STUDY THE DYNAMIC PERFORMANCE OF AN AC MULTIMACHINE POWER SYSTEM WITH PV INTEGRATION

By

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A thesis submitted to the Department of Electrical and Electronic Engineering in partial fulfillment of the requirements for the degree of
Master of Science in Electrical & Electronic Engineering

Department of Electrical and Electronic Engineering
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Declaration

It is hereby declared that

1. The thesis submitted is my own original work while completing degree at Brac University.
2. The thesis does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The thesis does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. I have acknowledged all main sources of help.

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Approval

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Ethics Statement

This is to certify that the project titled "Study the Dynamic Performance of an AC Multimachine Power System with PV Integration" represents my original research conducted as part of the partial fulfillment requirements for the degree of Master of Science in Electrical and Electronic Engineering. This work was carried out under the supervision of Dr. Abu Hamed M. Abdur Rahim, Professor, Department of Electrical and Electronic Engineering, Brac University. I affirm that this work has not been submitted or published elsewhere for the award of any other degree. All research papers, journals, articles, and other sources consulted during the project are duly acknowledged in the reference section.

Abstract

The integration of photovoltaic (PV) systems into multimachine AC power grids is vital for addressing the growing demand for clean and sustainable energy. This study investigates the dynamic performance of a multimachine AC power system with integrated PV generation. A detailed AC system model is developed. After conducting load flow analysis, one of the synchronous generators is replaced with a PV system to simulate renewable energy penetration. PV model is implemented to accurately represents its behavior in the grid. A PI controller is designed and applied to the system to enhance grid stability through voltage and frequency regulation. Since PV systems typically inject only real power and do not contribute reactive power support, thereby directly enhancing the damping characteristics of the system.

The model development and simulations are performed and validated in MATLAB. Results reveal the impact of PV integration on the multimachine system, showing variations in transient stability and fault response. The integration of PV into the AC system contributes energy production as well as improves system transient performance, reducing generator stress, and improving overall dynamic stability. This study offers 5th order modeling for generators and new insights into the role of renewable generation in supporting conventional grid systems, particularly under transient and dynamic operating conditions.

Dedication

DEDICATED

TO MY

BELOVED PARENTS,

LOVING WIFE,

SUPERVISOR

&

TANVIR MAHMUD MAHIM

Acknowledgement

This project would not have been possible without the consistent guidance, unwavering support, and invaluable insights of my project supervisor, Prof. Dr. Abu Hamed M. Abdur Rahim. His door was always open, offering help and clarification whenever I faced challenges or had questions regarding the project. I am profoundly grateful for his mentorship.

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List of Acronyms

CCM	Continuous Conduction
DCM	Discontinuous Conduction Mode
NREL	National Renewable Energy Laboratory
PCC	Point of Common Coupling
PCU	Power Conditioning Unit
PI	Proportional-Integral
PV	Photo-Voltaic
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
VSI	Voltage Source Inverter

Chapter 1

Introduction

1.1 Photovoltaic (PV) energy and electric power system

Photovoltaic (PV) energy, considered as nonpolluting and economically viable, has become one of the most promising and important sources of renewable energy all over the world. PV generation technology has experienced rapid development in the last few decades [1]. Countries like Germany, China, and the USA have made significant investments in PV technology, with Germany having more than 50 GW of installed solar capacity, contributing to a substantial portion of its electricity generation [2]. The European Union has set ambitious renewable energy targets, aiming to achieve at least 32% renewable energy contribution to the electrical energy demand by 2030 [3]. To work towards such targets, several energy policies and programs have been proposed globally. In the USA, solar power has grown to produce approximately 3% of the total electricity demand [4]. Presently, solar energy meets about 5% of the total electricity demand in Europe [5]. The annual growth rate of solar capacity continues to increase, with projections indicating solar energy could account for more than 15% of global electricity demand by 2040 [6]. PV technology has rapidly evolved, with commercial solar panels now reaching efficiencies exceeding 22% and larger utility-scale PV plants surpassing 100 MW capacities [7].

PV systems convert solar energy into electrical energy through semiconductor materials, typically using silicon-based solar cells [8]. Depending on the system design, PV systems can be connected to the grid via inverters, which transform the DC output of the solar panels into AC power compatible with the grid [9]. Grid-tied PV systems commonly use voltage source inverters (VSI) to synchronize with the utility grid, ensuring stable and reliable power injection

[10]. To enhance efficiency and flexibility, advanced inverter control strategies are often employed [11].

In large-scale PV power plants, inverters are used not only to feed power into the grid but also to provide ancillary services such as reactive power support, voltage regulation, and fault ride-through capabilities [12]. Integrating PV systems into an AC multimachine power system poses several challenges, including voltage fluctuations, frequency stability, and dynamic responses during grid disturbances [13]. Without proper control strategies, connecting a PV system directly to the AC grid can lead to suboptimal performance, such as voltage rise at the point of common coupling (PCC) and inefficient power delivery [14]. If the interconnection is made to a weak grid system, the fluctuating output power from PV systems can cause voltage instability at the PCC, necessitating reactive power management for voltage regulation [15]. The dynamic performance of the grid following faults and disturbances remains a crucial area of study, especially with the growing penetration of renewables like PV into conventional power systems [16].

1.2 PV System Studies

The composition of PV power generation systems is characterized by solar panels converting sunlight into electrical energy, which is then processed through inverters to produce AC power suitable for grid integration [17, 18]. Unlike wind turbines, PV systems have no rotating mass or mechanical inertia, making their dynamic behavior fundamentally different from conventional synchronous generators. This lack of inertia can impact frequency stability, especially under high PV penetration scenarios, posing challenges for maintaining grid stability [19]. When connected with the conventional power grid, these inverters interact asynchronously with synchronous generators. Consequently, the entire power generation system behavior differs from traditional setups [20]. The dynamic behavior of PV systems is influenced by various factors, including temperature, irradiance, and load conditions. These parameters affect voltage stability, necessitating comprehensive analysis to ensure reliable grid operation [21]. To address these challenges, accurate modeling of PV inverters is crucial. Advanced control strategies, such as model predictive control, have been proposed to enhance the dynamic performance and stability of grid-connected PV systems [22].

The assessment of the effects of PV power penetration into an existing power system necessitates the calculation of voltage and frequency profiles and examination of instability issues. As in the case of all AC systems, two types of instability issues may arise when a PV system is integrated into an AC system: dynamic stability and transient stability [23, 24]. In systems consisting solely of synchronous generation, loss of synchronism is the normal mode of transient failure. However, in networks having both PV and conventional synchronous generation, transient failure may be encountered for other reasons such as the collapse of system voltage or inverter control malfunctions [25]. The transient and dynamic stability of a power system are usually assessed through time-domain as well as frequency-domain analysis using large-signal and small-signal models respectively [26-27]. Although time-domain simulation offers direct appreciation of the PV generation system dynamic behavior in terms of visual clarity, it is not able to identify and quantify the cause of problems.

1.3 PV System Control

Operation of a PV system under disturbances within the nearby power system poses significant concerns. Faults in the network can lead to voltage instabilities and frequency fluctuations in conventional power systems. Unlike wind farms, which often use induction machines, PV systems rely on inverters that control the flow of active and reactive power. Tripping of the inverters due to voltage dips or control malfunctions can result in voltage instability, and even small disturbances may cause inverter disconnection, leading to further instabilities. To enhance transient stability, various methods have been suggested, focusing on voltage regulation and inverter control strategies.

In PV systems, the dynamic response to disturbances is largely governed by the inverter's control system. One widely used approach is the Proportional-Integral (PI) controller, which plays a critical role in maintaining grid stability by adjusting the inverter’s output to manage both active and reactive power. PI controllers are employed to regulate the voltage at the point of common coupling (PCC) and stabilize the frequency by modulating the power injected into the grid [28, 29]. Compared to STATCOM used in wind systems — which provides reactive power support and voltage control — the PI controller in PV systems works within the inverter control loop itself, offering a direct and seamless method to stabilize grid parameters without requiring additional hardware. This integrated approach ensures a fast and coordinated response to grid disturbances, helping restore voltage levels, re-establish grid synchronization, and prevent disconnection of the PV system during faults.

The choice of PI controllers for PV systems stems from their simplicity, ease of implementation, and effectiveness in maintaining steady-state and transient stability. While other advanced control methods like model predictive control or fuzzy logic control exist, PI controllers remain popular due to their proven reliability and minimal computational requirements. The effectiveness of PI controller hinges on proper tuning of control parameters, as poorly tuned controllers can result in oscillations or sluggish responses. Recent studies highlight various methods for tuning PI controllers, such as Ziegler-Nichol’s tuning [30], model-based tuning [31], and adaptive control strategies [32]. These methods aim to optimize the dynamic performance of PV systems under both steady-state and transient conditions. Additionally, combining PI control with advanced algorithms like feedforward control or state feedback control has been reported to further improve grid stability and fault ride-through capability of PV systems [33, 34].

1.4 Background and Motivation

The global shift towards sustainable energy has intensified efforts to integrate renewable energy sources (RES) into existing power grids. Among these, photovoltaic (PV) systems have gained prominence due to their ability to convert solar energy into electricity efficiently. The integration of renewable energy sources, especially solar and wind energy, into power systems has become increasingly important due to the growing need for sustainable and clean energy solutions.

