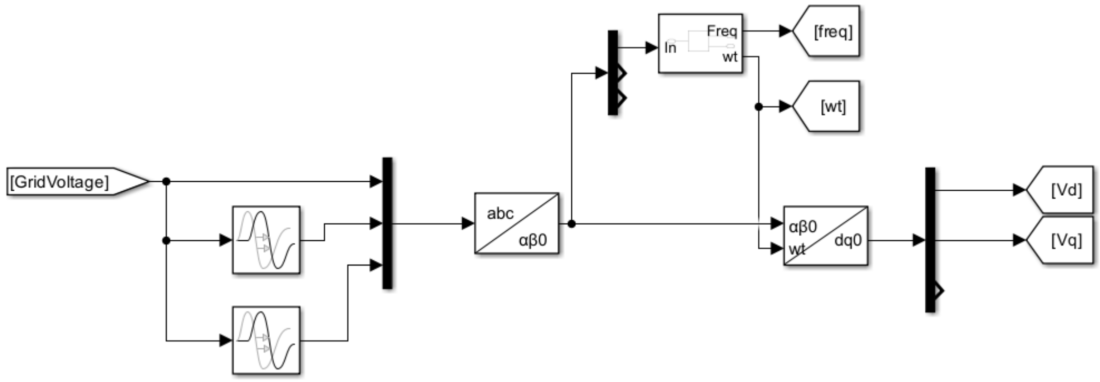



*Figure 3-3: Voltage Loop with PLL*

As this is a single-phase system, a phase shift or delay need to generate a balanced three phase signal which is required for Synchronous Reference Frame. Transport delay can be used in this case with exactly 120° of delay when to generate  a three-phase signal from the inverter, which allow the computation of dq0 transformation using single phase signal.

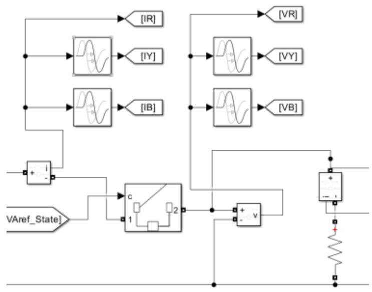



*Figure 3-4: Transport Delay for Three Phase Simulation.*

By writing the basic state space equations for our inductor current and capacitor voltage in ab0 domain, then rewriting it using transformation matrix will give us the systems equation in d-q domain. Since in dq domain the system is rotated along with ωt, the current and voltage dynamics can be represented as below:

$$\frac{di_{id}}{dt} = \frac{-R_f}{L_f} i_{id} + \omega_o i_{qL} + \frac{1}{L_f}(v_{id} - V_{dc}) \qquad (3)$$

$$\frac{di_{qL}}{qt} = \frac{-R_f}{L_f} i_{iq} - \omega_o i_{dL} + \frac{1}{L_f}\left(v_{iq} - V_{qc}\right) \qquad (4)$$

$$\frac{dv_{dc}}{dt} = \omega_o V_{qc} + \frac{1}{C_f}(i_{id} - i_{dL}) \qquad (5)$$

$$\frac{dv_{qc}}{dt} = -\omega_o V_{qc} + \frac{1}{C_f}(i_{id} - i_{dL}) \qquad (6)$$

$$\frac{di_{dL}}{dt} = \frac{-R_g}{L_g} + \omega_o i_{PL} + \frac{1}{L_f}(V_{dc} - V_{dL}) \qquad (7)$$

$$\frac{di_{dL}}{dt} = \frac{-R_g}{L_g} + \omega_o i_{PL} + \frac{1}{L_f}(V_{dc} - V_{dL}) \qquad (8)$$

## 3.2 Reference Current Generation

**Target Power Injection**

For the system reference, there are two main approaches. First will be the target power method, while the second method is the DC link Voltage regulation method. As the Direct Current ($I_d$) is the injected active power current from the inverter, we can use the equation below to generate the reference direct current ($I_d$*). As we are not including the reactive power control for our current model, quadruple current reference ($I_q$*) is set to 0 in this case.

$$I_d^* = \frac{P}{Vd} \qquad (9)$$

**DC Link Voltage Regulation Method**

For the DC Link Voltage Regulation method, the power from the Input Current and the Output current of the DC Link Capacitor is obtained. This information will be used to produce the integration for the equation (7). This equation will detect the changes of the input and output power, if the output power is higher than the input power, the reference will decrease to regulate the Voltage of the capacitor, which is directly linked to the $V_{pk}$ of the AC output voltage and $V_d$.

$$I_d^* = \frac{1}{V_d}\ (\ K_p(P_{in} - P_{out}) + K_1 \int (P_{in} - P_{out})dt) \quad (10)$$

For the reference generation block, we will take Direct and Quadruple Voltage and Current, and perform the operation shown in the Block diagram below. This reference can be generated by implementing C function in our MATLAB Simulink Model.

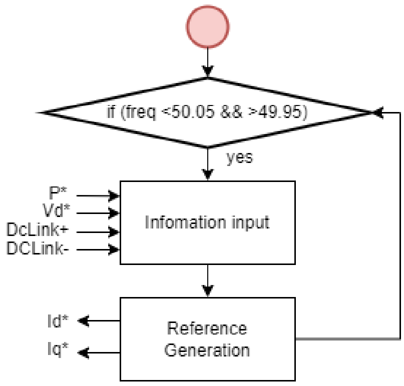



*Figure 3-5: Reference Id Generation*

The System will check the integration of the DC Link Power, if the integration returns positive, the generated reference will allow the system to reach target output. The target output will be the neutral point of the DC Link Output if the integration is returned negative.

```
double PowerIntegral(double Time,double currentPin, double currentPout) {

    if (currentPin != previousPin || currentPout != previousPout) {

       currentTime = Time; // Retrieve current simulation time

    if (lastTime >= 0) { // Check if this is not the first execution
        dt = currentTime - lastTime;
    } else { dt = currentTime;}

        double integralPin = 0.0, integralPout = 0.0;
        if (dt > 0) { // Ensure dt is positive and not the first run
            integralPin = 0.5 * (currentPin + previousPin) * dt;
            integralPout = 0.5 * (currentPout + previousPout) * dt;
        }

        // Update for next iteration
        previousPin = currentPin;
        previousPout = currentPout;
        lastTime = currentTime; // Update the last change time
        return integralPin - integralPout;
    }

    // In case there's no change, we do not update lastTime
    return 0.0; // Or maintain the last calculated value
```

*Figure 3-6: Integration Algorithm for the Reference Generation*

## 3.3 PWM Modulator and IGBT Switch

In this model, PWM Modulator Block (2 Level) is used for our application with a Full Bridge Inverter consisting of 4 IGBT. For the Modulator, the operation mode is selected to synchronized as we are using the ωt from the PLL to generate the PWM signal. Switching Ratio is set to 200 as we are using 10kHz as our PWM Frequency. The output of the PWM modulator is directly fed into the IGBT which is shown below. The IGBT impedance is configured as shown in figure (3-9). The DC Link is connected at the VDC+ and VDC-, with a DC Link capacitor of 47uF.

