Development of a modified Kundur two area system with Solar PV farm for Typhoon HIL simulation

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Abstract

In this project, we aim to innovatively redesign and simulate the Kundur two-area test system, a model in power systems engineering, by integrating a solar PV farm in place of one of its conventional generators. This novel approach addresses a critical aspect of modern power systems: the incorporation of renewable energy sources and its impact on system dynamics and stability. By replacing a traditional generator with a solar PV farm, the project not only transitions towards sustainable energy but also provides a unique opportunity to study the effects of such integration on power system behavior.

This research is particularly relevant in the context of the global shift towards renewable energy sources. As the world increasingly adopts solar power, understanding its implications on the stability and reliability of power systems becomes imperative. This project, therefore, serves not only as an academic and technical exploration but also as a practical guide for future power system designs and modifications.

Furthermore, the project aims to highlight the potential challenges and solutions to integrating renewable energy sources into existing power grids. This includes addressing issues related to grid compliance, power quality, and the management of variable energy outputs. The findings from this project are expected to contribute valuable insights into the design and operation of future power systems that are more environmentally sustainable, efficient, and resilient.

This project stands at the intersection of traditional power system engineering and the evolving field of renewable energy. It aims to provide a comprehensive understanding of the dynamics of integrating solar PV into a conventional power system, using advanced simulation tools to predict and analyze system behavior under various conditions. The outcomes of this project are anticipated to have significant implications for the design and stability of future power systems, paving the way for a more sustainable energy landscape.

The utilization of Typhoon HIL's advanced hardware-in-the-loop (HIL) simulation environment is a cornerstone of this project. This technology allows for an accurate and detailed analysis of the system's dynamic responses to various operational scenarios. In particular, the project focuses on key areas like power interchange, which involves the exchange of electrical power between regions or systems; oscillation damping, which is crucial for maintaining system stability by mitigating fluctuations in power output;

and overall system reliability, an essential factor considering the variable nature of solar power.

Chapter 1

VOLTAGE SOURCE CONVERTER MODEL (VSC)

Voltage Source Converters (VSC) are a pivotal technology in the field of power electronics, enabling the efficient conversion between alternating current (AC) and direct current (DC) in a variety of applications, particularly in high-voltage direct current (HVDC) transmission systems. Their ability to manage active and reactive power independently makes them integral to modern electric grids, enhancing stability, and facilitating the integration of renewable energy sources. VSCs are comprised of semiconductor devices, usually Insulated Gate Bipolar Transistors (IGBTs) or similar, which can be switched on and off at high frequencies to control the direction and flow of electrical power. In contrast to Line Commutated Converters (LCC), VSCs do not require a strong AC system for commutation and are capable of generating an almost perfect sinusoidal AC voltage from a DC power source.

1.1 Applications of VSC in Power Systems

VSCs are utilized in various power system applications, including but not limited to:

1. HVDC Transmission: For long-distance power transmission with low losses and controlled power flows.

2. Renewable Energy Integration: To connect renewable energy sources with variable output, such as wind or solar, to the grid with the capability to control power quality.

3. Grid Stability and Support: Offering services like voltage regulation, frequency control, and reactive power support to maintain grid stability.

4. Microgrids and Remote Areas: Enabling reliable power supply in isolated regions and microgrids where grid stability is essential.

1.2 Average Models of a Voltage source converters

Average models, often used in simulations, represent the mean behavior of a system over time, abstracting the details of switching actions in power electronic converters. For a VSC, the fast-switching actions of devices like IGBTs or MOSFETs are replaced by their average effect over one or several switching periods. This simplification is particularly useful for studying the system's dynamics over longer periods where the switching details are less relevant compared to the overall system behavior. The key advantage of using average models in simulations is the reduction in computational complexity and simulation time. This is because the model does not need to compute the state of the system at each switching event, which can occur thousands of times per second. This model does not account for any losses, although is possible to add them. The active power equilibrium is ensured , which states that the DC power and active AC power must be always equal. $PDC = PAC$

1.3 SCHEMATIC REPRESENTATION OF THE AVERAGE MODEL

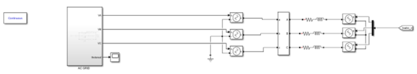

FIGURE 1.1: MATLAB SIMULATION OF AVERAGE MODEL VSC

1.4 AC Grid Block

This block serves as the AC voltage source for the converter. Within the average model, the sinusoidal AC source is typically not influenced by switching actions, and its parameters define the grid voltage level and frequency. For the VSC in question, these parameters include a nominal AC voltage (Ucn) of 690 volts and a nominal frequency (fg) of 50Hz, which are typical for many grid-connected systems. These values remain constant or follow a predetermined variation over time to simulate different grid conditions.

1.5 VSC Block

The average model of a VSC captures the essential function of converting between AC and DC. Instead of modeling each switch, it uses a mathematical representation, like a controlled voltage or current source whose output is based on the average value expected from the real switching devices. Control inputs for this block include reference voltages or currents, which are derived from the control strategy implementing, for example, a PID controller or a more complex algorithm like Model Predictive Control.

1.6 Inductors and Filters

In a typical two-level VSC setup, inductors act like buffers that smooth out any sudden changes in the current, ensuring a steady and clean flow of electricity. They're a bit like the shock absorbers in a car, helping to provide a smooth ride by ironing out the bumps. In our model, these inductors are imagined as perfect components that perform this smoothing job without adding any complications. They have a value of 30.31 microhenries (µH), which is a measure of their ability to manage these current changes and keep the electricity flowing smoothly.

1.7 Control Systems

Control systems are the brain of the Voltage Source Converters, tasked with ensuring that the conversion from AC to DC and back again happens smoothly, matching the precise electricity shapes needed. These systems are smart, set up to quickly adapt to what's happening on the power grid at any moment. They can handle unexpected events without interrupting power and actively manage the balance of power to keep everything running efficiently. In simulations using average models, these control systems are represented by algorithms that mimic these real-time adjustments without getting into the nitty-gritty of every single switch flip inside the converters

1.8 Measurement Blocks

In the configuration of Voltage Source Converters, measurement blocks serve a dual purpose. Not only do they monitor the current flowing through each phase, indicated by the current (i) symbols, but they also keep tabs on the voltage levels. This dual-functionality is crucial for the feedback control mechanisms of the VSC. By tracking both current and voltage in real time, these blocks provide the detailed electrical information necessary for the control systems to fine-tune the converter's operations, ensuring that both voltage and current waveforms are precisely regulated for stable and efficient system performance.

Chapter 2

VOLTAGE SOURCE CONVERTER CONTROL

Voltage Source Converter (VSC) control is essential for the operation of modern electric power systems, especially those incorporating HVDC transmission and renewable energy sources. The control system in a VSC is responsible for managing the power conversion from DC to AC and vice versa, while ensuring that the conversion process is efficient, stable, and meets the quality standards of the electrical grid.

The main objectives of VSC control include:

1. Synchronization: VSC control ensures that the output frequency and phase match the AC grid, which is crucial for the integration of the converter with the power system.
2. Efficiency: Advanced control strategies optimize the switching of power electronic devices to minimize losses and improve the overall efficiency of power transmission.
3. Grid Stability and Support: Offering services like voltage regulation, frequency control, and reactive power support to maintain grid stability.
4. Renewable Integration: VSC control is integral to the integration of intermittent renewable energy sources, helping to balance supply and demand effectively.
5. Renewable Integration: VSC control is integral to the integration of intermittent renewable energy sources, helping to balance supply and demand effectively.
6. Fault Management: Control systems can rapidly detect and respond to grid disturbances, protecting the converter and maintaining grid reliability

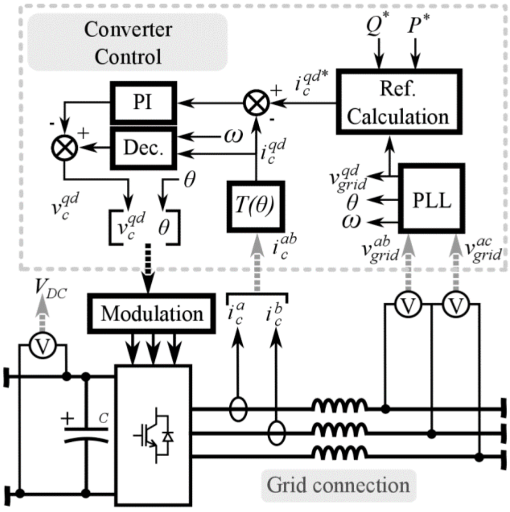

FIGURE 2.1: Enter Caption

2.1 The control block diagram of a common control strategy for a Voltage Source Converter (VSC) in power systems include the following :

1. Converter Control Block: This is the central hub for the control system of the VSC. It interprets the reference signals for active power (P*) and reactive power (Q*) and adjusts the converter's output to match these references.

2. Reference Calculation: This module computes the desired current components in a synchronous reference frame (dq-frame) based on the power references. It essentially translates the power commands into current commands that the converter can follow.

3. Reference Calculation: This module computes the desired current components in a synchronous reference frame (dq-frame) based on the power references. It essentially translates the power commands into current commands that the converter can follow.

4. Decoupling (Dec.): This component accounts for the coupling between the d and q axes in the AC system due to inductance and the changing magnetic field. Decoupling ensures accurate control of the VSC.

5. Transformation Block (T(theta)): This block applies the Park transformation to convert the control signals between the synchronous dq-frame and the stationary abc-frame, aligning them with the grid's phases.

6. Modulation: The modulation block takes the voltage commands from the control system and modulates them to generate the gating signals for the power electronic

switches in the converter. This typically involves pulse-width modulation (PWM) techniques.

7. DC Voltage Source: This represents the DC side of the VSC, providing the power to be converted. It's typically connected to an energy storage system, a DC transmission line, or a renewable energy source.

8. Grid Connection: This is where the VSC interfaces with the AC grid. The VSC injects or absorbs power through this connection, fulfilling its role in power conversion and grid support functions.

9. Voltage and Current Measurement: These measurement devices (represented by the V and I symbols) monitor the grid voltages (v_{grid}^{ac}, v_{grid}^{ab}) and currents (i_c^a, i_c^b) to provide feedback to the control system for real-time adjustments.

2.2 PHASE LOCKED LOOP

The Phase-Locked Loop (PLL) is a crucial component in the control system of a VSC. In an average model, which simplifies the power electronics by abstracting away the high-frequency switching actions, the PLL still plays a critical role in synchronizing the converter's output with the grid. The PLL works by taking the AC voltage input, often in three-phase form (Vabc), and transforming it into a two-phase orthogonal representation (dq-frame) using the Park Transformation. Once in the dq-frame, the PLL locks onto the phase of the grid voltage by adjusting its internal oscillator to match the grid's frequency and phase. The PLL's output includes the grid's angular frequency $\omega(g)$ and the angle θ. These are fed into the control system of the VSC to ensure that the power conversion aligns with the grid's voltage waveform, in terms of both frequency and phase.

In an average VSC model, the PLL allows the control system to generate the appropriate commands for the voltage source, ensuring that the VSC can properly inject or absorb power from the grid in a manner that supports the grid's stability and power quality.