Several studies have explored the dynamic behavior of multimachine power systems and the integration of PV systems. The importance of dynamic performance improvement in multimachine systems, particularly when incorporating renewable energy sources such as wind or PV systems [35]. We investigated that Dynamic performance is critical to ensuring stable operation in multimachine grids under varying load and generation conditions.

According to our study, integrating PV systems into power grids introduces challenges related to optimal power flow and voltage regulation. It can be highlighted that advanced control techniques are required to ensure stability and optimal performance when PV systems are added to traditional grids [36]. Furthermore, the intermittent nature of solar energy complicates the task of balancing supply and demand, thereby impacting overall grid reliability [37]. These challenges are magnified in multimachine systems where power flow, transient stability, and fault dynamics become increasingly complex with the integration of PV systems [38].

In recent years, control strategies for PV systems have evolved significantly. Modern controllers are designed to regulate voltage and frequency dynamically while ensuring optimal power flow. These advancements emphasize the need for a holistic approach to integrating PV systems into multimachine power grids [39]. The integration of PV systems into multimachine power systems requires a comprehensive approach that combines advanced modeling, synchronization strategies, and control techniques. This study builds on existing research to address the challenges of dynamic performance and grid stability.

This research seeks to address these challenges by developing a dynamic model for an AC multimachine power system integrated with a PV system. The study also aims to design and implement advanced control strategies to regulate voltage and frequency, ensuring grid stability and reliable operation under various conditions. The results will provide valuable insights into the dynamic performance of renewable energy-integrated power systems and contribute to advancing the integration of PV systems into the modern grid.

1.5 Objective

The main objective of this study is modeling and performance analysis of an AC multimachine power system integrated with a photovoltaic (PV) system.

- To develop an AC multimachine system model including a load flow model and also a transient stability model.
- To develop dynamic model of a PV system.
- To integrate the AC and PV dynamic models.
- To develop algorithms using MATLAB programming.
- To test the algorithm considering different PV inputs.
- To implement controllers to stabilize the system and to improve the overall grid performance.

Chapter 2

Literature Review

2.1 Introduction

The increasing integration of renewable energy sources (RES), particularly photovoltaic (PV) systems, into modern power grids has led to major transformations in power system planning, operation, and stability analysis. As global energy demand rises and environmental concerns grow, PV systems offer a promising solution due to their sustainability and decreasing cost. However, integrating PV into multi-machine power systems introduces complex challenges related to dynamic stability, control, synchronization, and power quality. This chapter reviews the existing literature on PV integration, modeling techniques, control strategies, and the dynamic behavior of such systems.

2.2 Synchronous Generators and Modeling

Synchronous generators, also known as alternators, play a critical role in conventional AC power systems as they are the primary sources of electrical energy in large-scale power generation. These generators operate based on the principle of electromagnetic induction, where a rotor with a DC field winding rotates inside a stator with three-phase armature windings to produce an AC voltage. The synchronous generator maintains a fixed relationship between the frequency of the output voltage and the mechanical speed of the rotor, making it essential for maintaining system stability and synchronization within multimachine networks [40].

The dynamic performance of synchronous generators is a key concern in power system stability studies. Their response to disturbances such as load changes, faults, or generator tripping significantly affects the overall behavior of the system. Classical modeling of synchronous machines includes the swing equation, which captures the rotor angle dynamics, while more detailed models incorporate the excitation system, governor, and damper windings to reflect electromechanical and electromagnetic dynamics accurately [41-42]. These models are crucial when analyzing the interaction between multiple synchronous machines and other dynamic elements in the power grid.

In multimachine systems, synchronous generators are interconnected through transmission networks and exhibit complex inter-machine oscillations. Small-signal and transient stability analyses are often performed to assess how these generators respond to disturbances and how power oscillations propagate through the system [43]. Modeling these dynamics accurately is vital, as it helps determine the impact of reduced mechanical inertia and altered power flow patterns on system stability.

The modeling of synchronous generators forms the foundation of dynamic analysis in power systems. These machines are inherently nonlinear and exhibit both electrical and mechanical dynamics, necessitating mathematical models that can capture their transient and steady-state behavior accurately. At the most basic level, the classical model of a synchronous generator simplifies the machine to a constant internal voltage source behind a transient reactance. This model is primarily used for transient stability studies where fast electrical transients are neglected, and the focus is on the rotor angle swing dynamics governed by the swing equation [44].

For detailed and accurate system studies, especially in multimachine configurations, higher-order models are used. These include fourth-order, sixth-order, and even ninth-order models that represent both d-axis and q-axis dynamics. The sixth-order model, for instance, includes stator dynamics, field winding, and damper windings on both axes, offering a comprehensive representation of electromagnetic transients. These models use Park's transformation to convert three-phase quantities into a rotating reference frame, simplifying the mathematical treatment of the machine under dynamic conditions [45], [46].

Moreover, the inclusion of control components such as excitation systems and governors enhance the fidelity of synchronous generator models. Excitation systems are responsible for voltage control and are typically modeled. Speed governors and turbine models, on the other hand, regulate mechanical input and influence frequency response. These components are crucial in modeling the primary frequency control behavior of the generator, and they are often incorporated as first- or second-order systems with specific time constants and gains [47].

In multimachine systems, modeling also accounts for the interaction between synchronous machines via the power network. This involves solving network equations simultaneously with the machine equations using numerical methods. Load flow data provides the initial conditions for dynamic simulations, while the network admittance matrix (Y-bus) is updated during each integration step to reflect changes in system topology and operating conditions. Accurate synchronous generator models, therefore, form a critical component of dynamic simulation environments used to assess power system performance under various disturbances [48].

2.3 Multimachine Systems Study

The procedure for conducting transient stability analysis in AC multimachine power systems is well-established [46]. However, this area remains underexplored when it comes to systems that include both synchronous generators (SGs) and induction generators (IGs). In recent years, several studies have emerged focusing on the stability of power systems with wind power integration. Some of these investigations utilized highly simplified system configurations, typically comprising a single SG, a single IG, and an infinite bus [47-49]. While these tools are powerful, their closed-source nature limits accessibility and flexibility for further academic research. The results from such studies have been presented using both time-domain simulations (TDS) [48], [50-51] and frequency-domain methods [52-53]. Among these, time-domain simulations are particularly valuable for visually interpreting system dynamics following disturbances; an advantage not offered by eigenvalue-based analyses [54].

For load flow studies, the induction generator is typically modeled as a PQ bus [55-56]. During steady-state analysis, parameters such as initial slip and reactive power consumption of the IG are calculated [57]. To ensure that the IG operates at unity power factor under steady-state conditions, a fixed capacitor is placed at the generator terminal to supply the required reactive power. Once the load flow solution is obtained, the dynamic initialization of the generators is carried out by solving their corresponding sets of differential-algebraic equations, with all time derivatives initially set to zero.

2.4 Photovoltaic System

Photovoltaic (PV) technology enables the direct conversion of solar energy into electricity using semiconductors through the photoelectric effect. A typical PV system consists of solar arrays made up of interconnected solar cells arranged in series-parallel configurations. The amount of electrical power generated is influenced by both the number of cells and the specific configuration of the array.

Numerous studies in the literature have focused on developing detailed PV models using power electronic components [58-61]. These comprehensive models often incorporate both the PV array and its control circuits, allowing for accurate representation of the system's behavior. However, due to their complexity, such models are computationally intensive and may not be suitable for microgrid-level studies. Alternatively, some researchers have represented PV systems using simplified models either as constant real power sources [62] or as negative constant power loads [63] primarily for steady-state analysis. While these simplifications help reduce computational burden, they are inadequate for dynamic analysis and control design.

One dynamic PV model, developed by T. Yun [64], was built using real-world data from a specific PV panel and a pulse-width modulated inverter. Although mathematically comprehensive, the model lacked flexibility for implementing control strategies due to its dependence on the fixed system structure. The National Renewable Energy Laboratory (NREL) introduced a simplified PV model [65] that treated the PV system as a current-controlled source, considering only current magnitude and phase angle. This model excluded the DC-side dynamics and lacked closed-loop control, limiting its applicability in dynamic studies. A more recent approach proposed modeling the PV system as a voltage source [58], which preserves a greater number of system signals and is more suitable for control design. However, its impact on the dynamic stability of microgrids still requires further investigation.

In another effort, a PV-based stabilizer was developed to improve network dynamic performance [66], though the model did not include DC-side components or control loops. A comparative study between detailed and simplified dynamic PV models integrated into power networks was carried out in [67]. However, the PV units were treated as non-dispatchable sources, making them unsuitable for microgrids where controllable power injection is required.

Widespread integration of PV systems into power networks can introduce technical challenges such as voltage and current harmonics, flicker, voltage fluctuations, and increased stress on distribution transformers. A common issue in heavily PV-penetrated systems is the voltage rise at the point of common coupling (PCC), often caused by reverse power flow on sunny days.