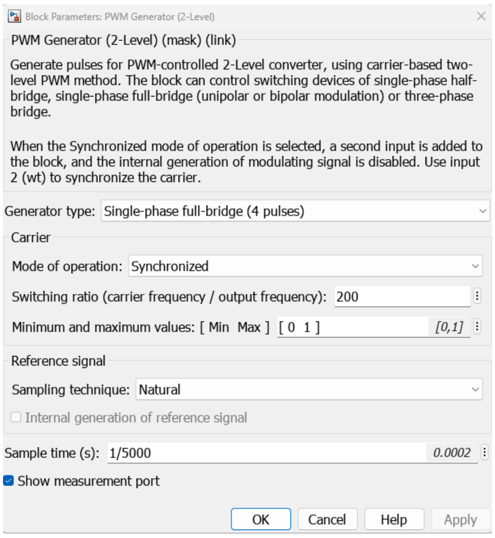



Figure 3-7: PWM Generator Setting

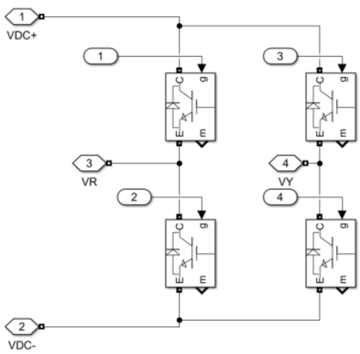



Figure 3-8: IGBT Full Bridge

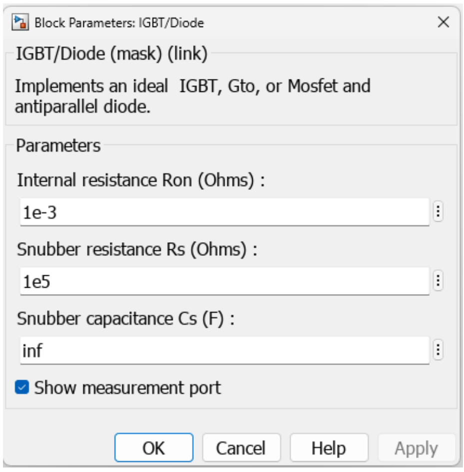



Figure 3-9:IGBT Parameters

## 3.4 Output LCL filter's Systematic Design Methodology

For the LCL output filter design, the method which is introduced in the paper "A Sequence Rule Analysis on Active and Passive LCL Filter for Three Phase inverter Grid Connection for Damping Stability Consideration" by Ronald Jackson, Shamsul Aizam and Suriana Salimin can be used for this application. This paper had provided a sequence rule and guidelines to design an LCL filter which meets the output requirement. From the paper, the design rule consists of 5 parts. This five-part will determine the components value based on the requirements.

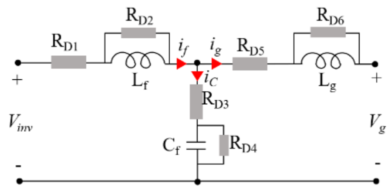



*Figure 3-10: LCL Filter with Damping Resistor Location*

The first step is to determine the Line-to-Line Voltage $V_{rms}$, Base Power $P_b$, inverter Switching frequency $f_{sw}$, and the rated current $I_{rated}$. The parameter can then be calculated as stated below. The information will be first used to determine the capacitance's base value, $C_b$. The value will be used to determine the filter capacitance, Cf by 5% of the base capacitance, Cb. The equation of the Cf can be found using the equation below:

$$C_f = 5\%\left(\frac{P_b}{2\pi f_g V_{rms}^2}\right) \qquad (11)$$

Then, the value of Inverter side Inductor, $L_f$, with the maximum current ripple can be found using the equation below:

$$L_f = \frac{V_{dc}}{6 f_{sw} \Delta_{Imax}} \qquad (12)$$

Usually, the $\Delta I_{max}$ is about 10% of the Rated Current, $I_{max}$ is given by:

$$\Delta I_{max} = 10\% \frac{P_b\sqrt{2}}{3V_{ph}} \qquad (13)$$

Grid side Inductor value, $L_G$ can be obtained using the equation shown below.

$$L_g = \frac{\sqrt{\frac{1}{\delta^2}+1}}{C_f(2\pi f_{sw})^2} \qquad (14)$$

Or it can be obtained using ratio (K) of $L_g$ and $L_f$, where $L_g = K*L_f$, and $L_g$ can be defined either less then $L_f$, or similar to $L_f$ when achieving K=1, To verify the resonance frequency, $f_r$ must be within the range of $10f_g<f_r<0.5f_{sw}$. The $f_r$ can be calculated using the equation given below. If is less than 10 fg, $C_f$ needs to be higher. If $f_r$ is higher than the $0.5f_{sw}$, $C_f$ or the $f_{sw}$ need to be amplified.

$$f_r = \frac{1}{2\pi}\sqrt{\frac{L_f+L_g}{L_f L_g C_f}} \qquad (15)$$

In our case, a damping resistor is added for internal stability. According to the paper, PD1,PD3 and PD5 are common to implement as they are equivalent to the capacitance for both Lf and Lg inductance as well as the Cf. PD3 is the sole primary approach applied in grid -connected filters as PD1 and PD5 cause significant damping loss factor due to the path of the power flux directly thru PD1 and PD5. [2] Meanwhile, PD3 utilizes a small resistance value, which is not applicable in other PD method while degrading the attenuation of high-frequency harmonics. Since this filter consists of 3 energy storing components, the G(s) of the LCL filter will be:

$$G_{PD3} = \frac{C_f R_3 s+1}{L_f L_g C_f s^3+(L_g+L_f)C_f R_3 s^2+(L_f+L_g)s} \qquad (16)$$

## 3.5 Power Injection Point Logic and Grid Switching

The power injection point is controlled using the logic shown below. This logic will detect the PLL tracked frequency and the Zero Crossing point. The Zero crossing point can be both the grid voltage and current. This logic will reduce the transient of the injected current at the PCC. This logic will prevent harmonics and transient in the grid system. The logic Block diagram is shown below.