The Phase-Locked Loop PLL takes in the grid voltages, denoted by Vzabc, and processes them to provide the grid's phase angle, θ, as its output. the PLL's role extends beyond just aligning the qd reference frame; it also guarantees that the Vd component is zero. This permits the discrete management of active power P through the iq component and reactive power Q through the id component, thereby streamlining the overall control strategy.

$$K_f(s) = G_c(s) = \frac{K_p s + K_i}{s}$$

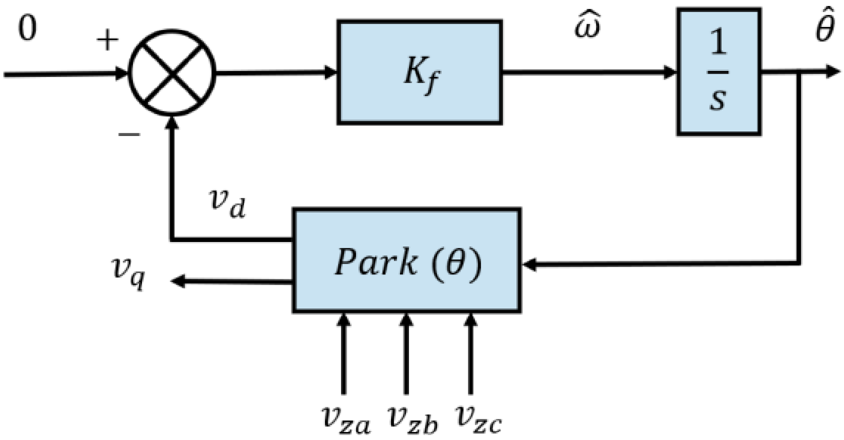

FIGURE 2.2: PLL implementation structure

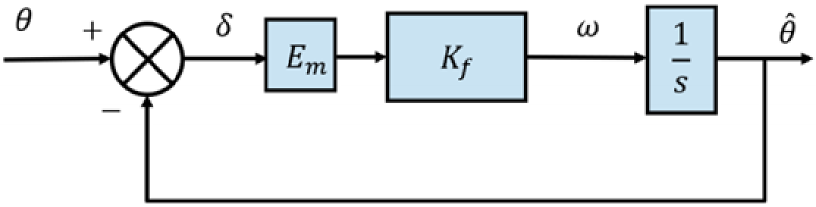

FIGURE 2.3: PLL design structure

2.2.1 In the given parameters for a Phase-Locked Loop (PLL) used in an engineering application:

1. xi_pll: represents the damping ratio, set here to $\frac{\sqrt{2}}{2}$. It's a unitless value that affects how quickly and smoothly the PLL can lock onto the grid frequency.

2. '$omega_pll$': is the natural frequency of the PLL in radians per second, calculated here as 2π times the grid frequency (50 Hz in this case), which is standard for many power systems.

3. 'kp_pll': (the proportional gain) is determined by the product of the damping ratio, twice the natural frequency, and the reciprocal of the peak AC voltage. This gain influences the responsiveness of the PLL to phase errors.

4. 'tau_pll': is the time constant for the PLL, computed as twice the damping ratio divided by the natural frequency. It's related to how fast the PLL responds to changes in the input signal.

5. 'ki_pll': (the integral gain) is derived from the proportional gain divided by the time constant, shaping how the PLL eliminates the steady-state error over time.

2.2.2 PARK TRANSFORMATION

Park transformations play a pivotal role in the management of Voltage Source Converters (VSCs). Even though control can technically be executed in the abc or $\alpha\beta$ frames following the Clarke transformation, the qd frame is preferred for its simplicity and familiarity. The qd frame transforms the multi-dimensional system into one where only a single constant magnitude needs to be managed, facilitating the application of traditional control techniques and widely-understood control frameworks.

In the context of VSC control, three key transformations are involved:

1. The grid voltage is shifted from the abc frame to the qd frame, which is then utilized by the PLL to synchronize the converter's output with the grid.
2. current flowing to or from the grid is also converted from the abc to the qd frame. This transformation is essential for nearly all control elements within the VSC structure, as it allows for the streamlined control of power delivery and quality.

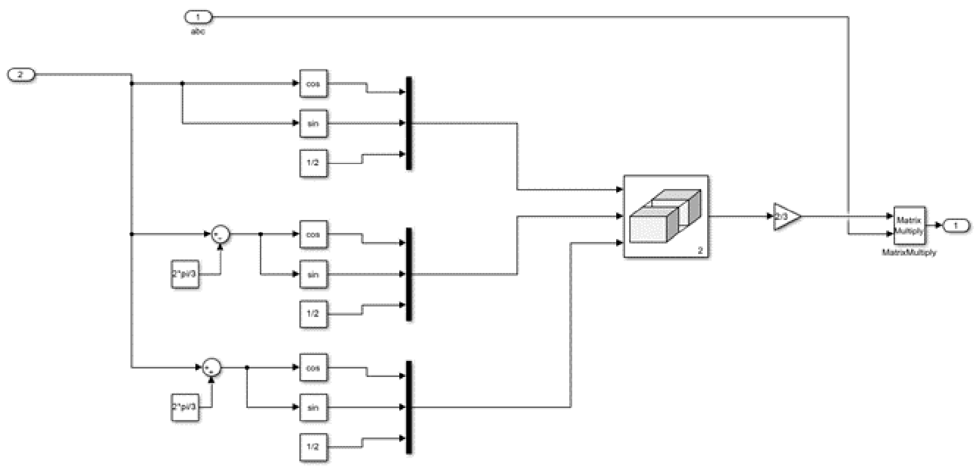

FIGURE 2.4: PARK TRANSFORMATION IN SIMULINK

The angular velocity graph of the PLL initially shows a stable state before a transient response occurs, the PLL is trying to align with the input signal's phase and frequency. The graph then enters an oscillatory phase, with the angular velocity fluctuating as the system overshoots and undershoots while attempting to lock on to the input frequency. This behavior is likely influenced by the loop's proportional and integral gains. Eventually, the PLL appears to stabilize, indicating that it has locked onto the input signal frequency. The steady-state angular velocity reached by the PLL can be expressed as $2*pi*fg$, where fg is the grid frequency of $50hz$. Thus, the steady-state angular velocity value that the PLL is aiming to achieve is a 314.16 rad/s.

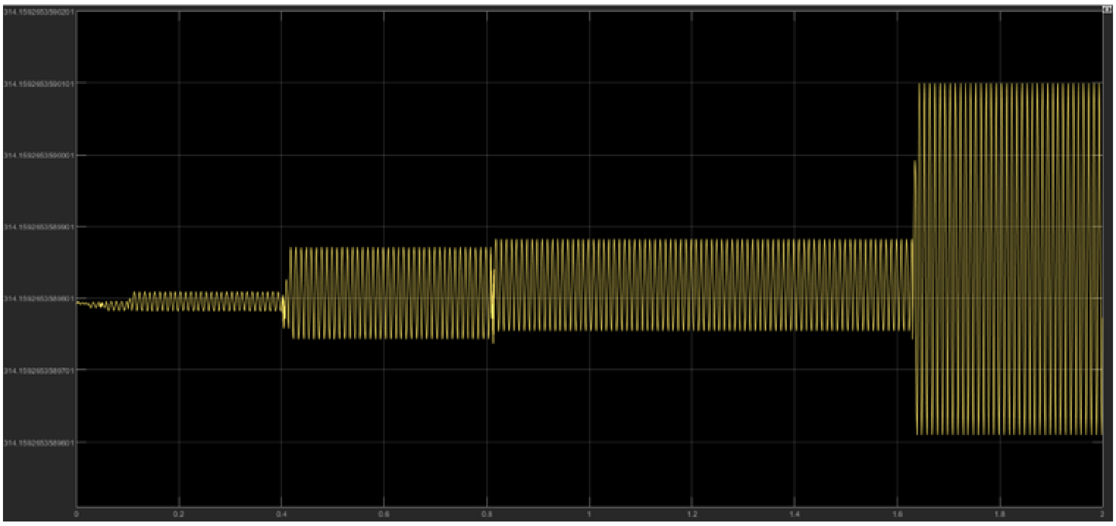

FIGURE 2.5: ANGULAR VELOCITY OF THE PLL

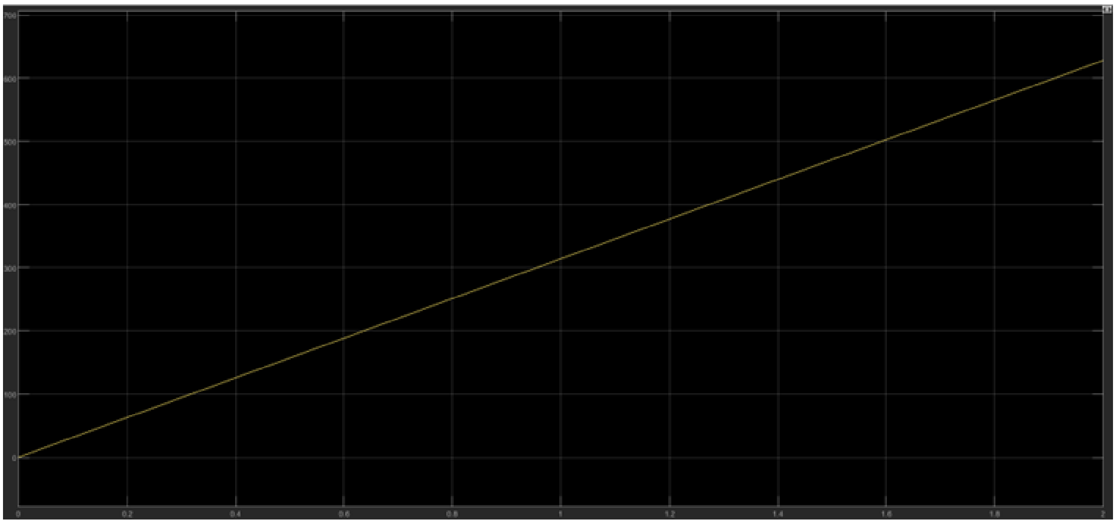

FIGURE 2.6: PLL ANGLE

The graph depicted that the Phase-Locked Loop (PLL) angle shows a linear increase over time, which signifies a constant angular velocity and thus stable operation of the PLL. This steady slope indicates that the PLL has locked onto the target frequency and is maintaining synchronization without any phase errors or corrections. The lack of fluctuations or transients shows that the graph captures the behavior after initial locking has occurred. Given a grid frequency of 50 Hz, the PLL's angle increases at a rate determined by the angular frequency.

2.3 CURRENT LOOP CONTROL

The current loop is a critical component in the control of Voltage Source Converters (VSC). It's designed to manage the flow of current from the converter to the electrical grid. Among the various strategies used to control this current, the one that is most widely adopted operates on the principle of the synchronous reference frame. This

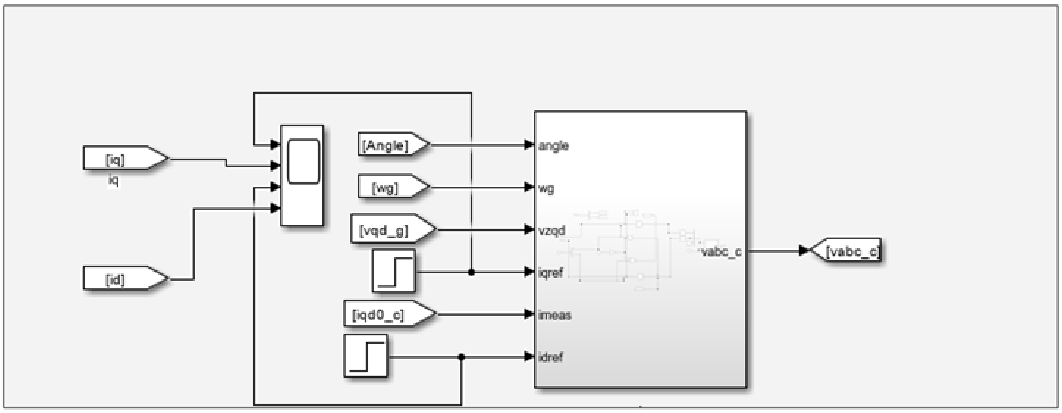

FIGURE 2.7: CURRENT CONTROL LOOP

method focuses on the independent regulation of q and d components of the current, which correspond to active and reactive power, respectively. A well-executed design of this control scheme can set the dynamic response rate of the control loop, ultimately influencing the converter's behaviour at fundamental levels. This helps ensure that the power delivery can be finely tuned to provide a balance between efficiency and performance.