2.5 Photovoltaic System Modeling

Photovoltaic (PV) system modeling plays a critical role in analyzing and predicting the dynamic behavior of solar energy integration in modern power systems. At the core of PV modeling is the electrical representation of solar cells, typically achieved using an equivalent circuit that includes a current source, a diode, a shunt resistance, and a series resistance. The output of a PV cell is influenced by factors such as irradiance, temperature, and shading, which are incorporated into the mathematical models to simulate realistic power output under varying environmental conditions [68-69].

For system-level analysis, PV arrays composed of multiple cells in series and parallel configurations are modeled along with the associated power electronic interface, usually a DC-DC converter and a voltage source inverter (VSI). The inverter plays a vital role in regulating voltage, frequency, and synchronization with the grid. Detailed dynamic models incorporate the control loops for maximum power point tracking (MPPT), voltage regulation, and current control. These models are essential for understanding how PV systems respond to transients and disturbances in both standalone and grid-connected modes [70-71].

Modeling approaches can be broadly categorized into detailed, simplified, and average models. Detailed models simulate switching behavior and internal dynamics of converters, providing high accuracy but at the cost of computational efficiency [72]. In contrast, average models neglect switching and focus on the dynamic response of the overall system, making them suitable for large-scale system simulations and control development. Simplified models often treat the PV system as a controlled voltage or current source, used in cases where the emphasis is on grid behavior rather than the internal dynamics of the PV system [73].

Furthermore, several modeling standards and guidelines have been proposed by institutions like the National Renewable Energy Laboratory (NREL) and IEEE to ensure uniformity and compatibility in simulation environments [74]. For instance, the NREL's System Advisor Model (SAM) offers validated PV models for performance prediction, while MATLAB/Simulink, PSCAD, and DIgSILENT provide platforms for dynamic simulations using both built-in and custom-designed PV blocks [75].

The level of model complexity is typically chosen based on the study objective whether it is power flow analysis, stability study, fault response, or control system development. In recent works, voltage source models have been preferred over current source models due to their closer alignment with actual inverter behavior and ability to preserve essential PV signals for control design [76-77]. However, challenges remain in accurately modeling grid disturbances, islanding conditions, and PV inverter fault ride-through capabilities under high penetration scenarios.

2.6 AC System with Integrated PV

The integration of photovoltaic (PV) systems into alternating current (AC) power networks has gained significant momentum in recent years, driven by the global transition toward renewable energy sources and sustainability goals [78]. While PV systems inherently produce direct current (DC) power, their integration into conventional AC grids requires sophisticated interfacing through power electronic converters typically involving inverters that enable synchronization with grid voltage and frequency. These inverters not only convert DC to AC but also regulate voltage, control power flow, and manage reactive power support [79].

Power system stability is a core focus in multi-machine grids. Research has shown that understanding the dynamic behavior of PV systems and their interaction with other grid components is essential for maintaining system reliability [80]. Dynamic models of multi-machine power systems, including those involving renewable generation sources, have become a critical tool for analyzing these systems under various operating conditions. State-space models, for instance, are widely used for dynamic analysis of multi-machine grids [81], providing valuable insights into system behavior and enabling the development of effective control strategies [82].

Integrating PV into AC systems introduces new dynamics that significantly affect both steady-state and transient performance. Several studies have investigated the impact of large-scale PV integration on voltage profiles, power quality, and system reliability [83]. For example, during high solar irradiance and low demand periods, reverse power flow may occur, causing voltage rise issues at the point of common coupling (PCC) and potentially disrupting conventional voltage regulation schemes [84]. Additionally, the variability and intermittency of solar generation impose new challenges for load balancing and frequency stability, especially in weak or lightly loaded grids [85].

From a dynamic perspective, PV systems lack the rotational inertia inherent in traditional synchronous generators. This absence of inertia reduces the system’s ability to withstand frequency deviations during disturbances, which is a key factor in transient stability. To mitigate these effects, advanced inverter control strategies such as grid-following and grid-forming inverters have been developed [86]. Grid-forming inverters, in particular, are designed to mimic synchronous machine behavior and contribute synthetic inertia, thus improving the dynamic response of PV-integrated systems [87].

Another critical area of research focuses on the interaction between PV inverters and other components in multimachine AC systems, such as synchronous generators, loads, and other renewable sources. Studies show that improper tuning of inverter control parameters can lead to instability, resonance, or undesirable power oscillations, especially in systems with high PV penetration [88]. Accurate dynamic modeling and coordinated control are therefore essential for ensuring reliable operation. Tools like MATLAB/Simulink, PSS/E, and PSCAD have been employed to simulate various scenarios, including fault ride-through, load changes, and grid disturbances, to evaluate the dynamic performance of integrated systems [89-90].

2.7 Controller System Studies

The importance of optimization and control techniques is also highlighted in the literature, with various strategies proposed to manage the inherent variability of renewable generation. Optimal power flow techniques, particularly in grids with PV integration, aim to maximize system efficiency while minimizing power loss [91]. Now-a-days hybrid control methods have been developed to enhance the performance of inverter-based PV systems in multi-machine grids, ensuring that they operate in harmony with other grid elements [92]. Differential equations are frequently used to model the dynamic interactions between these control systems and the power grid, enabling the analysis of transient stability and other key performance indicators [93].

Controller systems play a pivotal role in managing the operation and stability of PV-integrated AC systems. These systems are designed to optimize the interaction between the photovoltaic (PV) arrays, inverters, and the grid, ensuring maximum energy efficiency, voltage regulation, and seamless operation during disturbances. The most common control strategies for PV inverters are maximum power point tracking (MPPT) and voltage and current control. MPPT algorithms ensure that the PV system operates at its maximum power output, adapting to variations in solar irradiance and temperature. Voltage and current controllers, on the other hand, regulate the power exchange between the PV system and the grid to maintain stability and meet grid code requirements [94].

One of the most widely used MPPT techniques is the Perturb and Observe (P&O) method, which adjusts the operating point of the PV array by perturbing the voltage and observing the corresponding change in power [95]. Although simple and effective, the P&O method can be affected by rapid fluctuations in irradiance, leading to oscillations around the maximum power point. To address this, more sophisticated MPPT algorithms, such as Incremental Conductance

(INC), Constant Voltage, and Fuzzy Logic Control (FLC), have been developed. INC, for example, calculates the derivative of the power-voltage characteristic and adjusts the operating point based on the direction of change in power, ensuring faster convergence to the maximum power point under varying environmental conditions [96].

In addition to MPPT, inverter control is critical for the dynamic stability of the PV-integrated AC system. The inverters use voltage-oriented control (VOC) or current-oriented control (COC) strategies to ensure accurate synchronization with the grid. These control methods regulate the output voltage or current to match the grid frequency and voltage profile. VOC, which is commonly used in grid-connected PV systems, adjusts the voltage phase and amplitude to maintain synchronization with the grid and improve power quality [97]. COC, on the other hand, directly controls the current injected into the grid, often employing a PI (Proportional-Integral) controller to manage the power flow and ensure the grid operates within the specified voltage and frequency limits [98].

For enhanced stability and reliability in the event of grid disturbances, grid-forming inverters have been proposed. These inverters are designed to simulate the behavior of synchronous generators by contributing synthetic inertia to the system. This characteristic is essential for maintaining frequency stability during disturbances and load fluctuations in microgrids. Research indicates that grid-forming inverters, when properly coordinated with conventional generators, can significantly improve the robustness of the power system under high PV penetration [99].

Moreover, the integration of advanced control techniques such as model predictive control (MPC) and adaptive control has gained traction in recent years. MPC optimizes the control actions by predicting future system behavior, thus providing better performance in dynamic environments. Adaptive controllers, on the other hand, adjust their parameters in real-time to account for changes in system dynamics and external conditions, offering improved performance in systems with varying PV generation profiles [100].

In conclusion, dynamic modeling and the use of differential equations are central to understanding and optimizing the performance of PV-integrated multi-machine power systems. As renewable energy sources continue to be incorporated into modern grids, the development of sophisticated models and control strategies is essential to ensure system stability, reliability, and efficiency. Future work in this area should focus on refining these models, particularly in terms of handling transient stability, power flow optimization, and the dynamic interaction between PV systems and conventional grid components.

Chapter 3

Dynamic Modeling of AC-PV Systems

A synchronous machine is one of the most crucial components in power systems, functioning as a generator. For transient and stability analysis, dynamic modeling is necessary, and the 5th-order model is a widely used representation. This model considers the rotor dynamics and the effects of flux linkages in the d-q-axes.