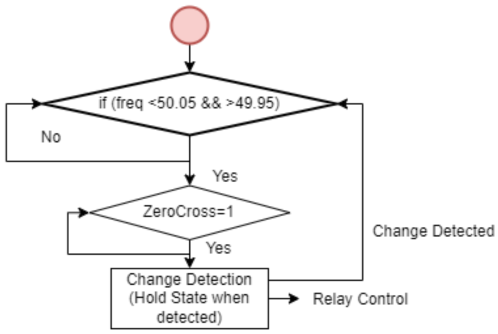



*Figure 3-11: Power Injection Logic Block Diagram*

For this model, an ideal switch is implemented with a snubber. Capacitor based snubber is implemented to the system to reduce the in-rush energy by providing a damped response at the connected between grid and the inverter. For the testing environment, this model will utilize an ideal grid with a single-phase AC Voltage Source, paired with a Resistive Load to act as an Ideal Grid Environment. The Load Configuration is given at Figure (3-13).

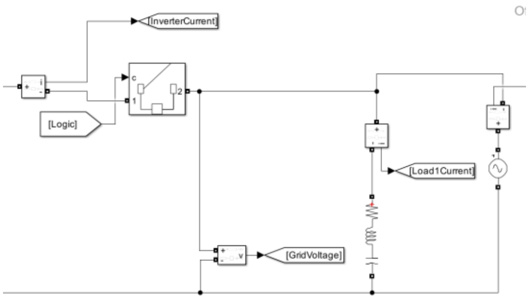



*Figure 3-12: Ideal Grid Implementation*

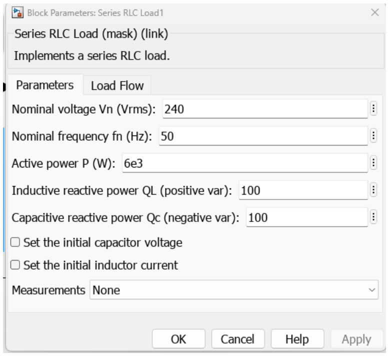



*Figure 3-13:RLC Load Configuration*

# Chapter IV: MATLAB Simulink Modelling and System Response Analysis

For this model, we are simulating a 3kW Single Phase Inverter with Ideal Grid connected to a single resistive Load as we are only interested in the active power injection. For this paper, four tests will be conducted to validate the system behavior. Each test will be using the same LCL Filter and Load. The Specification of the designed inverter is shown below:

| Specification | Value |
|---|---|
| DC Link Voltage | 400Vdc |
| Output Rms Voltage | 240Vrms |
| Inverter Side Inductor | 20.4mH |
| Filter Capacitor | 5.526uF |
| Grid Side Inductor | 148.33uH |
| $R_{DampingCap}$ | 100Ω |
| Maximum Power Output | 3kW |
| Switching Frequency | 10Khz |

*Table 4-1:Filter Specification*

**Frequency Response of the LCL Filter:**

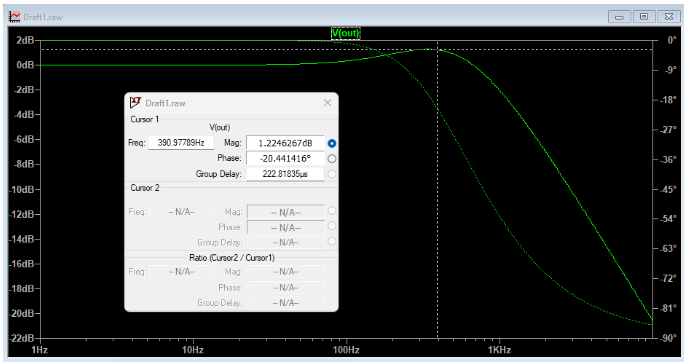



*Figure 4-1 : Filter Frequency Response*

This system is simulated within MATLAB Simulink, which the PowerGUI Block set to discrete at 50kHz sampling rate. The data shown below is from the scopes that were set up for such data collection. THD% is calculated by using the THD block connected to the Output Waveform of the Inverter Current at $L_f$, and the Real Power and Reactive Power can be calculated using the equation below:

$$P = v_d i_d \quad (17)$$
$$Q = -v_d i_q \quad (18)$$

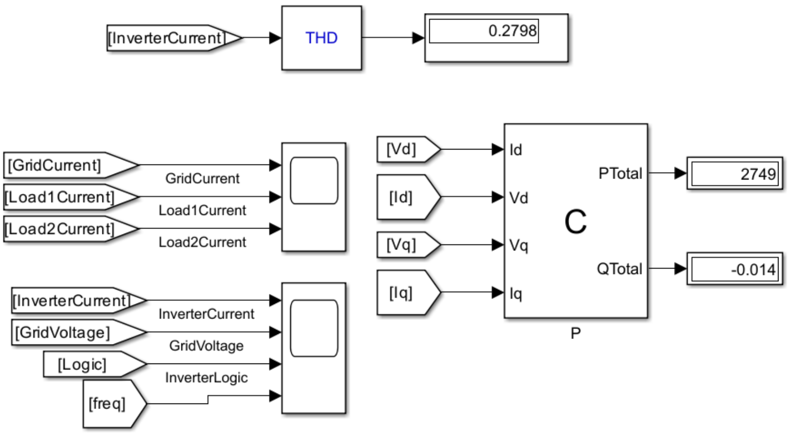



*Figure 4-2: Testing and Analysis Scope Setup*

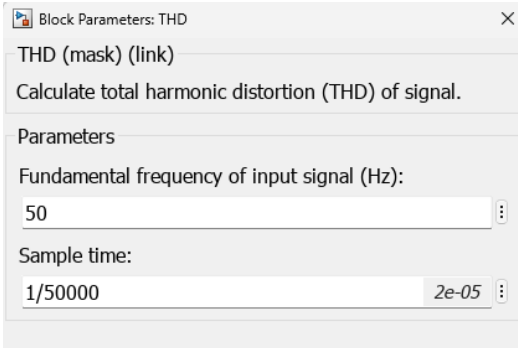



*Figure 4-3: THD% Block Setup*

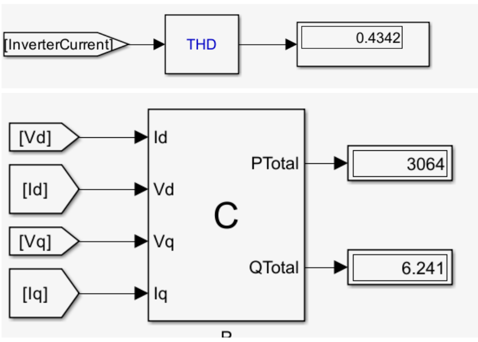
## 4.1 Power Output Response Under Different Output Reference