The system equation :

$$\begin{bmatrix} v_{za} \\ v_{zb} \\ v_{zc} \end{bmatrix} - \begin{bmatrix} v_{ua} \\ v_{ub} \\ v_{uc} \end{bmatrix} - (v_{o1} - v_{o2}) \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} r_i & 0 & 0 \\ 0 & r_i & 0 \\ 0 & 0 & r_i \end{bmatrix} \begin{bmatrix} \dot{i}_a \\ \dot{i}_b \\ \dot{i}_c \end{bmatrix} + \begin{bmatrix} l_i & 0 & 0 \\ 0 & l_i & 0 \\ 0 & 0 & l_i \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}$$

In compact form (without neutral):

$$v_{abc} - v_{labc} = \begin{bmatrix} r_l & 0 & 0 \\ 0 & r_l & 0 \\ 0 & 0 & r_l \end{bmatrix} i_{abc} + \begin{bmatrix} l_l & 0 & 0 \\ 0 & l_l & 0 \\ 0 & 0 & l_l \end{bmatrix} \frac{d}{dt} i_{abc}$$

The decoupling loop can be defined by:

$$\begin{bmatrix} v_q \\ v_d \end{bmatrix} = \begin{bmatrix} -\dot{v}_q + v_{zq} - l\omega_e i_d \\ -\dot{v}_d + l\omega_e i_q \end{bmatrix}$$

Which leads to a completely decoupled system, in which it can be controlled:

1. Current in the q-axis with the q-axis voltage
2. Current in the d-axis with the d-axis voltage

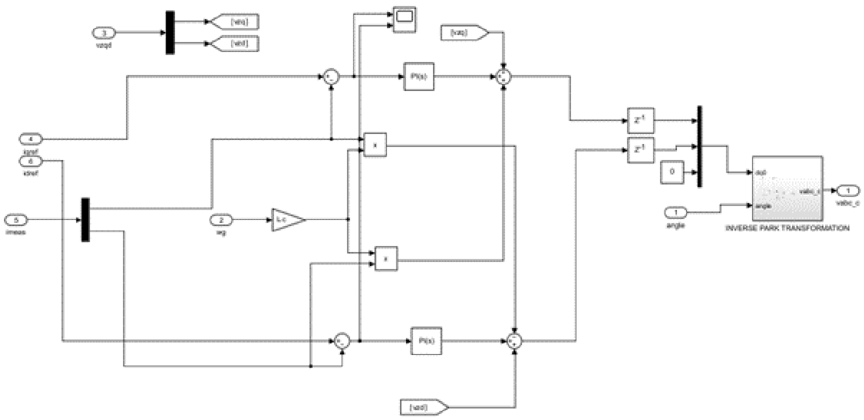

FIGURE 2.8: INTERNAL STRUCTURE OF CURRENT LOOP CONTROL SUB-SYSTEM

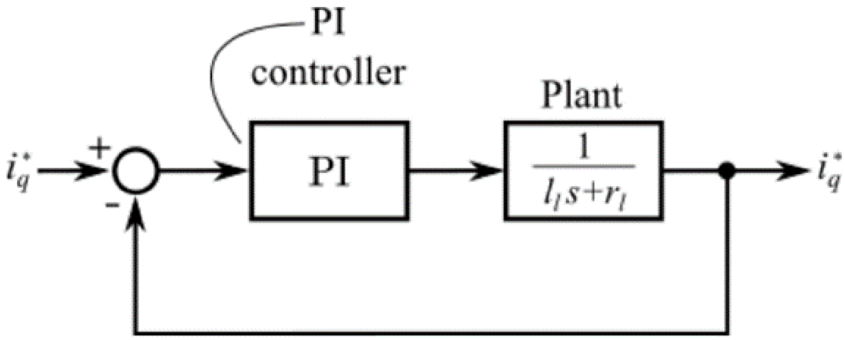

FIGURE 2.9: CURRENT LOOP DESIGN STRUCTURE

$$K(s) = \frac{K_p s + K_i}{s}$$

$$K_p = \frac{l}{\tau}$$

$$K_i = \frac{r_l}{\tau}$$

The graph indicates a transient error at the beginning of the simulation, which is a common occurrence when the system is responding to initial conditions or a step change in the reference signal. The swift reduction to zero signifies that the control system, specifically the PI controller that follows this measurement point, is responding appropriately to correct the error. The quick convergence to zero and the maintenance of this value suggest the PI controller downstream is effectively bringing the system into the desired state and regulating the current as intended. This performance indicates a

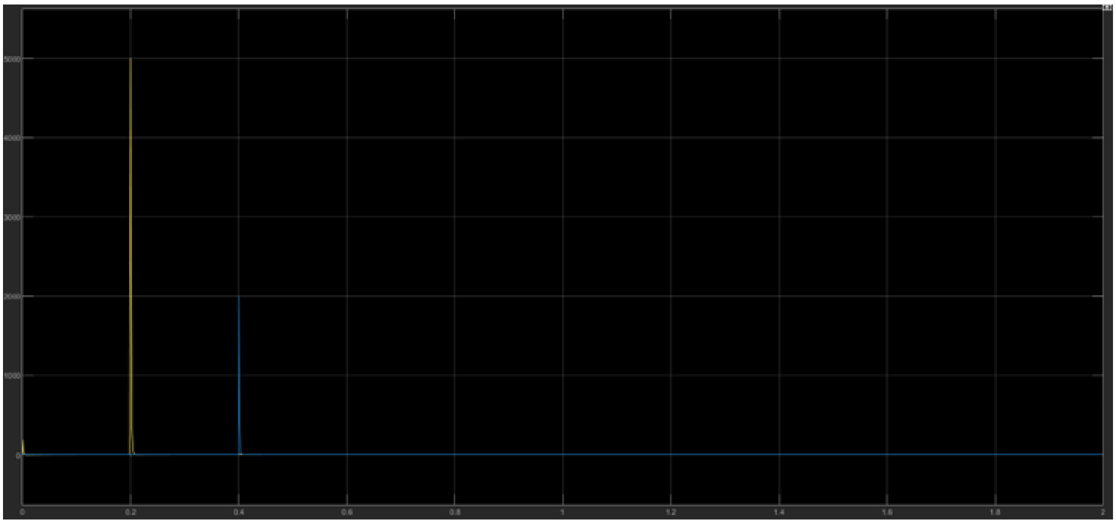

Figure 2.10: Transient Response and Stabilization of Current Control Loop Before PI Controller

properly functioning current control loop, where the PI controller compensates for the initial discrepancy, resulting in a stable process control.

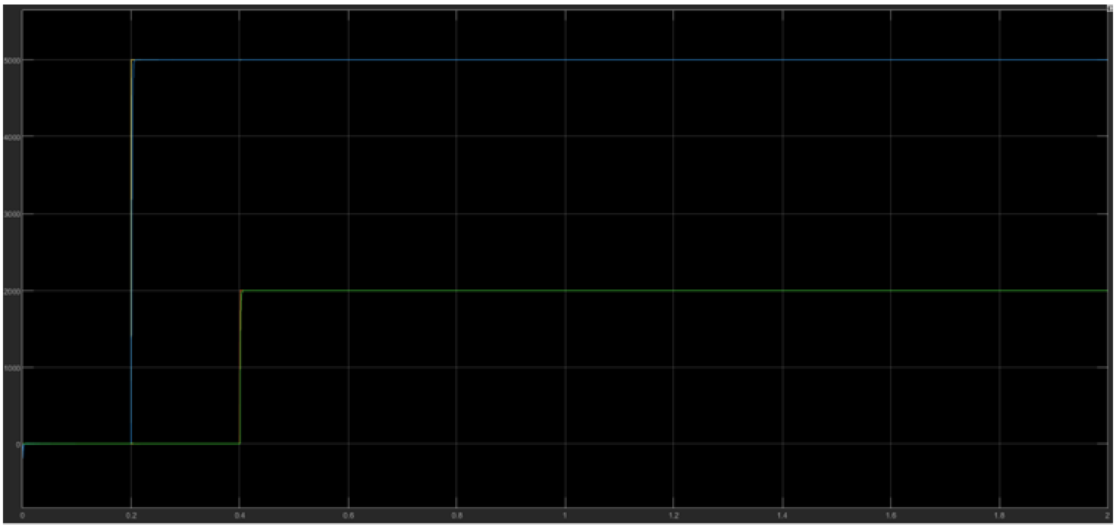

Figure 2.11: CURRENT LOOP SHOWING Iq ,Id ,Iqref and Idref

The graph shows the performance of a current control loop, specifically for the iq (quadrature-axis current) and id (direct-axis current) components in relation to their respective reference values, iqref and idref. In the upper plot, representing the iq and iqref, the current iq closely follows iqref, showing that the control loop is effectively managing the quadrature-axis current to align with the reference. This indicates robust control dynamics, as the actual current swiftly reaches and maintains the reference value without significant overshoot or oscillation. The lower plot shows id in relation to idref. The near-perfect overlap of the id current with its reference idref demonstrates the control system's precision in maintaining the direct-axis current at the desired level.

This is indicative of a well-tuned controller that ensures the direct-axis current component remains stable and at the setpoint, which is critical for optimal performance of the system the controller is part of. The model was checked

2.4 POWER LOOP

In the domain of Voltage Source Converters (VSC), the significance of power references, namely active (P*) and reactive (Q*) power, is paramount for the computation of reference currents on the q-axis (iq) and d-axis (id). The conversion process of these power commands into their respective current references, highlighting the role of the q-axis grid voltage(vq) in these calculations, especially under the condition where the d-axis voltage (vd) is zero.

2.5 Tie-Line Bias Control and Oscillations with Variable Generation in a Two-Area Power System

The research outlined in the paper titled "Tie-Line Bias Control and Oscillations with Variable Generation in a Two-Area Power System" enhances our understanding of tie-line bias control and oscillations in a two-area power system, particularly in the presence of variable generation sources. This study specifically tackles the ever-changing difficulties presented by fluctuating power generation, which is a relevant factor to consider for our project's incorporation of a Solar PV farm.

The main objective of this research is to clarify the complex connection between tie-line bias management and system oscillations, with a particular emphasis on the influence of variable generating sources. With the growing importance of renewable energy in power systems, it is crucial for our modelling work to comprehend the impact of variable generation on control techniques and oscillations.

The paper offers useful insights into the many control mechanisms that can be utilised to effectively minimise tie-line bias while dealing with variable generation. The inherent variability of Solar PV farms can cause oscillations in power generation, which may affect the stability of the system. Hence, the insights obtained from this work contribute to our project by providing a detailed comprehension of how tie-line bias management can be enhanced to mitigate the oscillatory consequences linked to variable generation.

Moreover, the study examines the wider consequences of variable generation on system oscillations, providing insights into the interrelated dynamics that regulate power systems with renewable energy sources. By integrating these discoveries into our simulations, we can enhance our ability to forecast and examine the performance of our modified Kundur two-area system when connected with a Solar PV farm.

Chapter 3

Modeling of a modified Kundur two area system with Typhoon HIL

3.1 Diesel Generator System

3.1.1 Introduction

Diesel generators play a crucial role in power systems by supplying dependable backup power and energy in isolated areas. The given diagram illustrates the internal structure and governing processes of a diesel generator system, which can be examined to comprehend its functioning, regulatory approach, and incorporation into larger power grids.