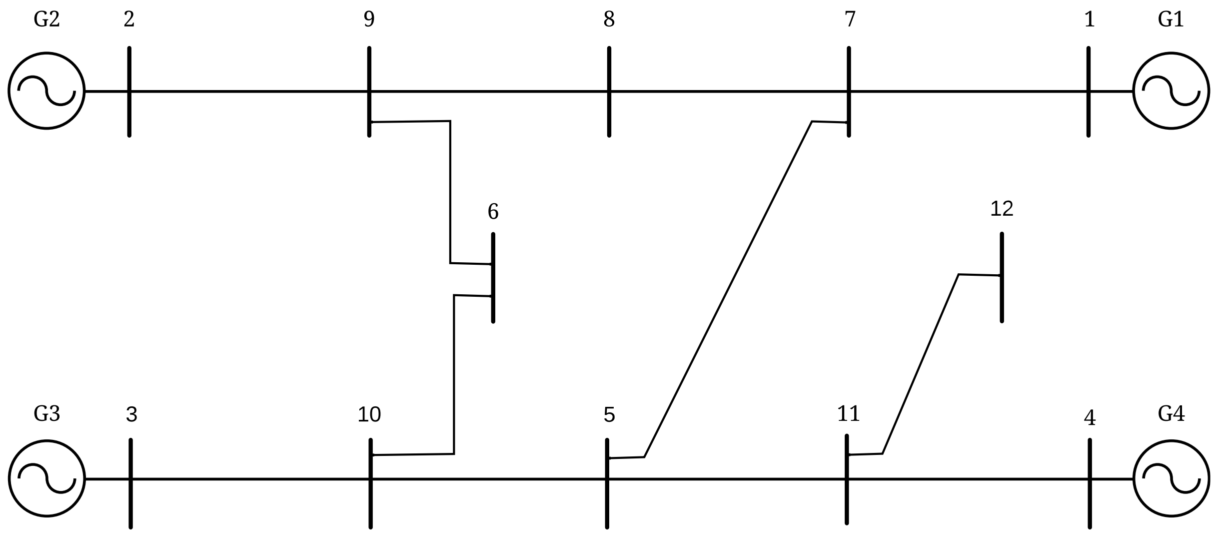

Fig. 3.1 Bus diagram of the Multimachine System

A 4-machine 12-bus power system considered in this study as shown in Figure 3.1. The generation and load data for the base case are given in Appendix A. The loads are represented by constant impedance and all network voltages and currents are written in common network reference frame [D-Q] rotating at synchronous speed.

3.1 Dynamic Modeling of Synchronous Generator

In this work, the generator model was extended from a 3rd-order to a 5th-order representation to achieve greater accuracy in capturing the dynamic behavior of synchronous machines. While the 3rd-order model includes rotor angle, speed, and the transient EMF on the direct axis, it omits key dynamics associated with the excitation system and damper windings. The 5th-order model incorporates these additional states, specifically the field winding and quadrature-axis transient EMF, enabling a more realistic representation of transient and sub-transient responses.

The generators are linked to the bus, and the system is modeled using a 5th-order representation that includes the swing equation and the internal voltage equation of the generator [101]. The swing equation can be expressed as two first order differential equation as

$$\frac{d\delta}{dt} = \omega_0(\omega - 1) \tag{3.1.1}$$

$$\frac{d\omega}{dt} = \frac{1}{2H}[P_m - P_e] \tag{3.1.2}$$

In equations (3.1.1) and (3.1.2) δ and ω represent the rotor angle and rotor speed, respectively. P_m and P_e denote the mechanical power input and the electrical power output of the generator. and H is the inertia constant of the generator. The internal voltage e'_d and e'_q is expressed as follows,

$$\frac{de'_q}{dt} = \frac{1}{T'_{d0}}\left[E_{fd} - (x_d - x'_d) \cdot i_{d1} - e'_q\right] \tag{3.1.3a}$$

$$\frac{de'_d}{dt} = \frac{1}{T'_{q0}}\left[-e'_d - \left(x_q - x'_q\right) \cdot i_{q1}\right] \tag{3.1.3b}$$

here x_d, x'_d, x_q, x'_q, T'_{d0} and T'_{q0} refer to the d-axis and q-axis synchronous reactance, transient reactance, and open-circuit field time constant, respectively. The voltage, e'_d and e'_q represents the internal voltage behind the transient reactance along the d-axis and q-axis. Additionally, an IEEE Type Static excitation system is utilized for the voltage regulator.

$$\frac{dE_{fd}}{dt} = \frac{1}{T_a}\left[k_a\left(U_{ref} - V_{t1}\right) - \left(E_{fd} - E_{fd0}\right)\right] \tag{3.1.4}$$

here E_{fd} denotes the field voltage along the d-axis, while k_a and T_a represent the gain and time constant of the exciter, respectively.

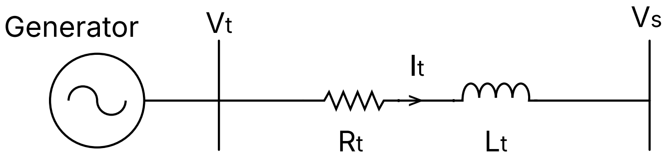

Fig. 3.2 Generator connected to the Grid

Based on Figure 3.2, the terminal voltage of the generator is expressed as follows

$$V_t = V_s + (r_t + jx_t) \cdot i_t \tag{3.1.4a}$$

Expressed in d-q terms

$$V_d + jV_q = V_{sd} + jV_{sq} + (r_t + jx_t) \cdot \left(i_{td} + ji_{tq}\right)$$

$$x_q i_{tq} + j\left(e'_q - x'_d i_{td}\right) = \left(V_{sd} + r_t i_{td} - x_t i_{tq}\right) + j\left(V_{sq} + r_t i_{tq} + x_t i_{td}\right)$$

Real part:

$$x_q i_{tq} = V_{sd} + r_t i_{td} - x_t i_{tq}$$

$$\left(x_q + x_t\right) i_{tq} - r_t i_{td} = V_{sd} \tag{3.1.5}$$

Imaginary part:

$$e'_q - x'_d i_{td} = V_{sq} + r_t i_{tq} + x_t i_{td}$$

$$r_t i_{tq} + (x'_d + x_t) i_{td} = e'_q - V_{sq} \tag{3.1.6}$$

After solving (3.1.5), (3.1.6) and putting $x_1 = (x'_d + x_t)$ and $x_2 = \left(x_q + x_t\right)$ we get,

$$i_{td} = \frac{-r_t V_{sd} + (e'_q - V_{sq})\{x_q + x_t\}}{r_t^2 + \{x'_d + x_t\}\{x_q + x_t\}} \tag{3.1.7}$$

$$i_{tq} = \frac{V_{sd}[\{x'_d+x_t\}\{x_q+x_t\}]+r_t(e'_q-V_{sq})\{x_q+x_t\}}{\{x_q+x_t\}[r_t^2+\{x'_d+x_t\}\{x_q+x_t\}]} \quad (3.1.8)$$

The terminal voltage of the generator is expressed as

$$V_t = \sqrt{V_d^2 + V_q^2}$$

$$V_t = \sqrt{\left(x_q i_{tq}\right)^2 + \left(e'_q - x'_d i_{td}\right)^2} \quad (3.1.9)$$

The power output is represented as follows

$$P_e = V_d i_{td} + V_q i_{tq}$$

$$P_e = \left(x_q i_{tq}\right) i_{td} + \left(e'_q - x'_d i_{td}\right) i_{tq}$$

$$P_e = \left(e'_q i_{tq}\right) + \left(x_q - x'_d\right) i_{td} i_{tq} \quad (3.1.10)$$

By substituting equations (3.1.7) and (3.1.8) into equations (3.1.9) and (3.1.10), the terminal voltage and the generator's power output can be expressed in terms of the grid voltage components V_{sd} and V_{sq}.

3.2 Photovoltaic (PV) system

A solar cell is the fundamental unit of a photovoltaic array, composed of a semiconductor device that functions as a current source driven by solar radiation from the sun. The characteristics of an ideal solar cell, when not illuminated, are similar to those of an ideal diode. The performance of a photovoltaic (PV) system is largely influenced by factors such as irradiation, array short-circuit current, array open-circuit voltage, cell temperature, and the load connected to the array [102]. The output current and power of the PV system are approximately proportional to the irradiance. Additionally, at a given irradiance, the array voltage is determined by the load characteristics. PV systems exhibit nonlinear current-voltage (I-V) and power-voltage (P-V) characteristics, which vary with radiation intensity and cell temperature. While the output current of the PV system is minimally affected by temperature changes, an increase in temperature leads to a slightly higher output current. However, this temperature rise causes the PV cell to operate at a lower voltage, significantly reducing the power output of the PV system [103].