This test will obtain the THD% and output power of such inverter system. This test is done by injecting a direct power reference using the equation (3). The inverter will adjust the output current to match the power reference signal. The output Id and the current signal will be analyzed using a THD% calculator.

Response Under the condition (3kW, 2kW and 1kW)

<table>
<tr><th>Power Reference</th><th>Result</th></tr>
<tr><td>

$P_{target}$ =3kW



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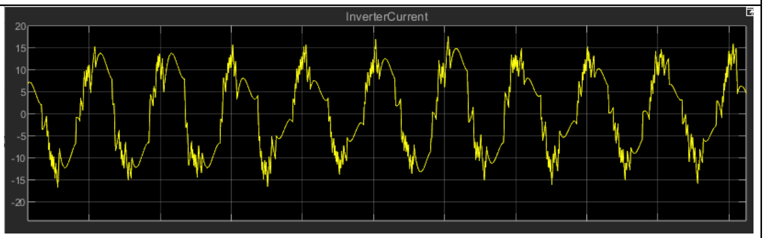
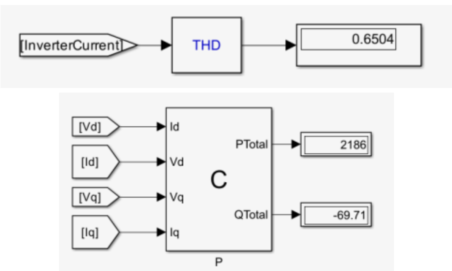


</td></tr>
<tr><td>

$P_{target}$ =2kW



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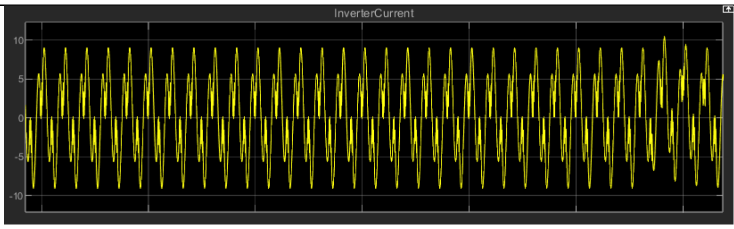
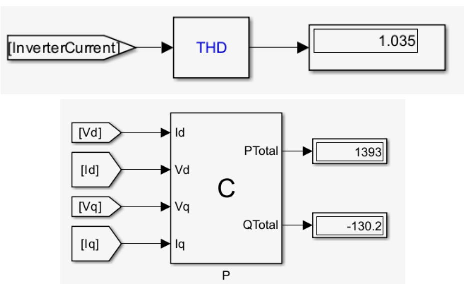
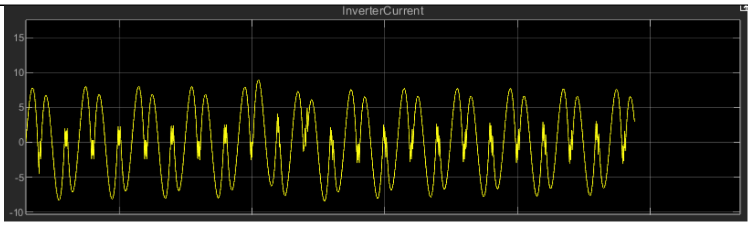


</td></tr>
<tr><td>

$P_{target}$ = 1kW



</td><td>


</td></tr>
</table>

*Table 4-2 : Response Under Different Power Target*

**Power Target vs Actual Power Value(w):**

| Power Target | Actual Power Value (W) | Error% |
|---|---|---|
| 1kW | 1393 | 39.3 |
| 2kW | 2186 | 9.3 |
| 3kW | 3064 | 2.13 |

*Table 4-3: Actual Power Value to Power Target*

**THD% under different power reference:**

| Power Target | THD% |
|---|---|
| 1kW | 1.035 |
| 2kW | 0.6504 |
| 3kW | 0.4342 |

*Table 4-4: THD% Under Different Power Reference*

## 4.2 System Direct Current Startup Transient Response using different Kp and Ki.

This test will use different Kp and Ki to test the behavior of the current controller. To evaluate the effects of Ki and Kp to wards to the transient of the Id, we will use two different scenarios which are constant Ki and constant Kp. By injecting different gains for proportional and Integral controller, we can determine the behavior. Below are the testing environment and conditions.

| Variable | Value |
|---|---|
| Target Power ($P_{Target}$) | 3kW |
| Target Reactive Power ($VAR_{target}$ ) | 0 |
| Load System | Constant 6kW /w Ideal 240$V_{RMS}$ Grid |

*Table 4-5 : Startup Transient Test Environment*

For the constant Ki, Kp that will be tested are 0.5, 2 and 5.  For the constant Kp conditions, the Ki will be set to 0.5, 2, and 5.