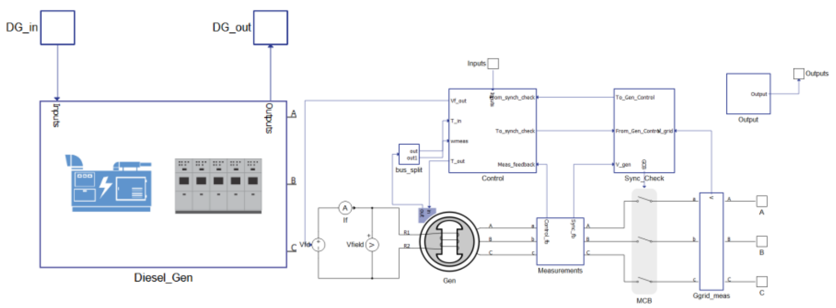

FIGURE 3.1: Diesel Generator.

3.1.2 Internal Architecture

The supplied schematic depicts a thorough depiction of the internal structure of a Diesel Generator system, showcasing the progression from diesel input to electrical output, along with the accompanying control systems.

3.1.3 Diesel Input and Generation

1. DGin: The 'DGin' label designates the point at which diesel fuel enters the system. This fuel is crucial for the functioning of the diesel engine that powers the generator.

2. The core component of the system is the diesel generator, which consists of an engine that combusts diesel fuel to generate mechanical motion, and an alternator that transforms this mechanical energy into electrical energy. The illustrated configuration probably comprises multiple subsystems such as fuel injectors, an engine cooling system, an exhaust system, and an electrical alternator.

3.1.4 Control and Monitoring

1. Control: This block serves as the central hub of the generator. It continuously analyses the performance of the engine and makes necessary adjustments to operational parameters in order to achieve the best possible performance. The system incorporates controls for initiating and ceasing the generator, regulating its speed, managing voltage levels, and implementing protective measures.

2. Measurements: This architectural component is specifically designed for the continuous monitoring of essential metrics, including voltage, current, frequency, and power, in real-time. The control system receives these measurements to ensure that the generator works within its designated parameters and responds accordingly to changes in load requirements.

3. SyncCheck: Ensuring synchronisation is of utmost importance when connecting the generator to a grid or while working in parallel with other generators. The synchronisation check verifies that the generator's frequency and phase align with those of the electrical system it is connecting to, thus preventing any harmful electrical disturbances.

3.1.5 Power Distribution

1. The MCCB (Moulded Case Circuit Breaker) serves as the main protective component in the generator's output portion. This device offers safeguards against excessive current and electrical faults, guaranteeing secure functionality and connection to the load or power system.

2. DGout: The term 'DGout' refers to the electrical output of the generator, which is prepared to be provided to the linked load, such as an electrical grid, an industrial facility, or emergency power for a building.

3. Supplementary elements Gen: This symbol commonly signifies the alternator component of the generator, which is accountable for turning mechanical energy into electrical energy via electromagnetic induction.

3.1.6 Functionality

The generator commences by commencing the burning of diesel fuel within the engine, resulting in the generation of mechanical motion. The motion is transmitted to the alternator, which subsequently produces energy. The control systems regulate the engine speed and the output of the alternator in order to generate a reliable and steady electrical supply. The monitoring systems guarantee the generator's efficient, secure, and compliant operation with environmental regulations. If there is a disparity or defect, the control systems have the ability to make adjustments or shut down the generator in order to avoid any potential damage. The MCCB functions as a protective measure by interrupting the power supply in the event of an excessive load or malfunction, so safeguarding both the generator and the equipment it is attached to.

After being produced, the electricity is directed through the MCCB and exits the DGout, ready to be utilised for operating linked devices. The sync check feature is essential when the generator is utilised alongside other generators or the grid, since it guarantees that the generator's output is synchronised with the current power system, hence eliminating any phase mismatch or frequency disparities that may result in inefficiencies or harm.

3.1.7 Governor and Engine

The governor and engine control subsystem play a crucial role in maintaining the stability and responsiveness of power output in a power production system. The governor is a crucial regulatory device responsible for controlling the rotational speed of the engine, which then determines the frequency of the generated electrical power. The engine, regardless of whether it is a turbine or a conventional internal combustion engine, transforms basic energy sources (such as fuel or flowing water) into mechanical energy. The governor's function is to regulate the input of the engine, such as fuel, steam, or water flow, in order to achieve the appropriate operational parameters. This ensures that the electrical power generated is in accordance with the requirements of the grid.

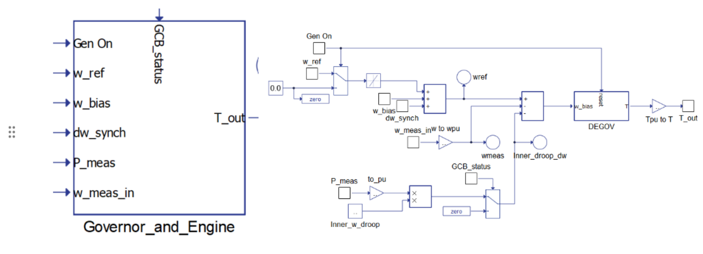

FIGURE 3.2: Governor and Engine.

The performance and stability of a power system depend on the accurate regulation of the generator's output. A governor ensures this level of accuracy by regulating the mechanical input of the engine to align with the required load. The governor in a synchronous generator is crucial for preserving frequency stability by regulating the speed of the engine. Its primary function is to regulate the mechanical power input to the generator, so ensuring that the frequency and phase of the electricity stay within the prescribed limits. This is of utmost importance for the smooth operation and seamless integration of the generator into the power grid.

The incorporation of the governor and engine into a Typhoon HIL simulation requires the precise adjustment of several parameters and controls to accurately mimic the dynamics and reactions observed in real-world scenarios.

1. wref (Reference Speed): The governor aims to maintain the generator's necessary frequency by striving to keep the engine's rotational speed at the desired objective.
2. wbias (Speed Bias): This parameter represents an additional value that is applied to the reference speed. It is used to account for system variances or to rectify any steady-state inaccuracy that may occur.
3. dwsynch (Synchronisation Speed Difference): This parameter represents the difference between the actual speed of the generator and the synchronous speed, which is the speed required for the generator to stay in sync with the frequency of the power grid. The governor use this data to make precise adjustments to the engine's speed.
4. wmeasin (Measured Speed Input): Indicates the precise and accurate recorded rotational speed of the engine. This feedback is crucial for the governor's control loop as it offers real-time data for direct comparison with the reference speed.
5. Pmeas (Measured Power): It represents the instantaneous measured electrical power output of the generator. The governor employs this input to optimise the engine's input in order to align power generation with the load demand.
6. The acronym DEGOV stands for Digital Electronic Governor. This block emulates the digital control logic of a contemporary electronic governor. The system analyses input signals, including the reference speed, measured speed, and power outputs, in order to calculate the required modifications to the engine's functioning.
7. Tout (Torque Output): This governor output represents the required torque to be applied to the engine in order to attain the specified operational state. The critical signal converts the governor's computations into practical modifications to the engine's mechanical inputs.

3.1.8 Overview of the Exciter System

An exciter system is a crucial component of a synchronous generator that is utilised to regulate the magnetic field and, consequently, the voltage output of the generator. The main purpose of this device is to provide direct current (DC) to the winding of the rotor in the synchronous machine. This electrical current creates the magnetic field that is required for the conversion of electromechanical energy in the generator.

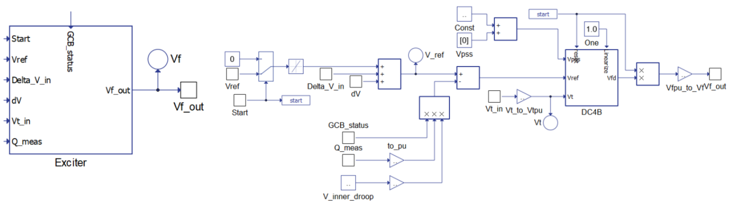

FIGURE 3.3: Exciter System.

The excitation system must exhibit rapid responsiveness to variations in load demands and possess the ability to provide stability within the system. Additionally, it plays a vital function in regulating the voltage of the power supply. Contemporary exciter systems are commonly automated, possessing the ability to dynamically regulate the field current of the generator, guaranteeing that the generator's output aligns with the power system's demands.

Components of the Exciter System in the Schematic:

1. Exciter: The central component in the diagram represents the exciter. Its function is to produce the direct current that will be delivered to the rotor of the generator.

2. Input Parameters: Start: This input is most likely used to commence the excitation process. The exciter can be initiated by a control signal.

3. Vref (Reference Voltage): The reference voltage is the desired voltage level that the exciter strives to maintain at the generator terminals. It functions as the reference point for the voltage regulator in the exciter system.

4. DeltaVin (Delta Voltage Input): This parameter signifies a variation or departure from the reference voltage (Vref). It could signify the disparity between the real terminal voltage and the intended reference voltage, prompting the system to modify the excitation level in order to restore the terminal voltage to the desired value.

5. dV (Differential Voltage): This input may be associated with a protection function or a control method that considers the voltage's rate of change. It has the capability to offer responsive and adaptable reactions, as well as safeguarding the system against sudden increases in voltage.

6. Vtin (Terminal Voltage Input): This refers to the instantaneous measurement of the voltage at the terminals of the generator. The feedback parameter is essential for the excitation control system to compare the actual terminal voltage with the reference voltage and make appropriate adjustments to the exciter output.

7. Qmeas (Reactive Power Measurement): Reactive power is crucial for regulating voltage levels in the power system. Qmeas is a probable indicator of the reactive power produced by the generator. It is utilised to optimise the exciter output in order to guarantee the stability and effectiveness of the generator's functioning.

8. Output Parameter: Vfout (Field Voltage Output): This represents the direct current (DC) output of the exciter, which is connected to the generator's rotor windings. The magnitude of Vfout has a direct impact on the intensity of the magnetic field in the generator, which subsequently impacts the voltage and reactive power output of the synchronous generator.

9. Exciter Control Strategy: The exciter system incorporates a control strategy that utilises the inputs to ascertain the optimal level of excitation required. If the terminal voltage (Vtin) falls below the reference voltage (Vref), the exciter can enhance the field voltage (Vfout) to increase the terminal voltage to the required level. Similarly, if the magnitude of the reactive power (Qmeas) is excessively high or low, modifications in the exciter output can rectify the power factor, hence optimising the performance of the generator.

10. Output Parameter: Vfout (Field Voltage Output): This refers to the direct current (DC) output of the exciter, which is supplied to the rotor windings of the generator. The magnitude of Vfout has a direct impact on the intensity of the magnetic field in the generator, which subsequently impacts the voltage and reactive power output of the synchronous generator.

3.1.8.1 Exciter Control Strategy

The exciter system's control method utilises the inputs to ascertain the optimal level of excitation required. If the terminal voltage (Vtin) falls below the reference voltage (Vref), the exciter can enhance the field voltage (Vfout) in order to elevate the terminal voltage to the desired level. In the same manner, if the reactive power (Qmeas) deviates excessively from the desired range, modifications in the exciter output can rectify the power factor, hence enhancing the efficiency of the generator.

3.1.9 Frequency Set Point Control

Frequency is a crucial parameter in power systems since it serves as a reliable measure of the equilibrium between electricity supply and demand. The stability of frequency is crucial for the secure and optimal functioning of the power system. The frequency set point refers to the desired frequency that the system aims to uphold, typically around 50 or 60 Hz, depending on the geographical location.

Preserving the frequency of an electrical power system within close limits around a predetermined setpoint is crucial for maintaining stability and dependability. This study provides an investigation of frequency setpoint control utilising the Typhoon HIL simulation environment.