A general mathematical model for the I-V characteristics of a solar cell has been extensively studied over the years. The typical equivalent model includes a photocurrent, a diode, a shunt resistor to represent leakage current, and a series resistance to account for the internal resistance to current flow, as shown in Figure 3.3. The net output current from the PV cell is the difference between the photovoltaic current I_{ph} and the sum of normal diode current I_D and leakage current I_{sh} through the shunt resistance R_{sh}.

$$I_{pv} = I_{ph} - I_D - \frac{(V_{pv}+I_{pv} \cdot R_s)}{R_{sh}} \qquad (3.2.1)$$

The diode current I_D is given as

$$I_D = I_s\left(e^{\frac{V_{pv}+R_S \cdot I_{pv}}{nV_T}} - 1\right) \qquad (3.2.2)$$

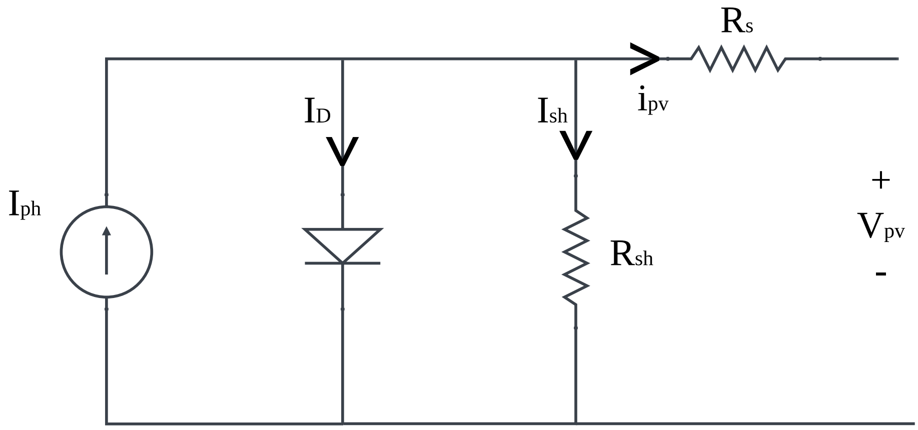

Fig. 3.3 Equivalent model of solar cell

where, I_{pv} is the cell current, V_{pv} is the cell voltage, I_s is the reverse saturation current (which is strongly dependent on temperature), n is an ideality factor (for ideal diode, n = 1), R_s is a series resistor, R_{sh} is the shunt resistance, $V_T = \frac{kT}{q}$ is the thermal voltage also the same as output voltage of PV, $k = 1 \cdot 38 \times 10^{-19}$ is a Boltzmann constant, T is a cell’s working temperature and $q = 1 \cdot 6 \times 10^{-19}$ is the charge of the electron. The light-generated current primarily depends on the cell's working temperature and solar irradiance. For a given cell temperature (T), the photocurrent is given as:

$$I_{ph} = \left[I_{sc} + a\left(T - T_{ref}\right)\right]G \tag{3.2.3}$$

In the above, I_{sc} is the cell’s short current at a 25^0C and 1 kW/m^2, ‘a’ is the temperature coefficient of I_{sc}, T_{ref} is the cell’s reference temperature and G is the irradiation in kW/m^2. The reverse saturation current is also temperature dependent and at a given temperature (T) it is given as

$$I_s = I_{sref}\left(\frac{T}{T_{ref}}\right)^{\frac{3}{n}} \cdot e^{\frac{-q \cdot E_g}{nk}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)} \tag{3.2.4}$$

where I_{sref} represents the cell’s saturation current at a reference temperature and solar irradiation, and E_g is the energy band-gap of the semiconductor material used in the solar cell. The shunt resistance R_{sh} is inversely related to the leakage current that flows to the ground. Generally, the PV system’s performance is not greatly affected by R_{sh}, so it is often assumed to be infinite. However, even a slight change in R_s (the series resistance) can have a considerable effect on the power output of the PV system. The approximate model of the PV system is illustrated in Figure 3.4.

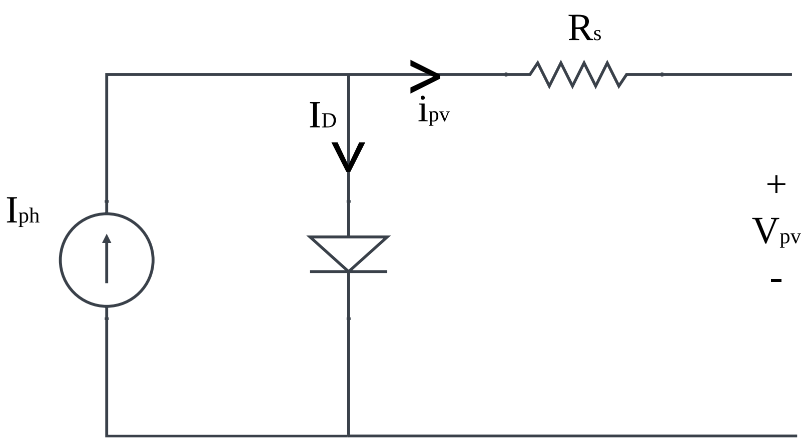

Fig. 3.4 Approximate model of solar cell

The characteristic equation of the cell, based on the approximate model, is given as

$$I_{pv} = I_{sc} - I_s \left[e^{\left(\frac{V_{pv}+I_{pv}\cdot R_S}{nV_T}\right)} - 1 \right] \qquad (3.2.5)$$

The power generated by a solar cell is typically around 2W at 0.5V. Since this power is relatively small, solar cells are often connected in series and parallel to generate power in the range of watts. The characteristic equation for an approximate photovoltaic array, which consists of series modules and parallel modules, can be derived from the approximate PV cell equation and is expressed as

$$I'_{pv} = N_p I_{ph} - N_p I_s \left[e^{\left(\frac{V_{pv}}{N_S}+\frac{I_{pv}\cdot R_S}{N_p}\right)/nV_T} - 1 \right] \qquad (3.2.6)$$

It can be seen from equation (3.2.6) that for a single PV cell, N_s = 1 and N_p = 1. The current-voltage relationship of a PV array, as shown in (3.2.6), is nonlinear. To solve this nonlinear equation, Newton's method [104] is used.

3.2.1 Newton Raphson Algorithm

The Newton-Raphson method is a widely used iterative numerical technique for solving nonlinear equations of the form,

$$f(x) = 0 \qquad (3.2.7)$$

starts from an initial guess x_n the solution is refined iteratively using the update formula,

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \qquad (3.2.8)$$

The iterations can be continued until the error is less than or equal to pre-specified tolerance E_s, defined as

$$\left| \frac{x_{n+1} - x_n}{x_n} \right| \leq E_s \qquad (3.2.9)$$

The Newton-Raphson method, originally developed by Isaac Newton and later generalized by Joseph Raphson, provides a powerful and efficient approach for solving nonlinear equations, such as those encountered in PV system modeling. In this thesis, it is employed to iteratively solve the nonlinear current-voltage relationship of the photovoltaic module, enabling accurate voltage estimation under varying operating conditions [105]. For the PV, the I-V characteristics are related as,

$$V_{pv} = N_s \left[ln\left(\frac{N_p I_{ph} - I_{pv}}{N_p I_s} + 1\right) nV_T - \frac{I_{pv} \cdot R_s}{N_p} \right] \tag{3.2.10}$$

Rewriting the above expression into the function form $f(V) = 0$ we obtain,

$$f(V) = V - N_s \left[nV_T \cdot ln\left(\frac{N_p I_{ph} - I_{pv} - N_p I_s}{N_p I_s}\right) + \frac{I_{pv} \cdot R_s}{N_p} \right] = 0 \tag{3.2.11}$$

Since $f'(V) = 1$, the recursive formula can be written as

$$V_{n+1} = N_s \left[nV_T \cdot ln\left(\frac{N_p I_{ph} - I_{pv} - N_p I_s}{N_p I_s}\right) + \frac{I_{pv} \cdot R_s}{N_p} \right] \tag{3.2.12}$$

3.3 Modeling of PCU of Photovoltaic (PV) Systems

The power conditioning unit (PCU) contains the devices which required for connection of PV array to the grid. The main components of the PCU are DC/DC converter, DC link capacitor, DC/AC inverter and the output filter circuit as shown in figure 3.5. The DC power produced by the PV array is fed to the DC/DC converter. The converter transforms the PV output voltage from one level to another. The DC-link capacitor is a storage device used to maintain constant inverter voltage. The inverter is the core of grid-connected PV system which converts the DC to AC and injects it into the grid. For smoothing the output current, an LC filter is commonly employed between the PV system and utility network. The resistance R_{pdr} in series with the filter capacitor is used to avoid the resonance between the filter capacitor and the coupling inductance. The models for the different components of the PCU are presented in the following. The filter at the output of the inverter is characterized by a resistance R_{pf} and inductance L_{pf}, which help smooth the inverter’s output current. Additionally, a capacitance C_{pf} is used in the filter's parallel branch, along with a resistance R_{pdr}, to further filter the inverter output. The coupling line between the PV system and the grid is modeled with a resistance R_p and inductance L_p. The modulation index of the PV-side inverter is m_p, which determines the degree of modulation applied to the inverter output voltage. On the DC side, the boost converter is represented by a DC inductance L_{dc} and DC capacitance C_{dc}, both of which help regulate the DC voltage before conversion to AC. These parameters collectively define the electrical characteristics of the PV system and play a crucial role in its interaction with the grid. Figure 3.5 shows the schematic representation of the photovoltaic (PV) system parameters.