**Results:**

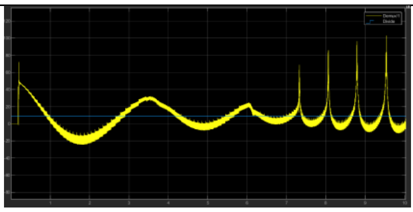
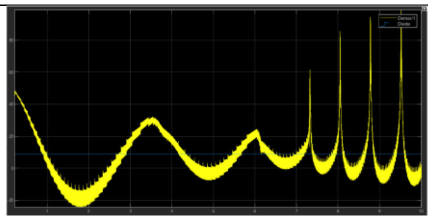
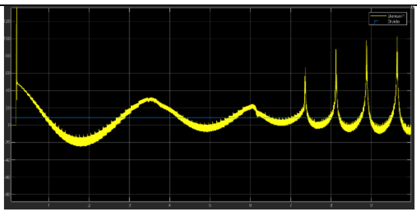
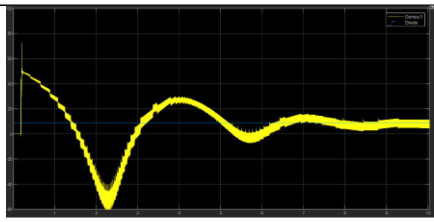
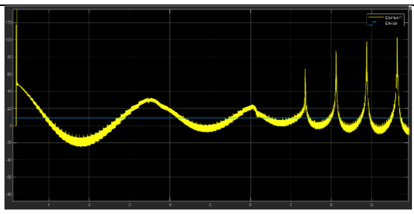
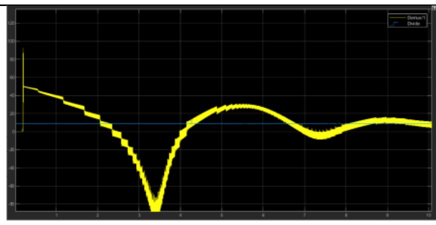
| Kp | Result ( Constant  Ki = 2) | Ki | Result ( Constant ) Kp =2 |
|---|---|---|---|
| 0.5 |  | 0.5 |  |
| Kp=2 |  | 2 |  |
| Kp=5 |  | 5 |  |

*Table 4-6 : Id Behaviour Under Different Ki and Kp*

## 4.3 Transient Response of Id for Target Power Changes

This test will see the response of the current controller on the changes of the target power. This will be done by providing different power target from 2000 to 3000. This test is done to analyze the system's ability on the change of the reference, validate the functionality of the current control logic. Below are the testing variables:

| Variable | Value |
|---|---|
| Target Power ($P_{Target}$) | 2kW to 3kW |
| Target Reactive Power ($VAR_{target}$ ) | 0 |
| System Ki and Kp | Ki=30, Kp =20 |
| Load System | Constant 6kW /w Ideal 240$V_{RMS}$ Grid |

*Table 4-7 : Testing Variables for Target Power Changes*

**System behavior:**

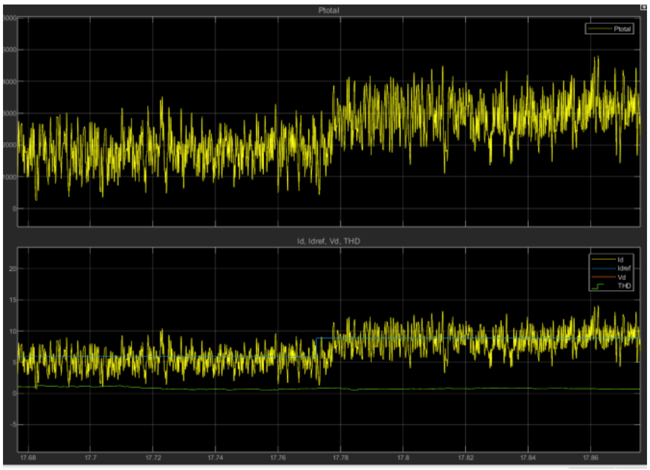



*Figure 4-4: Direct Current Response and THD to the Power Target Changes*

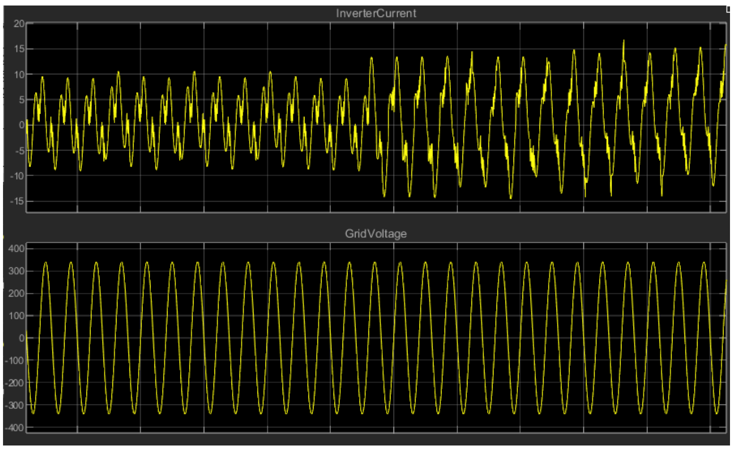



*Figure 4-5 : Inverter Current and Grid Voltage Waveform*

## 4.4 System Reference Generation using the DC Link Regulation method.

For this test, we will limit the output current of the DC link Source with a resistor. This test will determine the behavior of such DC Link regulation method towards to the Current Output. The testing environment was shown below:

| Variable | Value |
|---|---|
| DC Link Output Resistance | 10Ω |
| Target Reactive Power ($VAR_{target}$) | 0 |
| System Ki and Kp | Kp =30, Ki =20 |
| Load System | 6kW /w Ideal 240$V_{RMS}$ Grid |