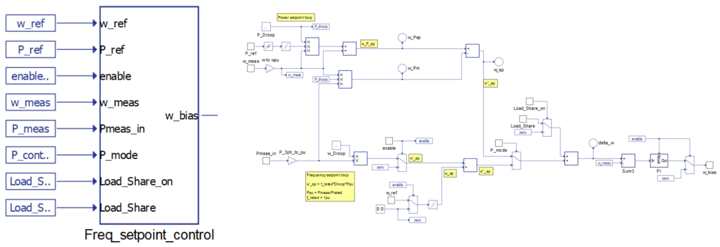

Figure 3.4: Frequency Setpoint Control.

By thoroughly analysing the control loop parameters and their interactions, our goal is to illustrate the effectiveness of contemporary control systems in preserving system frequency in the face of fluctuating load and generation circumstances.

3.1.9.1 Typhoon HIL Simulation of Frequency Setpoint Control

Typhoon HIL offers a simulation environment that allows for real-time testing of control strategies, eliminating the need to implement them in real power systems, which can be costly and risky. We employ Typhoon HIL to simulate and evaluate the performance of a frequency setpoint control system in our investigation.

3.1.9.2 Model Architecture

The fundamental elements of the Typhoon HIL frequency setpoint control model, as illustrated in the diagram, consist of the following:

1. PDroop: This parameter denotes the power-frequency droop characteristic, which is an essential control feature enabling controlled variation of the frequency within a specified range as the load fluctuates. This characteristic plays a crucial role in the primary frequency response of the system.

2. Pref and wref: These represent the desired power and frequency values, respectively. They function as the standard against which the real results are evaluated.

3. Pmeas and wmeas: The power and frequency parameters that have been measured offer immediate feedback to the control system.

4. LoadShare: This mechanism oversees the allocation of workload among several generators or control systems, guaranteeing that no individual unit is burdened excessively.

3.1.10 Control Loop Analysis

The control loop serves as the central component of the frequency setpoint control system. The actual frequency (wmeas) is compared to the reference frequency (wref). A control action is initiated whenever there is a deviation (deltaw) in order to restore the frequency to the setpoint. The loop is regulated using a PI (proportional-integral) controller, which delivers a well calibrated response (wbias) to variations in frequency.

3.1.11 Load Sharing and Power Control Modes

Load sharing is an essential component of power networks with several generators. The Typhoon HIL model includes capabilities for both active load sharing and power control modes. The LoadShareon option enables the allocation of load across generators, while the Pmode parameter allows for the transition between fixed power output and load-dependent operation. These functions are essential for simulating the combined reaction of generators to uphold a stable system frequency.

3.1.12 Droop Control and Power Setpoint Adjustment

The PDroop and wDroop parameters in the model incorporate droop control, a key principle that enables the adjustment of power output in response to frequency variations. This enables a decentralised method for frequency adjustment, hence reducing the requirement for quick reaction from external control systems. The power setpoint (PSp) is dynamically modified in order to obtain the appropriate frequency stability, taking into account the PDroop and wDroop values.

3.1.13 Results and Discussion

The simulation results demonstrate that the Typhoon HIL model accurately replicates the frequency setpoint regulation of a power system. The system can immediately adapt to deviations from the frequency setpoint by utilising a feedback loop that is facilitated by real-time measurements of power and frequency. The PI controller precisely modulates the excitation of the generator to either augment or diminish power production, as required to rectify frequency deviations. The load-sharing functionality was seen to evenly spread the variations in load among numerous simulated generators, hence eliminating both overloading and underutilization. This is especially crucial in a practical situation where generators with different capacities and reaction times work together.

3.2 Transformer

Transformers are essential components of contemporary electrical power systems, facilitating the effective conveyance and dispersion of electricity across extensive distances. These devices play a crucial role in increasing the voltage from power generation levels to high transmission voltages. This helps to decrease the current and minimise the energy lost as heat in the conductors. On the other hand, transformers are employed at the consumption stage to decrease the voltage to levels that are safer and more practical for commercial and domestic purposes.

Transformers essentially enhance the flexibility of electrical power systems to accommodate the fluctuating requirements of power generation and consumption. These machines are specifically engineered to function optimally when operating at maximum capacity and are constructed to endure for several decades with minimal upkeep. Their dependability and effectiveness are the fundamental principles of electrical engineering, facilitating the extensive dissemination of energy that energises our urban areas and industrial sectors.

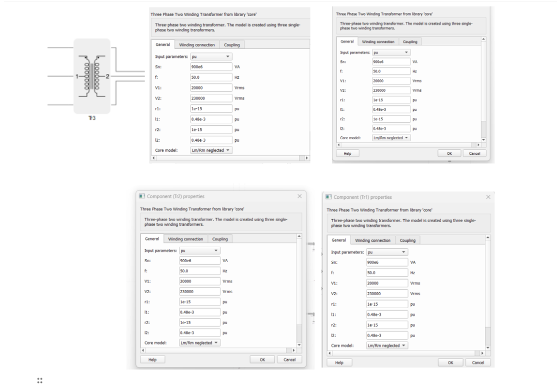

Figure 3.5: Transformer.

Transformers in power systems that incorporate renewable energy sources must be capable of managing the inherent fluctuation and intermittency associated with these sources. In order to preserve grid stability, it is imperative that they promptly react to fluctuations in voltage and current. The success and dependability of transformers in renewable-integrated power systems depend heavily on their design and operational factors.

Transformers in the Typhoon HIL Simulation The research, named "Development of a modified Kundur two-area system with Solar PV farm for Typhoon HIL simulation," employs advanced transformer modelling techniques to simulate the behaviour of a power system during the integration of solar electricity. The Typhoon HIL simulation necessitates precise depiction of the physical constituents within the power system to anticipate the system's reaction to diverse circumstances, such as grid disruptions, load fluctuations, and fault occurrences.

Within the given Typhoon HIL simulation screenshots, Four unique transformers are illustrated, with each one customised for this particular power system analysis. The transformers have been meticulously configured to accurately simulate the exact conditions that would be faced in a real-life scenario. The selected parameters encompass the essential electrical properties necessary for accurate and lifelike simulation results.

The Typhoon HIL versions utilise the subsequent transformer specifications:

1. Sn: Each transformer has a power rating of 900e6 VA, indicating its capacity to handle significant power levels, which is characteristic of high-capacity power lines that are connected to large-scale solar farms.

2. f: The transformers operate at a standard industrial frequency of 50 Hz, which is designed to align with the grid frequency that is commonly observed in various places globally.

3. V1 and V2: The primary and secondary voltages are configured to be 20000 Vrms and 23000 Vrms, respectively, signifying the transformers' functions of increasing or decreasing voltages for the purposes of transmitting and distributing electricity.

4. r1 and r2: The resistances are adjusted to a value of 1e-15 pu, which effectively eliminates resistive losses in the model. This allows the simulation to primarily focus on the reactive aspects of the transformers.

5. l1 and l2: The leakage inductances, with a value of 0.48e-3 pu, bring non-ideal characteristics to the simulation, which impact the voltage control and stability of the power system.

The "Core model" parameter is configured as 'Lm/Rm disregarded', simplifying the magnetic properties of the transformer cores and prioritising the examination of the windings' behaviour, which is more crucial for dynamic simulations.

The Typhoon HIL simulation environment offers a robust platform for conducting real-time testing and analysis, allowing the project to accurately model the functioning of the power system. It enables the analysis of the transformers' behaviours under different operational circumstances, including the incorporation of solar power generation, and offers valuable insights into their functioning. Systems can be enhanced to achieve optimal levels of both performance and dependability.

The transformers undergo a variety of situations using Typhoon HIL's real-time simulation capabilities to assess their performance and capacity to uphold grid stability. This involves replicating the sporadic characteristics of solar energy as it is captured and integrated into the power network, guaranteeing that the transformers can manage the variations in power production without jeopardising the reliability of the electrical system.

The project's focus on precise transformer modelling within the Typhoon HIL environment demonstrates a dedication to excellence and meticulousness. This highlights the need of accuracy in designing grid-integration solutions for renewable energy sources, especially in power systems that need to maintain their resilience in the presence of fluctuating generation conditions and possible disruptions.

3.3 Transmission Line

Transmission lines serve as the channels through which electrical energy is transported, connecting the production and utilisation stages. These devices are designed to efficiently transmit high voltage electricity over long distances by carefully choosing materials and following electrical design principles that take into account resistance, inductance, and capacitance. The efficiency of the transmission line is determined by these characteristics, which are represented in models like the *pi* model. This model accurately represents the physical behaviour of the line in power system simulations.

The performance of a transmission line is dictated by its resistance, inductance, and capacitance. These metrics are crucial in determining the electrical properties of the line, including its ability to carry power, the amount of voltage drop, and its sensitivity to power losses. In the technical domain, resistance (R) plays a role in thermal losses in the line, which are determined by multiplying the square of the current by the resistance (I^2R losses). Inductance (L) causes voltage reductions when alternating current is present, as a result of magnetic field generation, and has a significant impact on the reactive power equilibrium of the system. Capacitance (C) enables the line to accumulate and discharge electric charge, which affects voltage levels and can introduce the flow of reactive power in the system.

For the purpose of creating a comprehensive report on the transmission line configuration in Kundur's Two-Area System, as depicted in the Typhoon HIL simulation environment, the following observations and analyses have been conducted.

3.3.1 Transmission Line in Typhoon HIL

This study provides a comprehensive investigation of the configuration and analysis of transmission lines in Kundur's Two-Area System, as simulated in the Typhoon HIL environment. The objective of our study is to analyse the function and influence of six specific transmission lines, each spanning distances of 25 km, 10 km, and 110 km, that connect two regions involved in electricity generation and distribution.

This study provides a comprehensive investigation of the configuration and analysis of transmission lines in Kundur's Two-Area System, as simulated in the Typhoon HIL environment. We aim to analyse the function and influence of six separate transmission lines, each spanning 25 km, 10 km, and 110 km, that connect two regions involved in generating and distributing power.

The simulation configuration in Typhoon HIL serves as a crucial instrument for comprehending the complexities of power system dynamics. The shorter transmission lines, consisting of two lines measuring 25 km and two lines measuring 10 km, function as regional interconnects within each respective area. These lines are expected to enhance the local distribution of power and contribute to the stability within each area. Their comparatively limited length implies reduced impedance values, which, in practical circumstances, would lead to less voltage drop and power dissipation. This idea can be examined and confirmed using the Typhoon HIL simulation environment.

The two 110 kilometre lines serve as the main infrastructure for inter-area linkages. These lines are responsible for transmitting the majority of power, specifically 400 MW, between the two regions. The length and impedance of these lines play a critical role in determining the system's capacity to sustain stability when faced with changing load conditions and potential disturbances. Their influence on the power system's dynamic response is significant, as they impact the propagation and damping of oscillations after a disturbance.

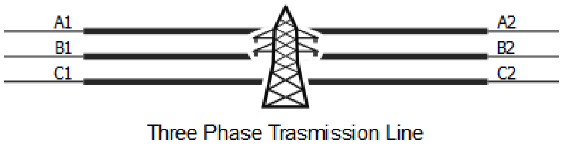

FIGURE 3.6: Transmission Line

During the Typhoon HIL simulation, we have the opportunity to precisely input and modify the electrical parameters of the gearbox lines, such as resistance, inductance, and capacitance. This allows us to evaluate how these changes impact the stability of the system, the flow of power, and the occurrence of oscillations. This allows us to establish connections between the simulated environment and real-life expectations, guaranteeing that any theoretical planning and design efforts are based on a simulation that accurately represents the difficulties faced in realistic situations.