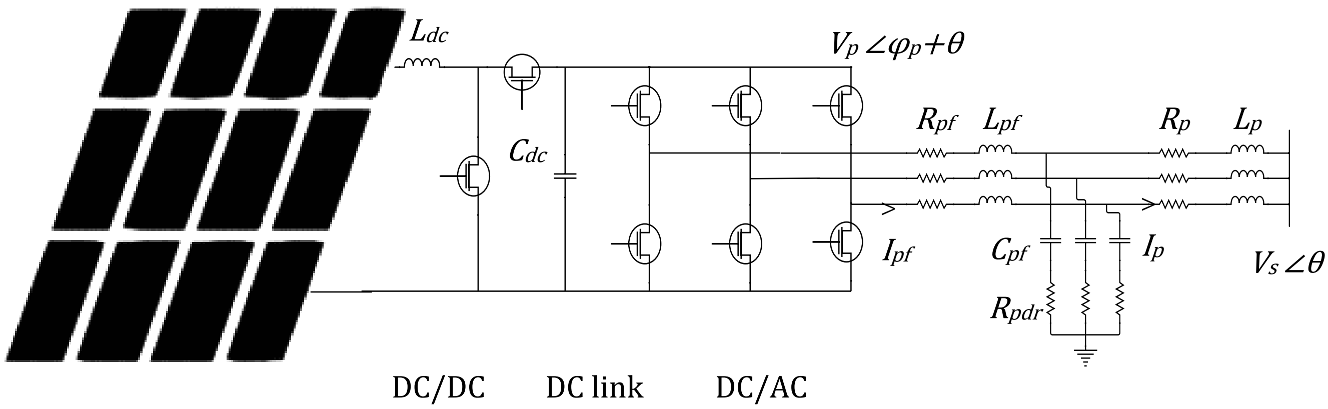

Fig. 3.5 PV array connected to the Grid

3.3.1 DC/DC converter model

The primary function of a DC/DC converter is to either step up or step down the DC output voltage. It consists of power electronic switches and storage components arranged in a manner that allows dynamic control of power transfer from the input to the output via switching. The design of the storage elements ensures a low output ripple voltage (typically less than 3%), which can be achieved by incorporating a low-pass filter [106].

There are various topologies of DC/DC converters, with the two most basic being the boost converter and the buck converter. In this study, a boost converter is used because the output voltage of the PV system always needs to be stepped up. The duty cycle of the DC/DC converter, defined as the ratio of the ON period to the total switching period (T), determines the level of the DC output voltage. A DC/DC converter can operate in continuous conduction mode (CCM) or discontinuous conduction mode (DCM). In CCM, the current fluctuates but never drops to zero, whereas in DCM, the current fluctuates and eventually falls to zero before or at the end of the switching period. For this work, continuous conduction mode is chosen, as the photovoltaic array must supply power to the grid without any interruptions.

Boost Converter:

The primary function of the boost converter is to increase the DC voltage level. It consists of an inductor, a power electronic switch, and a diode. Additionally, it may include a capacitor to smooth the output.

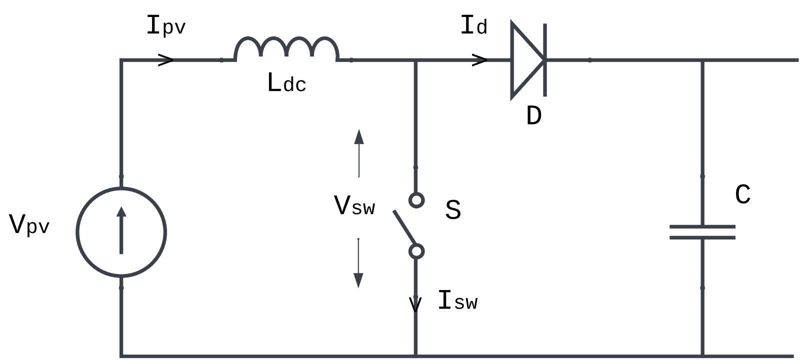

Fig. 3.6 Boost converter

Dynamics of the DC/DC inverter can be easily obtained by applying as

$V'_{pv} = L_{dc}I_{pv} + (1 - dc)V_{dcp}$

which can be written as

$$I'_{pv} = \frac{1}{L_{dc}}\left(V_{pv} - (1 - dc)V_{dcp}\right) \tag{3.3.1}$$

Here, L_{dc} is the inductance of the DC/DC converter.

3.3.2 DC-link Capacitor model

The DC link capacitor in the pulse width modulated (PWM) inverter serves as both an energy storage element and a filter for the DC voltage. The DC/DC converter regulates the voltage across the capacitor, regardless of the inverter's operation, while the inverter adjusts to supply the appropriate current to the grid, which may lead to variations in the capacitor voltage. If the output current of the converter is made equal to the input current of the inverter, no current will flow through the DC-link capacitor, significantly reducing the required size of the capacitor [107]. The dynamics of the DC-link capacitor can be determined by applying Kirchhoff's Current Law (KCL) at the DC-link node.

$$\frac{dV_{dcp}}{dt} = \frac{1}{C_{dc}}(I_{dc1} - I_{dc2}) \tag{3.3.2}$$

where $I_{dc1} = (1 - dc)i_{pv}$ and I_{dc2} is the input current to the inverter. The expression for I_{dc2} can be derived in terms of inverter output current, V_{dcp} represents the DC voltage across the capacitor C_{dc}.

3.3.3 Inverter model

The inverter converts the DC output from the PV array and supplies power to the grid at the correct frequency. In this study, the voltage gain model of the voltage source inverter (VSI) operating in pulse width modulation (PWM) mode is used.

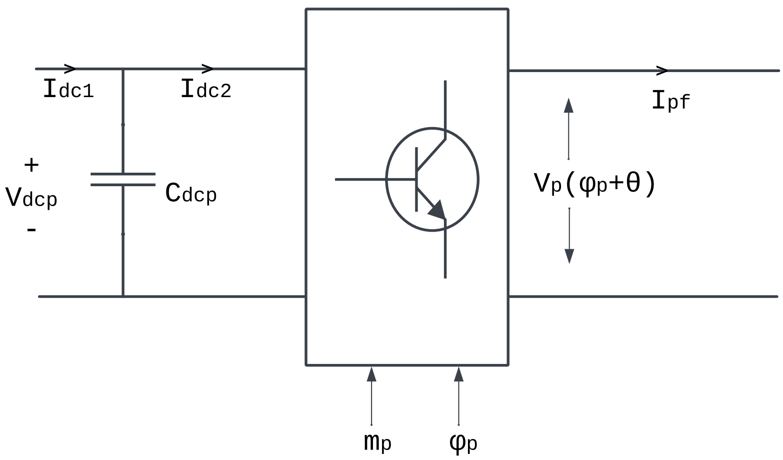

Fig. 3.7 Inverter Model

From Figure 3.7, the power on the DC side of the inverter is expressed as

$$P_{dc} = V_{dcp} \cdot I_{dc2} \tag{3.3.3}$$

The instantaneous active power on the AC side of the inverter is given as

$$P_{ac} = Re\left[V_p \cdot I_{pf}^*\right] \tag{3.3.4}$$

where, V_p and I_{pf} are the inverter output voltage and inverter output current respectively. In terms of d-q axes, V_p and I_{pf} are written as

$$V_p = V_{pd} + jV_{pq}$$

$$I_{pf} = I_{pfd} + jI_{pfq}$$

Substituting V_p and I_{pf} values in (3.3.4), we get

$$P_{ac} = V_p I_{pfd} + V_{pq} I_{pfq} \tag{3.3.5}$$

Equating the DC and AC side power gives,

$$P_{dc} = P_{ac}$$

$$V_{dcp} \cdot I_{dc2} = V_p I_{pfd} + V_{pq} I_{pfq} \tag{3.3.6}$$

When the inverter operates in the PWM mode, the output voltage can be expressed in terms of the DC-link voltage, modulation index m_p and phase angle φ_p of the inverter.

$$V_p = m_p \cdot V_{dcp} \angle \varphi_p \tag{3.3.7}$$

In terms of d-q axes, equation (3.3.7) can be written as

$$V_{pd} = m_p \cdot V_{dcp} \cdot cos(\varphi_p) \tag{3.3.8}$$

$$V_{pq} = m_p \cdot V_{dcp} \cdot sin(\varphi_p) \tag{3.3.9}$$

Substituting the equations (3.3.8) and (3.3.9) into (3.3.6), we get the expression of

$$I_{dc2} = I_{pfd} \cdot m_p \cdot cos(\varphi_p) + I_{pfq} \cdot m_p \cdot sin(\varphi_p) \tag{3.3.10}$$

3.3.4 LC Filter and the Coupling Inductance Model

A passive low-pass filter is employed to attenuate the switching frequency ripple of the inverter output voltage. The filter consists of a T-section RL circuit in parallel with a capacitor. The equivalent circuit is shown in fig 3.8.