*Table 4-8 : Testing Environment for DC Link Regulation Reference Method*

**System behavior:**

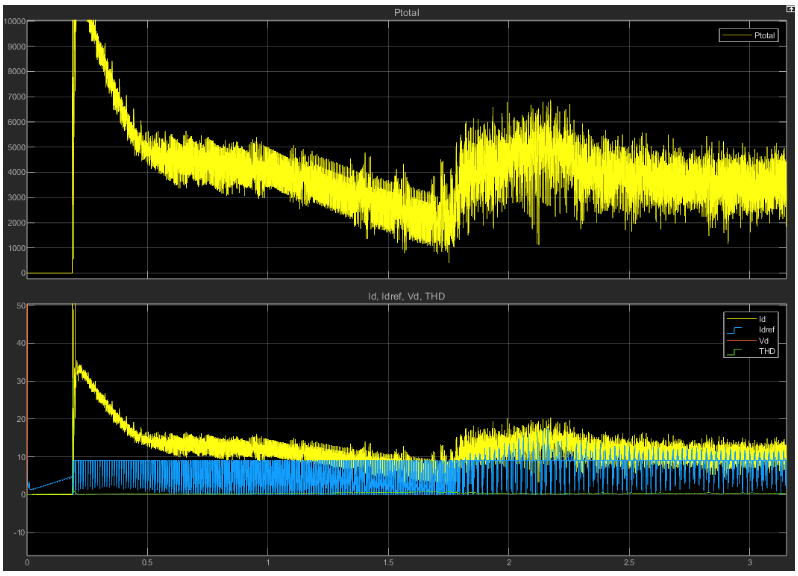



*Figure 4-6 : Reference to Id Behavior*

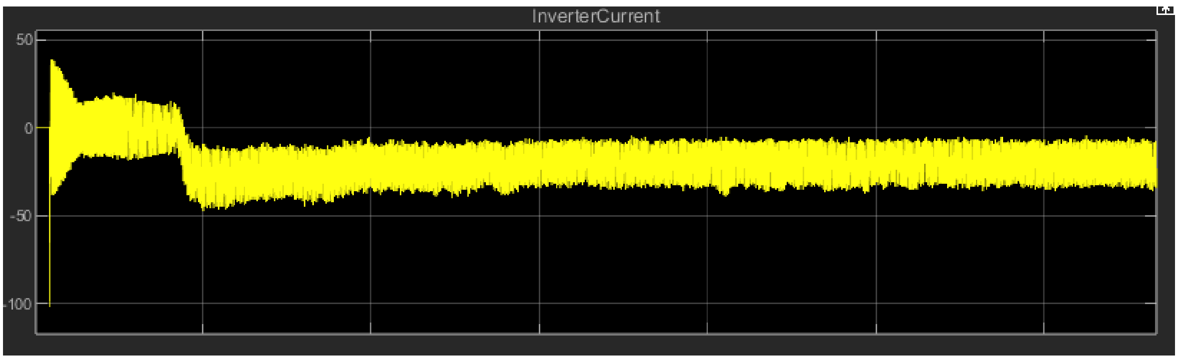



*Figure 4-7 : Output Current of the Inverter*

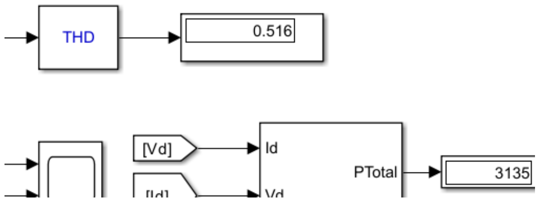



*Figure 4-8:  THD% and the Power Output*

## 4.5 Result analysis and discussion

**System Direct Current Startup Transient Response using different Kp and Ki.**

From the data, we can see that the harmonics distortion is getting lower when the $P_{target}$ is increased. Table (3) shows a significant variance in the actual power output compared to the targeted values, especially notable at the 1kW target with a high error of 39.3%. The error percentage decreases as the power target increases, with 9.3% at 2kW and a minimal error of 2.13% at 3kW. This shows that the inverter has better accuracy and stability at higher power levels.

According to the requirement of the project, we need to achieve < 5% of the THD% of the output current. From the result, all 3-testing scenarios were able to achieve such requirement, by having 1.035% at 1kW, 0.6045% at 2kW and 0.4342% at 3kW. This THD% performance behavior is identical to the output power error, which the 1kW will have the lower accuracy than rest of the testing conditions.

The high error at lower power could indicate inefficiencies or control system inadequacies at lower operating points. By Looking at the Id for both 1kW at Figure (4-9) and 3kW case at Figure (4-10), we can know that the waveform at 1kW and 3kW shows a noisy signal, indicating high error on current control. As the 3kW system had a much higher floor for the noise, which aligns with the higher THD and larger error in power output at this level. This supports the quantitative findings of lower THD and error percentage at higher power outputs.

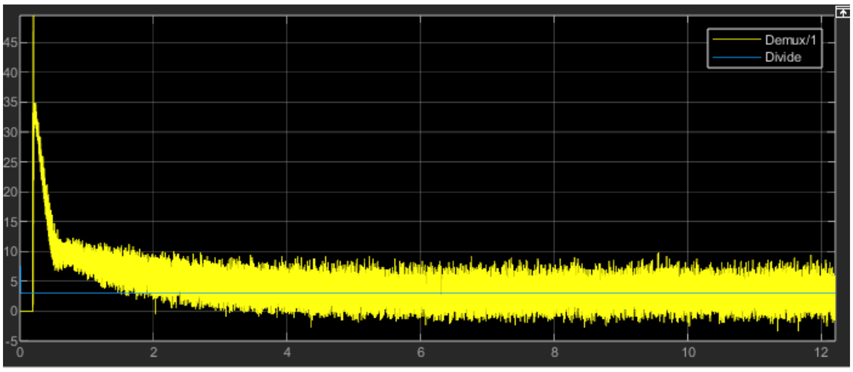



*Figure 4-9: Id vs Reference ID at 1kW Reference.*

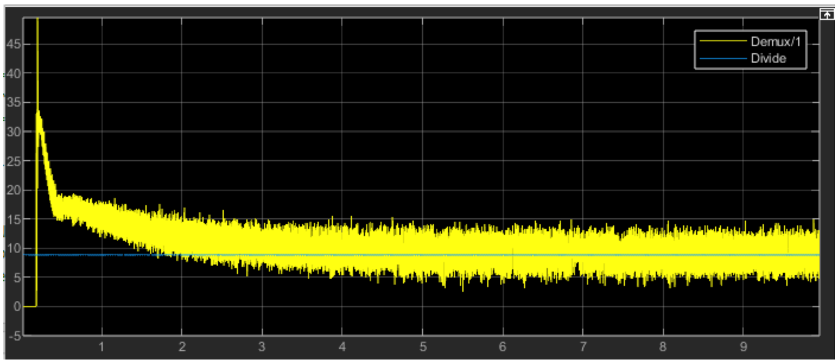



*Figure 4-10: Id vs Reference Id at 3kW Reference.*

The inaccuracies had been caused by the noise that exists in the system. Which indicates the system is prone to noise and causes a high error at low level. By looking at the zoomed in reading of the Id, we can see the output is contaminated with noise.