The Typhoon HIL model also enables the integration of line filters, which are described in the earlier parameters as Lfil1, Lfil2, Cfil1, and Cfil2. These filters are crucial components for effectively managing power quality. In Kundur's Two-Area System, these filters play a crucial role in reducing undesirable harmonics that may occur due to the switching of power electronic equipment, as well as other sources. We analyse the effect of these transmission lines on the angular stability between the generators in both areas. The 110 km lines play a crucial role in this regard, since they can bring about inter-area oscillation modes that require meticulous control to avoid significant disruptions to the whole system.

To summarise, the Typhoon HIL simulation is a very helpful tool for doing thorough study and verification of theoretical transmission line parameters and behaviours in the context of Kundur's Two-Area System. The knowledge acquired from this simulation is crucial for the development of robust and effective power systems, guaranteeing their ability to fulfil the requirements of contemporary energy networks. By utilising simulation technologies such as Typhoon HIL, we can guarantee the durability and strength of power systems in response to changing needs and technological progress. The research emphasises the crucial significance of transmission lines, which serve as the essential arteries of our power infrastructure. Simulating and studying intricate systems empowers engineers with the capacity to anticipate and uphold the integrity and dependability of the system in a sustainable and effective manner.

3.4 Photovoltaic (PV) System

3.4.1 PV System Design

Create and incorporate a solar photovoltaic (PV) farm into the Kundur system, taking into account power capacity and system dynamics. Create a model that accurately simulates the properties of real-world photovoltaic (PV) systems, such as the fluctuating power generation and the ability to adapt to varying solar radiation levels.

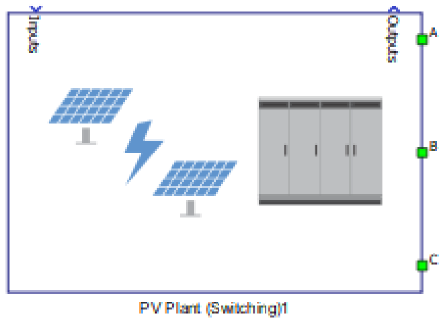

FIGURE 3.7: PV Plant System

3.4.2 Control Strategies for PV Integration

Apply control mechanisms to effectively manage the incorporation of solar power. Tackle issues such as voltage fluctuations and dynamic stability. Investigate grid-following control systems with the purpose of achieving synchronisation between the PV system and the electrical grid.

3.4.3 Simulation of Disturbances with PV

Expose the integrated system to diverse disruptions, such as abrupt alterations in load, reductions in voltage, and fluctuations in frequency. Assess the effectiveness of the control strategies in preserving stability and optimising power exchange.

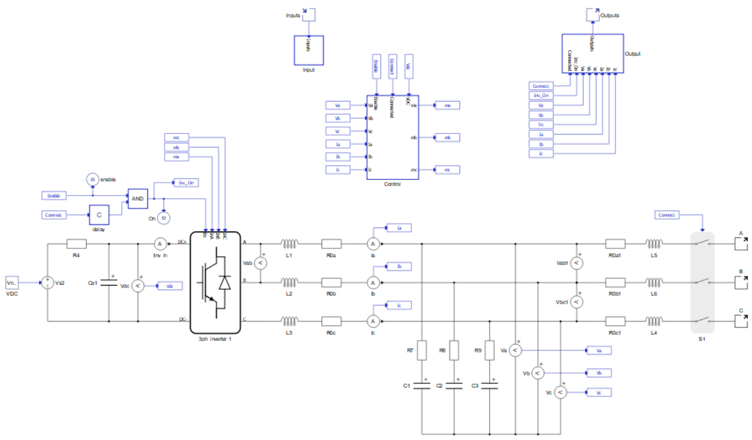

FIGURE 3.8: Inside PV Plant System

3.5 LCL Filter Design

3.5.1 LCL Filter Overview

Create an LCL filter with the purpose of reducing the amplitude of harmonics and ensuring the stability of the system. Present a comprehensive elucidation of the constituents of the LCL filter, encompassing inductors, capacitors, and resistors.

3.5.2 LCL Filter Simulation

Employ the Typhoon HIL simulator to replicate the performance of the LCL filter in the integrated PV-Kundur system. Examine the influence of the LCL filter on voltage and current waveforms, specifically detecting resonant frequencies and damping properties.

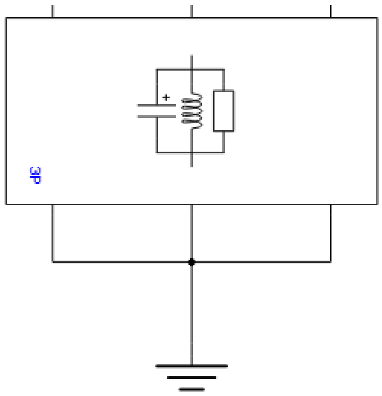

FIGURE 3.9: LCL Filter

3.5.3 LCL Filter Parameter Optimization

Maximise the parameters of the LCL filter to guarantee efficient suppression of harmonics. Examine the compromises between the effectiveness of filters and the financial issues involved.

3.5.4 Impact on System Stability

Examine the impact of the LCL filter on the stability of the entire system. Examine the simulation outcomes to comprehend how the filter contributes to reducing oscillations and enhancing the dynamic response of the PV-integrated Kundur system.

Chapter 4

Integrated Model of Kundur Two-Area System with Solar PV and LCL Filter

4.1 Overview

In this chapter, we present the culmination of our efforts to create a comprehensive and dynamic model by integrating the Kundur two-area system with a solar photovoltaic (PV) farm. Additionally, we incorporate an LCL filter to address harmonic distortion and enhance system stability. The integrated model aims to mirror real-world power system behavior and provides a platform for in-depth analysis and simulations.

4.2 Kundur Two-Area System Implementation

4.2.1 Model Refinement

Building upon the Kundur two-area system model developed in Chapter 3, we refine and optimize the parameters to ensure accurate representation within the Typhoon HIL simulator. This involves fine-tuning generator characteristics, transmission line parameters, and load profiles.

4.2.2 Typhoon HIL Implementation

Utilizing the Typhoon HIL simulator, we implement and validate the Kundur two-area system model. This phase involves rigorous testing to verify that the model's responses align with expected power system behavior under various operating conditions.

4.3 Transmission Line Calculation

$$
\begin{aligned}
R_0 &= 1.61 \\
R_1 &= 0.0529 \\
L_0 &= 0.0001 \\
L_1 &= 0.0001403 \\
C_0 &= 5.2489 \times 10^{-9} \\
C_1 &= 8.7248 \times 10^{-9} \\
R_d &= \frac{R_0 + 2R_1}{3} = 0.57819 \\
R_{nd} &= \frac{R_0 - R_1}{3} = 0.5190 \\
L_d &= 2L_1 = 2.
\end{aligned}
$$

Power Load Iteration Analysis

First Iteration

Area 2:

- Resistance (R): 300 mΩ
- Inductance (L-fil2): 1 mH
- Capacitance (C-fil2): 1 μF
- Active Power at Node 9 (Pat9): 900 MW
- Reactive Power at Node 9 (Qat9): 750 MVAR

Area 1:

- Resistance (R): 50 mΩ
- Inductance (L-fil1): 2 mH
- Capacitance (C-fil1): 2 μF
- Active Power at Node 7 (Pat7): 300 MW
- Reactive Power at Node 7 (Qat7): 50 MVAR

Second Iteration

Area 2:

- Resistance (R): 0.5 Ω
- Inductance (L-fil2): 10 mH
- Capacitance (C-fil2): 10 μF

- Active Power at Node 9 (Pat9): 2,600 MW
- Reactive Power at Node 9 (Qat9): 340 MVAR

Area 1:

- Resistance (R): 0.2 Ω
- Inductance (L-fil1): 10 mH
- Capacitance (C-fil1): 10 μF
- Active Power at Node 7 (Pat7): 1,100 MW
- Reactive Power at Node 7 (Qat7): 60 MVAR

Final Iteration

Area 2:

- Resistance (R): 0.34 Ω
- Inductance (L-fil2): 4.4 mH
- Capacitance (C-fil2): 4.4 μF
- Active Power at Node 9 (Pat9): 1,760 MW
- Reactive Power at Node 9 (Qat9): 360 MVAR

Area 1:

- Resistance (R): 0.19 Ω
- Inductance (L-fil1): 2.2 mH
- Capacitance (C-fil1): 2.2 μF
- Active Power at Node 7 (Pat7): 960 MW
- Reactive Power at Node 7 (Qat7): 220 MVAR

4.4 PV System Design

The PV system model was implemented in Typhoon Hil using the schematic block 'PV plant switching' which is designed with a three phase two level inverter connected to an LCL filter at the output as shown in figure . This is a simplified model as DC link voltage is of constant source.But to imitate the behavior of the intermittency nature of the PV system there is a control implemented to increase or decrease the radiation.

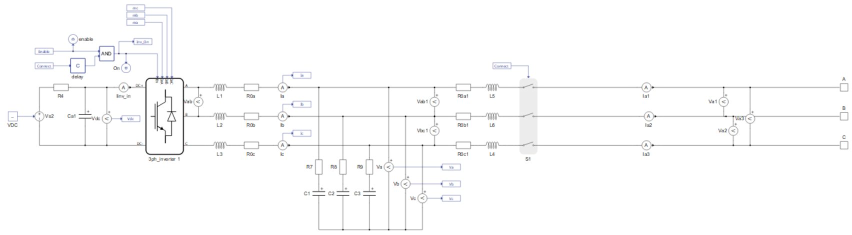

FIGURE 4.1: PV plant in Typhoon HIL

4.4.1 Three phase two level inverter

A three-phase two-level inverter is a power electronic device that converts direct current (DC) into alternating current (AC) using electronic switches. It is called "two-level" because it can produce two voltage levels at the output for each phase: a positive and a negative voltage level relative to the neutral point. These inverters are widely used in applications ranging from small-scale renewable energy systems, such as solar photovoltaic (PV) inverters, to large-scale applications like motor drives and grid power conditioning.

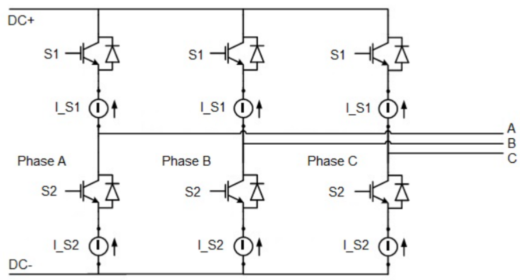

FIGURE 4.2: Three phase two level inverter

4.4.1.1 Working Principle

The inverter consists of six switches, typically insulated gate bipolar transistors (IGBTs) or power MOSFETs, arranged in three 'legs'. Each leg corresponds to one phase of the AC output. In each leg, there are two switches that never close simultaneously to avoid short circuits. When the top switch of a leg is on, the bottom switch is off, and vice versa. This allows each leg to output either the positive DC bus voltage or the negative DC bus voltage (which can be considered as zero voltage in reference to the center point of the DC bus).The inverter is set to internal modulator.

The internal modulator three-phase two-level inverter typically refers to the control circuit or algorithm that generates the Pulse Width Modulation (PWM) signals for the switches; which is a technique used to create an AC waveform from the DC input. It involves rapidly switching the inverter's electronic switches on and off. By adjusting the duration (width) of the on-time of each switch (the pulse), the average voltage and frequency of the AC output can be controlled. PWM allows the inverter to simulate a sinusoidal waveform by varying the duty cycle of the switching devices.