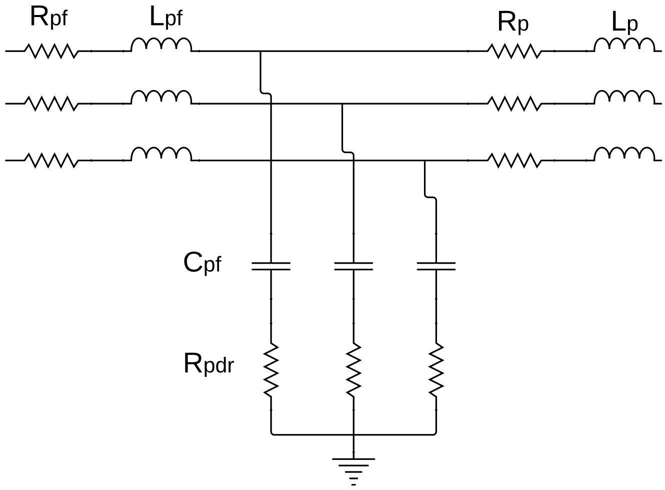

Fig. 3.8 T-type LC Filter and coupling model

The inductance and capacitance are the two reactive components that respond to frequency changes in opposite manners. The inductor blocks high-frequency harmonics and passes low frequencies, while the capacitor permits high frequencies and blocks low frequencies. These reactive components effectively block most harmonics, reducing the ripple in the system [108]. To prevent resonance, which can occur between the coupling inductance and the filter capacitor, a passive damping circuit, such as a damping resistor, is added to the filter. By applying Kirchhoff's Voltage Law (KVL) around the PV inverter and filter capacitor, a nonlinear differential equation is derived.

$$V_p = i_{pf} \cdot R_{pf} + L_{pf} \cdot \frac{di_{pf}}{dt} + V_{cp} + \left(i_{pf} - i_p\right) R_{pdr} \tag{3.3.11}$$

where, R_{pf} is the filter resistance, L_{pf} is the filter inductance, R_{pdr} is the damping resistance, V_{cp} is the capacitor voltage. In d-q reference frame the above equation is written as

$$i'_{pfd} = \frac{-\omega_0 \cdot R_{pf} \cdot i_{pfd}}{L_{pf}} + \omega_0 \cdot i_{pfq} + \frac{\omega_0 \cdot m_p \cdot V_{dcp} \cdot cos(\Psi p)}{L_{pf}} - \frac{\omega_0 \cdot V_{cpd}}{L_{pf}} - \frac{\omega_0 \cdot R_{pdr}\left(i_{pfd} - i_{pd}\right)}{L_{pf}} \tag{3.3.12}$$

$$i'_{pfq} = \frac{-\omega_0 \cdot R_{pf} \cdot i_{pfq}}{L_{pf}} - \omega_0 \cdot i_{pfd} + \frac{\omega_0 \cdot m_p \cdot V_{dcp} \cdot sin(\Psi p)}{L_{pf}} - \frac{\omega_0 \cdot V_{cpq}}{L_{pf}} - \frac{\omega_0 \cdot R_{pdr}\left(i_{pfq} - i_{pq}\right)}{L_{pf}} \tag{3.3.13}$$

Similarly, a non-linear equation is obtained from the coupling transmission line between PV filter capacitor and grid as,

$$V_{cp} = i_p R_p + L_p \frac{di_p}{dt} + V_s\left(i_{pf} - i_p\right) R_{pdr} \tag{3.3.14}$$

In d-q terms this gives,

$$i'_{pd} = \frac{-\omega_0 \cdot R_p \cdot i_{pd}}{L_p} + \omega_0 \cdot i_{pq} + \frac{\omega_0 \cdot \left(V_{cpd} - V_{ds}\right)}{Lp} + \frac{\omega_0 \cdot R_{pdr}\left(i_{pfd} - i_{pd}\right)}{L_P} \tag{3.3.15}$$

$$i'_{pq} = \frac{-\omega_0 \cdot R_p \cdot i_{pq}}{L_p} - \omega_0 \cdot i_{pd} + \frac{\omega_0 \cdot \left(V_{cpq} - V_{qs}\right)}{Lp} + \frac{\omega_0 \cdot R_{pdr}\left(i_{pfq} - i_{pq}\right)}{L_P} \tag{3.3.16}$$

where i_p is the coupling line current, R_p is the coupling resistance, L_p is the coupling inductance. The voltage across the filter capacitor is given as

$$\frac{dV_{cp}}{dt} = \frac{1}{C_{pf}}\left(i_{pf} - i_p\right) \tag{3.3.17}$$

where C_{pf} is the filter capacitor. Splitting the equation in d-q terms yields

$$V'_{cpd} = \frac{\omega_0\left(i_{pfd} - i_{pd}\right)}{C_{pf}} + \omega_0 \cdot V_{cpq} \tag{3.3.18}$$

$$V'_{cpq} = \frac{\omega_0\left(i_{pfq} - i_{pq}\right)}{C_{pf}} - \omega_0 \cdot V_{cpd} \tag{3.3.19}$$

3.4 Linearized Model

In this section the model of the various components of the Multimachine system is obtained by linearizing the non-linear equations developed in the previous section. The model of the AC system includes the linearized state space model of generator, photovoltaic system and that of the central controller. The linearized model is obtained by perturbing the set of equations around a normal operating point.

3.4.1 Linearized model of Generator

The linearized state equations of the generator are obtained from the non-linear model described in section 3.1 as follows

$$\dot{\Delta}\delta = \omega_0 \Delta\omega \tag{3.4.1}$$

$$\dot{\Delta}\omega = \frac{1}{2H}[-\Delta P_e] \tag{3.4.2}$$

$$\dot{\Delta}e'_q = \frac{1}{T'_{d0}}\left[\Delta E_{fd} - \Delta e'_q - (x_d - x'_d)\Delta i_{td}\right] \tag{3.4.3}$$

$$\dot{\Delta}E_{fd} = \frac{k_A}{T_A}\Delta V_t - \frac{1}{T_E}\Delta E_{fd} \tag{3.4.4}$$

The generator output current is given as

$$\Delta i_t = \Delta i_{td} + j\Delta i_{tq} \tag{3.4.5}$$

From (3.1.7), the d-axis generator output current is given as,

$$i_{td} = \frac{-r_t V_{sd} + (e'_q - V_{sq})x_2}{r_t^2 + x_1 x_2}$$

Differentiating on both sides gives,

$$\Delta i_{td} = \frac{-r_t}{r_t^2 + x_1 x_2}\Delta V_{sd} + \frac{x_2}{r_t^2 + x_1 x_2}\left(\Delta e'_q - \Delta V_{sq}\right) \tag{3.4.6}$$

Similarly, from (3.1.8) the q-axis output current is given as

$$i_{tq} = \frac{V_{sd}[\{x'_d + x_t\}\{x_q + x_t\}] + r_t(e'_q - V_{sq})\{x_q + x_t\}}{\{x_q + x_t\}[r_t^2 + \{x'_d + x_t\}\{x_q + x_t\}]}$$

Differentiating gives,

$$\Delta i_{tq} = \frac{\Delta V_{sd}}{x_1} + \frac{r_t}{x_d' + x_t}\left(\Delta e_q' - \Delta V_{sq}\right) \tag{3.4.7}$$

The terminal voltage is

$$V_t^2 = V_d^2 + V_q^2$$

$$\Delta V_t = \frac{V_{dO}}{V_{tO}} \Delta V_d + \frac{V_{q0}}{V_{tO}} \Delta V_q$$

$$\Delta V_t = \frac{V_{dO}}{V_{t0}}\left(x_q \Delta i_{tq}\right) + \frac{V_{q0}}{V_{tO}}\left(\Delta e_q' - x_d' \Delta i_{td}\right) \tag{3.4.8}$$

The power output of the generator from (3.1.10) is given as

$$P_e = e_q' \cdot i_{tq} + \left(x_q - x_d'\right) i_{td} \cdot i_{tq}$$

$$\Delta P_e = e_{q0}' \Delta i_{tq} + i_{tq0} \Delta e_q' + \left(x_q - x_d'\right)\left[i_{td0} \Delta i_{tq} + i_{tq0} \Delta i_{td}\right] \tag{3.4.9}$$

The values of Δi_{td}, ΔV_t and ΔP_e are substituted in the linearized model (3.4.1) - (3.4.4) to get obtain the model in terms of state variables ΔV_{sd} and ΔV_{sq}.

3.4.2 Linearized model of Photovoltaic System

Linearized model of the photovoltaic system consists of characteristic equation of the PV array and that of power conditioning unit. From the equation (3.2.10), the characteristic equation of the PV arrays as a function of PV output current is given as

$$V_{pv} = N_s\left[ln\left(\frac{N_p I_{ph} - i_{pv}}{N_p I_s} + 1\right) n V_T - \frac{i_{pv} R_s}{N_p}\right]$$

Differentiating on both sides

$$\Delta V_{pv} = -N_s \left[\frac{nV_T}{N_p I_{ph} - i_{pv0} + N_p I_s} + \frac{R_s}{N_p}\right] \Delta i_{pv} \tag{3.4.10}$$

It can be written as

$$\Delta V_{pv} = k_{pv} \Delta i_{pv} \tag{3.4.11}$$

here, $k_{pv} = -N_s \left[\frac{nV_T}{N_p I_{ph} - i_{pv0} + N_p I_s} + \frac{R_s}{N_p}\right]$

The model of the power conditioning unit is obtained by linearizing its individual component which comprises of DC/DC converter, DC-link capacitor, LC output filter and coupling inductance. The corresponding non-linear state equation of the DC/DC converter is given in (3.2.5) along with the algebraic equation,

$$\Delta i_{pv} = \frac{1}{L_{dc}} \left[\Delta V_{pv} - (1 - dc) \Delta V_{dcp}\right] \tag{3.4.12}$$

The non-linear equation for the DC link is given in (3.3.2). Differentiation gives,

$$\Delta V'_{dcp} = \frac{1}{C_{dc}} \left\{(1 - dcp) \Delta i_{pv} - i_{pfd} \cdot m_p \cdot cos(\psi_p) - i_{pfq} \cdot m_p \cdot sin(\psi_p)\right\} \tag{3.4.13}$$

The linearized state equations of the LC output filter and coupling inductance are obtained from the non-linear model given from equation (3.3.12) to (3.3.19) are,