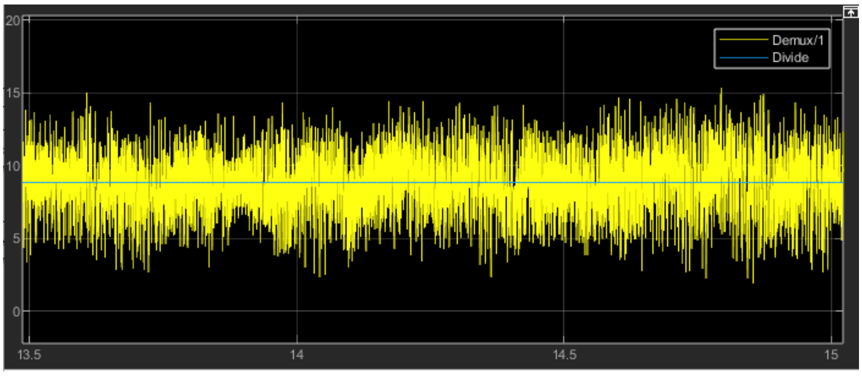



*Figure 4-11 : Zoomed in Waveform of the Id vs Id**

**System Direct Current Startup Transient Response using different Kp and Ki.**

From the response given at Table (4-6), we can see that the Constant Ki test System behavior is prone to been disturbed by the noise same as the previous test. The system will spike at the point where the system is at steady state. This had been caused by the constant gain of the system, responding to noise or fluctuation. By Looking at the response of the Constant Kp Test, we can see that the increase of the Ki will improve the system stability by increasing the damping ratio of the system, but the system will reach steady state much slower at high Ki. Comparing both scenarios, this system needs a higher Ki to achieve stability. This also can be improved by implementing limits to the system as shown in Figure (4-12) The controller is more stable when implemented with limits to prevent sudden overshot caused by the noise. As this system no do have an adaptive gain adjustment based on the situation, adding limits to the output will improve the performance of the system. Anti-windup also should be implemented in this case to further improve the system by avoiding windup in the Integrator, causing unexpected behavior from the controller.

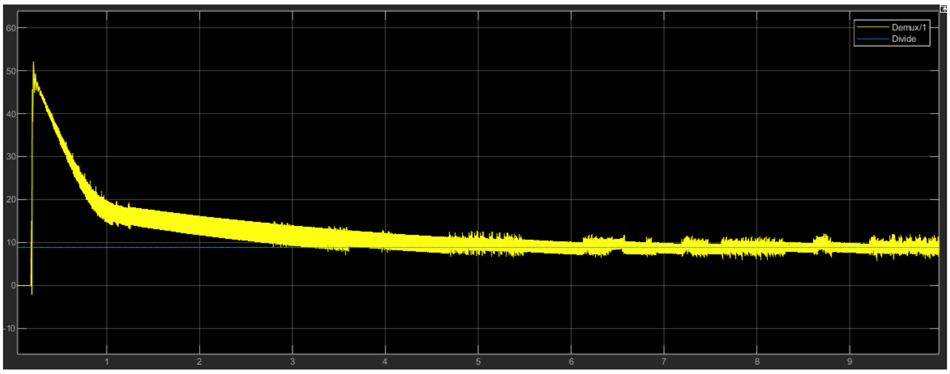



*Figure 4-12: Output Response with Limit on PI controller.*

Still, in the future development, a systematic and robust tuning procedure using root locus and other non-linear control will be required to achieve fast and robust tuning to reach system requirements.

**Transient Response of Id for Target Power Changes**

From Figure (4-4), we can see that the $I_d$ of the system does changes with the change of the power target. From Figure (4-5), we can clear see that the overall $P_{total}$ had been lifted when the reference was changed. The output current from the inverter does also increase in the amplitude of the output while the Grid Voltage remains at 340V, which we can observe when we look at the scope of the $V_d$.

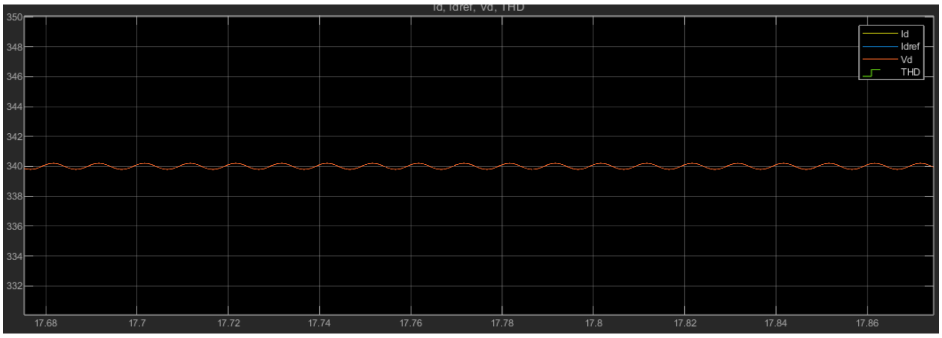



*Figure 4-13: Vd Reading for the During Target Power Changes*

This shows that the system can control the injected active power according to the current reference. From the current waveform, we can also see that output current from the inverter also increased when the reference direct current (Id*) changes. The Current waveform still has severe distortion for both target power. The THD% after target power changes had remains around <1%.

**System Reference Generation using the DC Link Regulation method.**

For the DC Link Regulation Reference Generation, we can see that the system is able to generate reference to allow power injection to the grid, but from Figure (4-7), we can see that the waveform suddenly shifted and having negative DC offset, causing system is not having the median at 0V. Still, the system can inject power at the correct maximum output of 3kW and the THD% is under 5%. Compared to the Power target reference method shown in the previous test, this system is not able to inject proper power into the grid as it consists of negative DC Components which is not allowed.

This system is also suffered by the high noise level which also plagued all others testing scenario. From figure (4-6), we can see that the reference had dips as low as 0, which will affect the system as the Current reference output for reference current generation, $E_d$* is based on the Id from the PI controller.

# Chapter V: Conclusion and Future Recommendations

From the result shown above, we can see that the system is able to inject different power levels according to the power target. Changes of different gain values on the PI controller and adding anti-windup with limits also show the change of behavior of the system. From the result, we also validate that our system can react to the changes of the power target using the Power Target Reference. For the DC Link Regulation method, there are some DC components that exist inside the system which are not permitted and require changes in the future. This shows that such regulation method still requires further development and validation to be fully functional   All the test scenarios can be achieved <5% harmonics distortion.