4.4.2 LCL Filter Design

The aim of the LCL filter is to attenuate the harmonics of the current to acceptable limits before injection to the grid as in grid tied mode, the converter operates in active power reactive power control mode of the current.In this project the PV system capacity is 1.1 MW and the PU base values are calculated as follow:

Parameter		Expression	Value	
Power	Sb	-	1.1	MW
Voltage(l-l)	Vb	-	480	Volts
Frequency	fb	-	60	Hz
Current	Ib	$\frac{Sb}{\sqrt{3}*Vb}$	1.3231	kA
Radian freq.	wb	$2*\pi*fb$	376.9911	rad/s
Impedance	Zb	$\frac{Vb^2}{Sb}$	0.2095	Ω
Inductance	Lb	$\frac{Zb}{wb}$	55.560	mH
Capacitance	Cb	$\frac{1}{wb*Zb}$	0.0127	F

TABLE 4.1: LCL Filter Parameters.

From figure, if the inductance, the Resistance and the voltage at the inverter side is given by Li and Ri, and that at the grid side by Lg and Rg and the capacitance and resistance of the capacitor by Cf and Rc as shown in fig.2 the following transfer function can be duducted from LCL circuit :

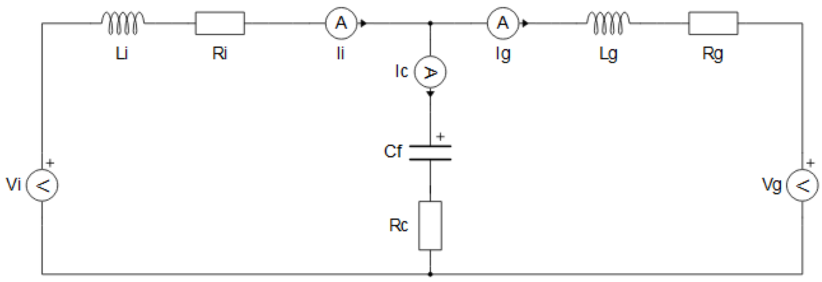

FIGURE 4.3: LCL filter

With Ri and Rg neglected:

$$\frac{Ig(S)}{Vi(s)} = \frac{1+C*S*Rc}{S*[s^2*(Cf*Lg*Li)+S*C*Rc*(Li+Lg)+Li+Lg]}$$

As frequency is equal to $f = \frac{w}{2*\pi}$, from this transfer function the frequency at resonance is

$$fres = \frac{1}{2*\pi} * \sqrt{\frac{Lg+Li}{Lg*Li*Cf}}$$

$$Wres = \sqrt{\frac{Lg+Li}{Lg*Li*Cf}}$$

Following the design of 'S.shahil(2016)' the following formulas in PU of Li,Lg,Cf can be obtained:

$$Li(pu) = \frac{(x/M)*wb}{wu*ri}$$

$$Lg(pu) = \frac{(x/M)*a*wb}{wu*rg}$$

$$Cf(pu) = \frac{wb}{wu*a} * \frac{(1-a)*ri-rg}{x/M}$$

$$Rc = \frac{1}{3*Wres*Cf}$$

After running the code in MATLAB, the following results are obtained:

Parameter	Abs. Value	Pu Value
Li	9.0682e-6 H	0.163
Lg	1.3602e-5 H	0.0245
Cf	9.0616e-4 F	0.0716
Rc	0.0258	0.1233

TABLE 4.2: LCL Filter Result obtained from MATLAB.

4.4.2.1 Discussion

The transfer function has no real part, only complex conjugate pairs which explain the resonance in the system's response as shown in figure. LCL filter introduce resonances in the system, which is why they often require damping strategies to maintain stability.

The shunt resistance at the capacitor damp out oscillations in the current, without which the system may go unstable. In fact when the the Rc was neglected in the simulation in Typhoon both the current and voltage and also the frequency went unstable. On the other hand both the resistances beside the inductors at the grid side and at the inverter side can be neglected without too much effect on the system. That is the whole purpose of LCL filter, limit grid current harmonics within limits. As shown in the bode diagram at lower frequencies the magnitude is not changing much,the filter allows those frequencies to pass through with little attenuation, but as it increase further the magnitude starts to decrease sharply. This indicates that the filter is attenuating high switching frequencies of the inverter. But as magnitudes drops, the phase also lags, so current will lag behind voltage, this is capacitive behavior. However beyond the resonant frequency the phase starts to increase suggesting inductive behavior at higher frequencies where the current leads the voltage across an inductor.

The Bode plot's information is used to verify that the filter's design meets the necessary criteria and to predict how it will behave in conjunction with other system components. Any resonance observed in the Bode plot must be addressed, as it could lead to large voltage or current oscillations that might damage the inverter or disrupt grid operation.

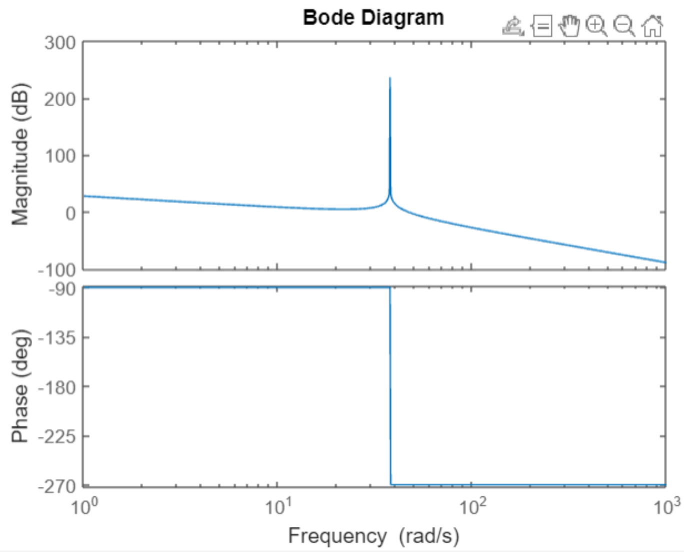

FIGURE 4.4: Rc neglected(Undamped)

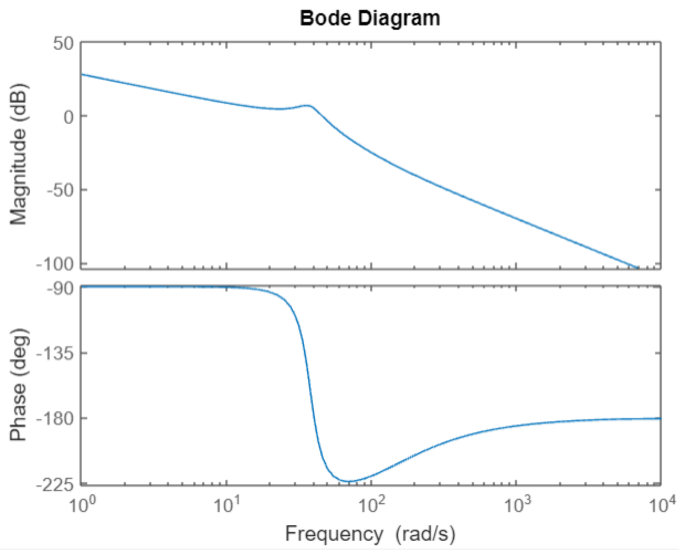

FIGURE 4.5: Damped system

4.4.3 PV system connected to a three phase source in typhoon

The connected transformer is a step up from 480volts to 230 kV to be fed to the grid. Under the mask as shown in figure 6 there is control system to ensure that the PV plant operates within specified parameters and responds appropriately to grid conditions. This control system is called "Grid-following" and it allows photovoltaic plant to synchronize its output with the electrical grid's voltage and frequency. The PV system efficiency is chosen by $n = 20percent$ and the area was calculated as such: $Apv = P/n * G$, G is the average insolation of $4.5KWh/m^2/day$.

After running this simulation the results are visualized in Typhoon HIL panel as shown in figure 8. The simulated results are as expected, but only at 1000 irradiation.

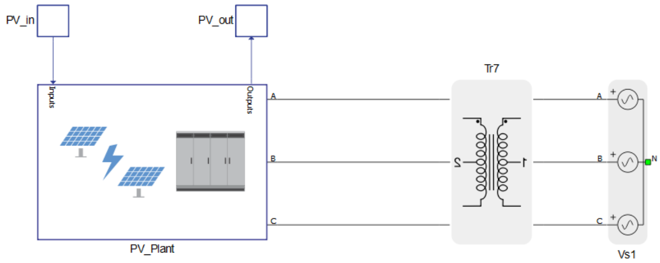

FIGURE 4.6: PV plant in typhoon

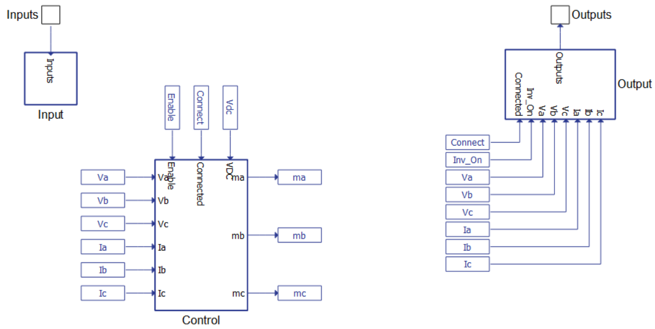

FIGURE 4.7: PV plant control system

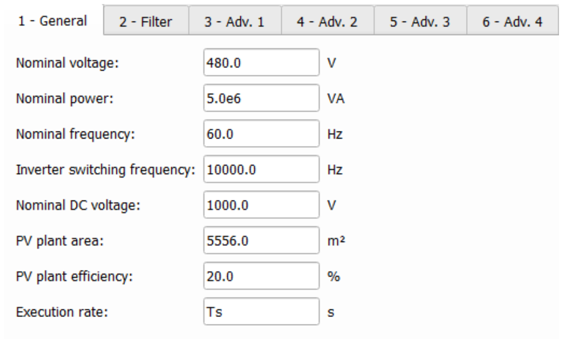

FIGURE 4.8: PV plant in typhoon

The following figures are the waveforms of the currents and volatges at different stages of the simulation process. Vdc is the constant voltage source of the pv system. Vab, the volatge right at the output of the inverter, the ripples make it inappropriate for grid unless regularized by some filter such as L or LCL. LC filter alone tends to be expensive due to the huge capacity requirement so LCL filter is prefered, beside it has better outputs. Vbc1 is the output after LC filter and some oxcillations are still present,which are damped out at the output of LCL filter as shown in Va1, Va2 and Va3. The current right at the output of the inverter are also shown, scattered, same as the voltage LCL filter damped out oxcillations as shown in Ia1,Ia2 and Ia3.

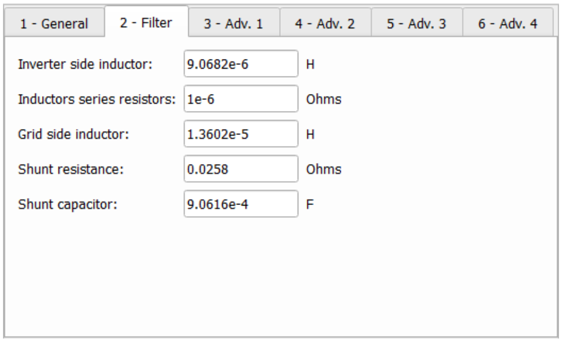

FIGURE 4.9: PV plant control system

4.5 System Results with Voltage Source

4.5.1 Voltage Measurements at Load 7

At Load 7, a voltage of 9.475 kV RMS line-to-neutral with a 69.1-degree phase shift was observed. This measurement indicates a significant phase shift, which can be attributed to the reactive power flow adjustments made within the system.