This paper is to provide a foundation to allow for future development, and which from the result is not yet perfect and functional. This system is suffering from high noise and lacks critical functions such as droop control, adaptive gain adjustment and limits. New reference generation is also introduced in this model, but the performance still requires extensive makeover to be usable in real-life environment. Due to the size of the system and lack of development time, this system also uses an Ideal Grid instead of a microgrid. Power Injection point of the inverter system is also introduced in this case. To further improve the model, this will be a continuing project in the future, here are some proposed future development and improvement.

## 5.2 Proposed Future Development Improvements

**Noise Filtering and Harmonics Compensation**

As in the Result and analysis, the system suffers from high frequency noise. To compensate for this, harmonics filtering, and compensation is necessary. Moving Average and other types of discrete filter can be implemented to improve the harmonics performance of the system.

**Microgrid modeling for system validation.**

Due to time constraints, this model only uses an ideal grid with constant load for testing. In real-life applications, Microgrid is more likely to be the case. In future, a microgrid model should be implemented to better simulate the usage of such PV inverters, allowing for better validation for performance and safety of such systems.

**Control System and safety system Development.**

As this is a foundation of an Inverter system modeling, there are a lot of systems such as Droop control and Islanding Protection are required to such inverter system. Droop control is an essential mechanism in power system management, primarily used to maintain stability and facilitate load distribution among multiple power sources, such as in microgrid applications or systems with several generators. The method is based on a deliberate reduction of output frequency or voltage as the power output increases, following a predefined droop characteristic. This approach, which mimics the natural behavior of traditional synchronous generators, is valued for its simplicity, autonomy, and robustness, as it does not require complex control systems or inter-generator communication. It is particularly advantageous in decentralized systems such as microgrids, enhancing the integration of renewable energy sources and improving overall reliability by allowing dynamic and autonomous load sharing.

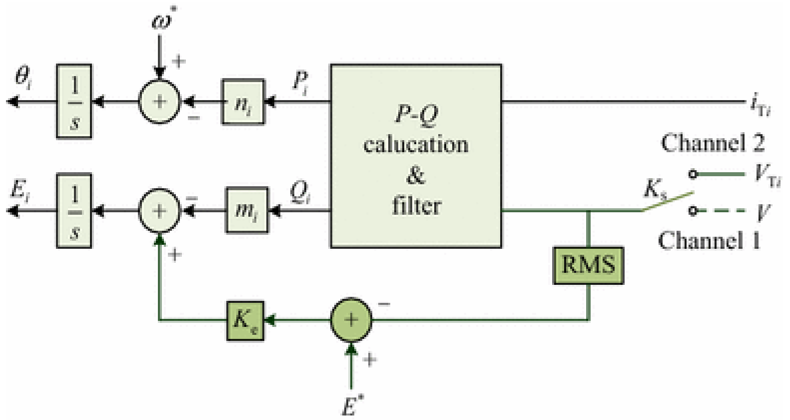



*Figure 5-1: Robust droop control for high voltage microgrid*

Islanding detection is a critical safety and operational mechanism in the context of grid-tied renewable energy systems, particularly solar photovoltaic (PV) systems and microgrids. When a power outage occurs in the main utility grid, islanding detection systems are responsible for quickly identifying whether a distributed generator, such as a solar inverter, continues to supply power to a local area, effectively forming an “island” of electricity. The main purpose of islanding detection is to prevent unintended operation of a grid-connected system in an islanded mode, which can pose serious safety risks for utility personnel during maintenance, potentially disrupt grid integrity, and affect power quality.

**Completion of the Three Phase Inverter System**

As the final target is to enable the system to be capable of three phase power injection, the completion of three phase power system is the final goal of the model along with others system mentioned before. To achieve this, negative sequence extraction and compensation is vital as typical microgrid will be imbalance in nature. DDSRF (Double Decoupled Synchronous Reference Frame) Control can be used to extract and control such systems as it also regulates the negative sequence of the three phase power instead of positive sequence only in SRF Control.

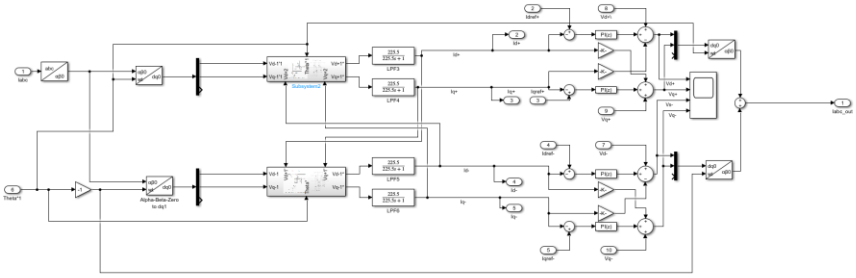


*Figure 5-2: Complete DDSRF Controller*

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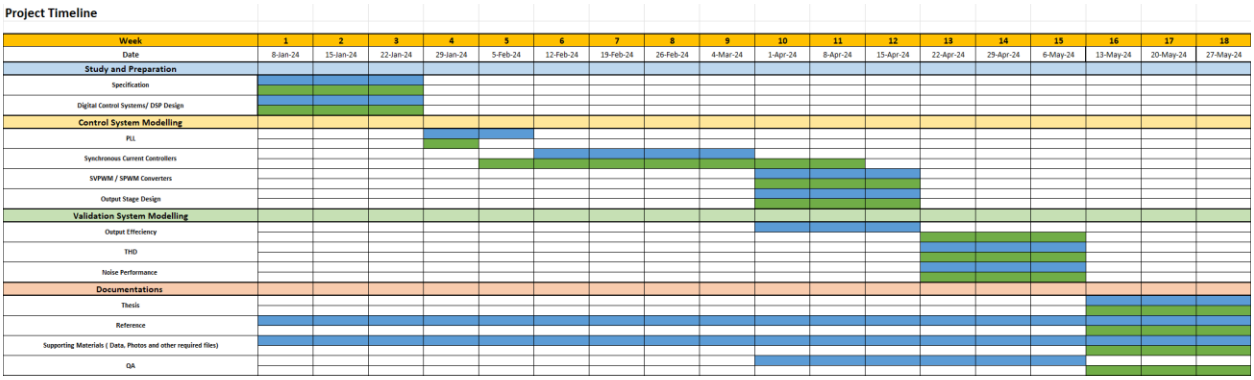
# Appendix

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