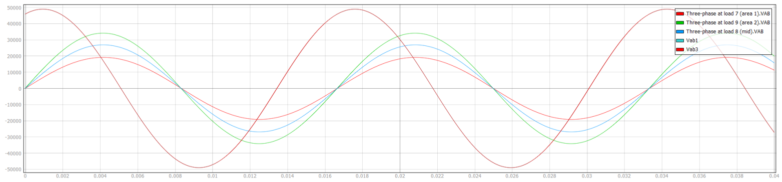

FIGURE 4.10: Voltage Measurements at Generator 1, 3 and node 7, 8, 9

4.5.1.1 Explanation

The phase shift of 69.1 degrees suggests that the generators in Area 1 and Area 2 are actively compensating for the reactive power requirements of Load 7. Reactive power is essential for voltage control. When the load demands more reactive power, the generators must supply it to maintain voltage stability. The phase shift indicates that the generators are providing the necessary reactive power to ensure that the voltage at Load 7 remains within acceptable limits.

4.5.2 Voltage Measurements at Node 8

Node 8, situated as the midpoint of the two-area system, displayed a voltage of 11 kV RMS line-to-neutral with a 69.1-degree phase shift.

4.5.2.1 Explanation

Similar to Load 7, the 69.1-degree phase shift at Node 8 indicates active control of reactive power by generators in both Area 1 and Area 2. This control is necessary to ensure that the voltage at Node 8 remains stable despite variations in the load and generation within the two areas. The phase shift demonstrates that the system is effectively managing voltage levels at this critical point.

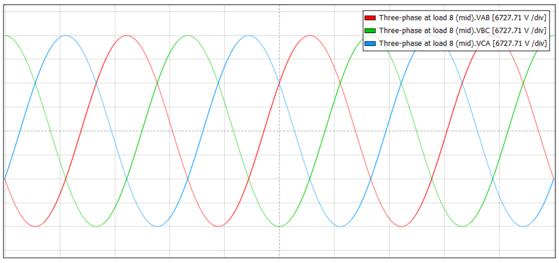

FIGURE 4.11: Voltage Measurements at Load 8

4.5.3 Voltage Measurements at Load 9

At Load 9, a voltage of 16.97 kV RMS line-to-neutral with a 69.1-degree phase shift was observed.

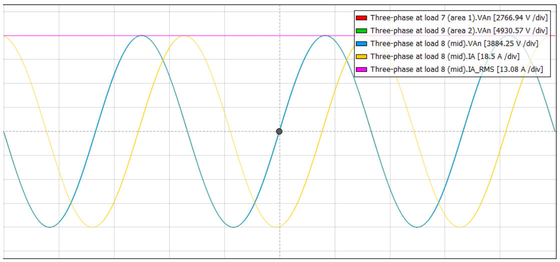

FIGURE 4.12: Voltage Measurements at Node 7,8,9 and Current at Node 8

4.5.3.1 Explanation

Like Load 7 and Node 8, Load 9's voltage characteristics with a 69.1-degree phase shift highlight the importance of reactive power support. In this case, the generators in both Area 1 and Area 2 are supplying reactive power to maintain the voltage at Load 9 within the desired range. This result underscores the role of generators in voltage regulation throughout the entire system.

4.6 Grid Integration

The successful integration of the Solar PV farm into the Kundur two-area system highlighted the need for enhanced control strategies to manage the intermittent nature of solar power.

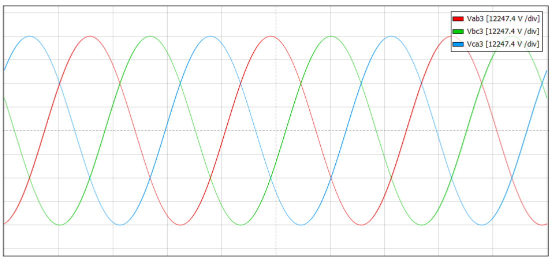

FIGURE 4.13: Voltage Measurements

4.6.1 Explanation

Solar power generation is intermittent and dependent on weather conditions. Therefore, effective control strategies, such as advanced grid-tied inverters and energy storage systems, are necessary to smooth out variations in solar power output. These control strategies ensure that the power system remains reliable and stable, even in the presence of renewable energy sources.

Simulation results reveal the complex interplay between conventional generators and renewable energy sources in the Kundur two-area system. While solar PV farms can contribute to reducing reliance on fossil fuels and lowering emissions, they also introduce challenges related to voltage stability and control. These findings emphasize the importance of advanced control mechanisms and grid integration strategies as we move towards a more sustainable and renewable energy-focused power grid. Further research and development in this area are vital to address these challenges effectively.

4.7 System Results with Generator with PV at 1 MVA

In order to attach PV and generators in the system the two areas are modified with Area 1 housing two 1 MVA diesel generators at Nodes 1 and 4, while Area 2 incorporates a 1 MVA PV power plant with a three-phase inverter at Node 3. All power sources deliver a 480 Vrms line-to-line output voltage. In Area 1, Node 9 carries a 230 kW active power load and an 80 kVAR reactive power load, while Node 7 sustains a 1.4 MW active power demand and 980 kVAR of reactive power. This configuration provides a comprehensive overview of the power generation, distribution, and load characteristics within the two areas, essential for system analysis and management.

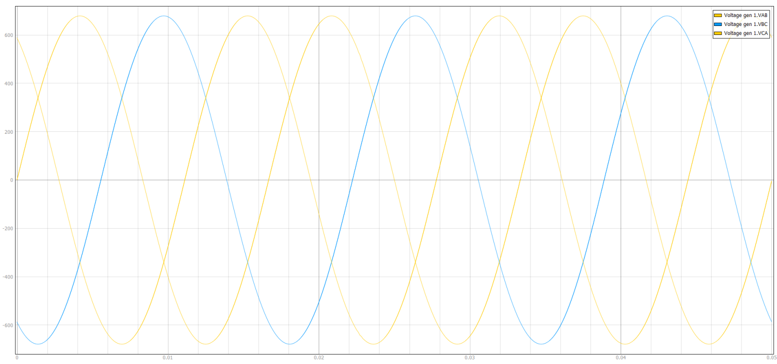

FIGURE 4.14: Voltage at Generator 1

4.7.1 Active and Reactive Power

The simulations demonstrated that the Solar PV farm contributes both active (real) and reactive power to the system.

4.7.1.1 Explanation

The addition of solar generation adds a new dynamic to the system. Solar PV farms generate active power, which can reduce the reliance on conventional generators to meet

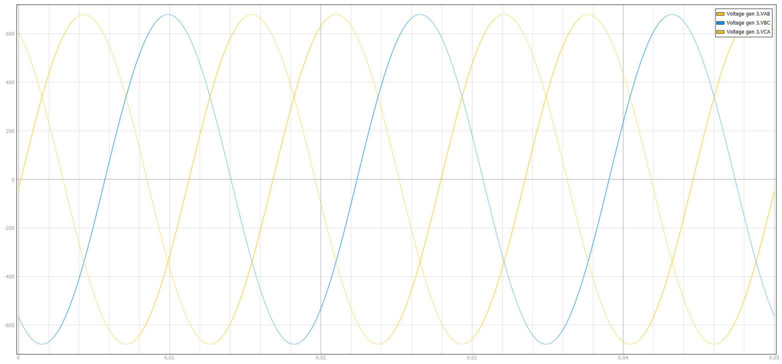

FIGURE 4.15: Voltage of PV at Node 3

the load demand. This reduction in active power generation from conventional sources can lead to fuel savings and a potential decrease in greenhouse gas emissions.

Additionally, the reactive power support from the generators in response to the introduction of solar generation emphasizes the importance of reactive power control in maintaining voltage stability.

4.7.2 Voltage of Load at Node 9

The voltage at Load 9 measures 2210 Vpk-to-pk (Volts peak-to-peak). This indicates that the voltage waveform oscillates between these values.

The voltage waveform at Load 9 leads the reference voltage or power sources in both Area 1 and Area 2. This means that the voltage waveform is ahead of the reference waveform in terms of phase.

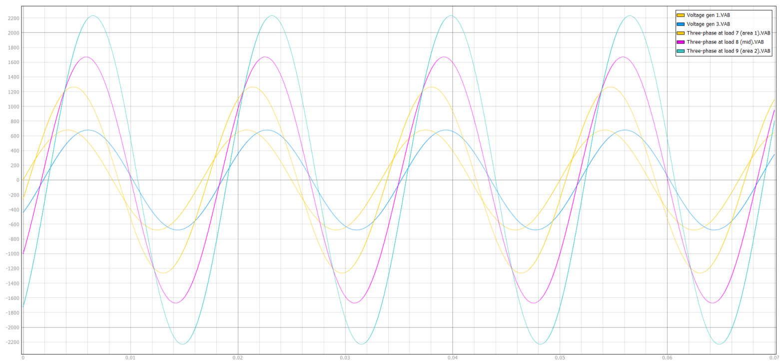

FIGURE 4.16: Voltage Measurement at PV and Generator at Node 7, 8, and 9

4.7.3 Voltage of Load at Node 7

The voltage at Load 7 measures 1220 Vpk-to-pk. Similar to Load 9, this represents the peak-to-peak variation in voltage.

The voltage waveform at Load 7 has a slightly leading phase shift compared to the reference voltage or power sources. This means it is also ahead of the reference waveform but to a lesser extent than at Load 9.

4.7.4 Voltage of Midpoint at Node 8

The voltage at the midpoint of the two areas, which is Node 8, measures 1670 Vpk-to-pk. This voltage level is between the values observed at Load 9 and Load 7.

The generator output in Area 1 and the PV power plant output in Area 2 are phase-shifted from each other. This means that the voltage waveforms from these two sources do not align perfectly in phase.

Despite the phase shift, both the generator and PV outputs share a common magnitude of 689 Vpk-to-pk. This means that although the phase relationship between the two sources differs, their peak voltage values are the same.

Chapter 5

Challenges faced in the Development of a Modified Kundur Two-Area System with Solar PV Farm for Typhoon HIL Simulation

This project aimed at the development of a modified Kundur two-area system integrated with a solar PV farm for Typhoon Hardware-in-the-Loop (HIL) simulation. While much effort was put in the realization of the model, we encountered several challenges during the course of our work, particularly concerning the integration of the solar PV farm and ensuring the stability of the system.

5.1 Power Limitations of the Solar PV Farm

One of the primary challenges revolved around the power limitations of the solar PV farm. Despite our efforts, we were unable to run the PV part at capacities higher than 1 MVA. This restriction not only posed a limitation on the overall system's power output but also affected the scalability and real-world applicability of our simulation.

5.2 Mismatch in System Capacities

Integrating a 1 MVA solar PV system into a configuration initially designed for 900 MVA posed a significant hurdle. When connected to the 900 MVA system, the power flow shifted disproportionately towards the PV side, leading to improper output. This disparity between the designed capacity and the actual operational capacity demanded a meticulous reassessment of the entire system architecture to ensure seamless integration and optimal performance.

5.3 Dynamic Power Flow Challenges

The dynamic nature of power flow, especially when the PV system was connected to the larger network, introduced complexities that were initially unforeseen. The challenges manifested as deviations in power distribution and fluctuations in output, highlighting the need for a more robust control strategy and thorough system analysis.

5.4 Generator Simulation Difficulties

Simulating a typhoon scenario, particularly in generating accurate and stable higher values such as 900 MVA and 20 kV, proved to be a daunting task. Achieving these values without introducing excessive oscillations and phase differences required a delicate balance between the simulation parameters, and the iterative process was both time-consuming and intricate.

In conclusion the intricacies of maintaining stability, preventing voltage deviations, and ensuring consistent power flow demanded an adequate understanding of the interactions between renewable sources and conventional generators.

Chapter 6

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