The PV inverter output filter current,

$$i'_{pfd} = \frac{-\omega_0 \cdot R_{pf} \cdot i_{pfd}}{L_{pf}} + \omega_0 \cdot i_{pfq} + \frac{\omega_0 \cdot m_p \cdot V_{dcp} \cdot cos(\Psi p)}{L_{pf}} - \frac{\omega_0 \cdot V_{cpd}}{L_{pf}} - \frac{\omega_0 \cdot R_{pdr}(i_{pfd} - i_{pd})}{L_{pf}}$$

$$i'_{pfq} = \frac{-\omega_0 \cdot R_{pf} \cdot i_{pfq}}{L_{pf}} - \omega_0 \cdot i_{pfd} + \frac{\omega_0 \cdot m_p \cdot V_{dcp} \cdot sin(\Psi p)}{L_{pf}} - \frac{\omega_0 \cdot V_{cpq}}{L_{pf}} - \frac{\omega_0 \cdot R_{pdr}(i_{pfq} - i_{pq})}{L_{pf}}$$

The PV output coupling inductance current,

$$i'_{pd} = \frac{-\omega_0 \cdot R_p \cdot i_{pd}}{L_p} + \omega_0 \cdot i_{pq} + \frac{\omega_0 \cdot (V_{cpd} - V_{sd})}{Lp} + \frac{\omega_0 \cdot R_{pdr}(i_{pfd} - i_{pd})}{L_P} \tag{3.4.14}$$

$$i'_{pq} = \frac{-\omega_0 \cdot R_p \cdot i_{pq}}{L_p} - \omega_0 \cdot i_{pd} + \frac{\omega_0 \cdot (V_{cpq} - V_{sq})}{Lp} + \frac{\omega_0 \cdot R_{pdr}(i_{pfq} - i_{pq})}{L_P} \tag{3.4.15}$$

And the voltage across the filter capacitor,

$$V'_{cpd} = \frac{\omega_0(i_{pfd} - i_{pd})}{C_{pf}} + \omega_0 \cdot V_{cpq}$$

$$V'_{cpq} = \frac{\omega_0(i_{pfq} - i_{pq})}{C_{pf}} - \omega_0 \cdot V_{cpd}$$

The linearized state variables are $\Delta i'_{pd}, \Delta i'_{pfq}, \Delta i'_{pd}, \Delta i'_{pq}, \Delta V'_{cpd}$ and $\Delta V'_{cpq}$

3.5 Controller in the system

A Proportional-Integral (PI) controller is employed to regulate the dynamic performance of the multimachine power system with integrated photovoltaic (PV) generation. The PI controller plays a crucial role in maintaining system stability by adjusting the control signals based on the deviation of generator speed.

Here, the controller regulates the field voltage in the excitation system of synchronous generators in response to speed deviations, thereby indirectly controlling the terminal voltage and reactive power output of the generators. This placement helps maintain rotor angle stability and ensures consistent voltage support during disturbances. Also, in the PV subsystem, the PI controller is applied to adjust the modulation index, which influences the active and reactive power injection from the inverter. This enhances the dynamic response of the PV system during grid disturbances and supports system-wide voltage regulation.

The input to the PI controller is the speed deviation, $\Delta\omega$, which represents the difference between the actual rotor speed of the synchronous generator (ω) and its synchronous speed (ω_s). This speed deviation can also be interpreted as the slip, which reflects the degree of mismatch between the generator's mechanical and electrical speeds.

The PI controller output, $u(t)$, is defined by the following equation:

$$u(t) = k_p \cdot \Delta\omega + K_i \cdot \int \Delta\omega \, dt$$

Where, k_p is the proportional gain, responsible for responding to the immediate changes in speed deviation and k_i is the integral gain, which eliminates steady-state error by integrating the past values of $\Delta\omega$.

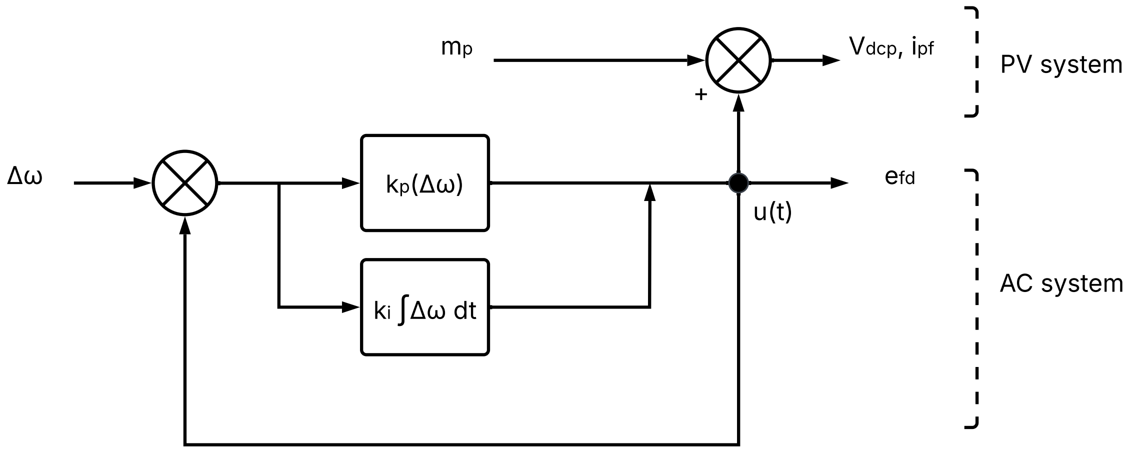

Fig. 3.9 Controller Canonical form

The control signal $u(t)$ is fed into the excitation system of the synchronous generator and the inverter of the PV system to regulate the voltage and reactive power output, ensuring synchronized operation within the multimachine setup. The use of a PI controller is essential in a multimachine AC system due to the complex interactions between multiple synchronous generators and inverter-based renewable sources. Without proper control, disturbances such as sudden load changes, PV output fluctuations, or voltage sags can cause rotor angle instability, voltage deviation, and power oscillations. The PI controller mitigates these effects by dynamically adjusting voltage and power references, thereby improving the system's damping characteristics, reducing oscillations, and ensuring a coordinated response among all generators and PV units. Ultimately, the PI controller provides a simple yet effective means of enhancing transient stability and supporting seamless PV-grid integration in large interconnected power systems.

Chapter 4

Integration of PV with AC System Dynamics

In the modeled power system, three synchronous generators Gen1, Gen2, and Gen3 are connected via transmission lines, with Gen 1 designated as the slack bus. Each generator is represented using its corresponding internal impedance, modeled as a series combination of resistance R_t and inductance L_t. As part of this study, one of the generators has been replaced with a photovoltaic (PV) generation unit. The PV generator is integrated into the system through a power electronic interface that includes DC-DC and DC-AC converters, filtering elements, and a coupling line to enable grid connection.

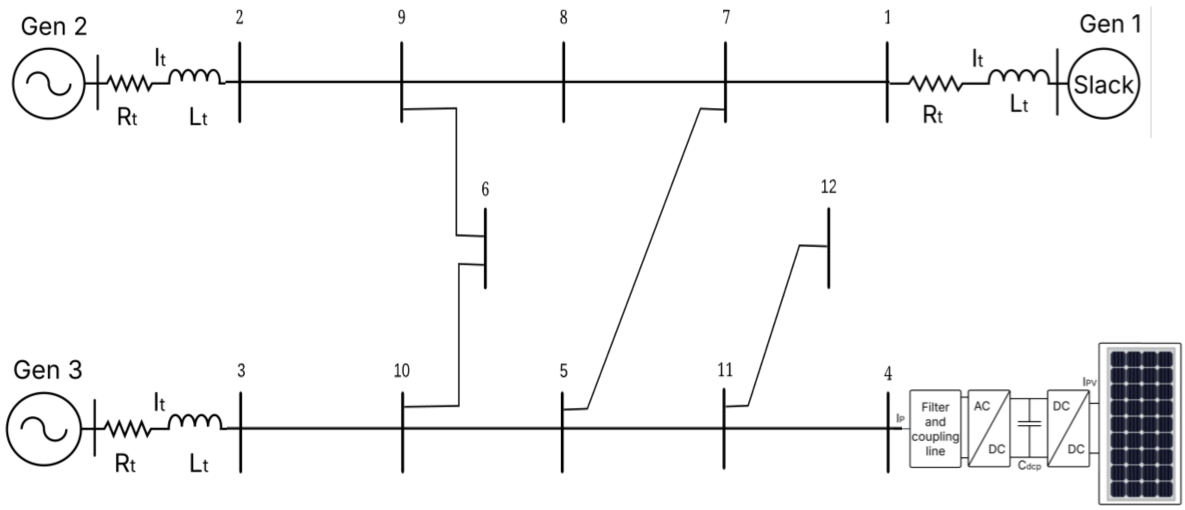

Fig 4.1 Multimachine System with PV Integrated

In order to understand the interaction of the system of Generator and PV system connected to the grid simple configuration is considered in this chapter. The load was considered to be integrated for the system. Both nonlinear and linearized integrated system models are developed. Non-linear simulations are carried out to verify the results.

4.1 Generator and PV system

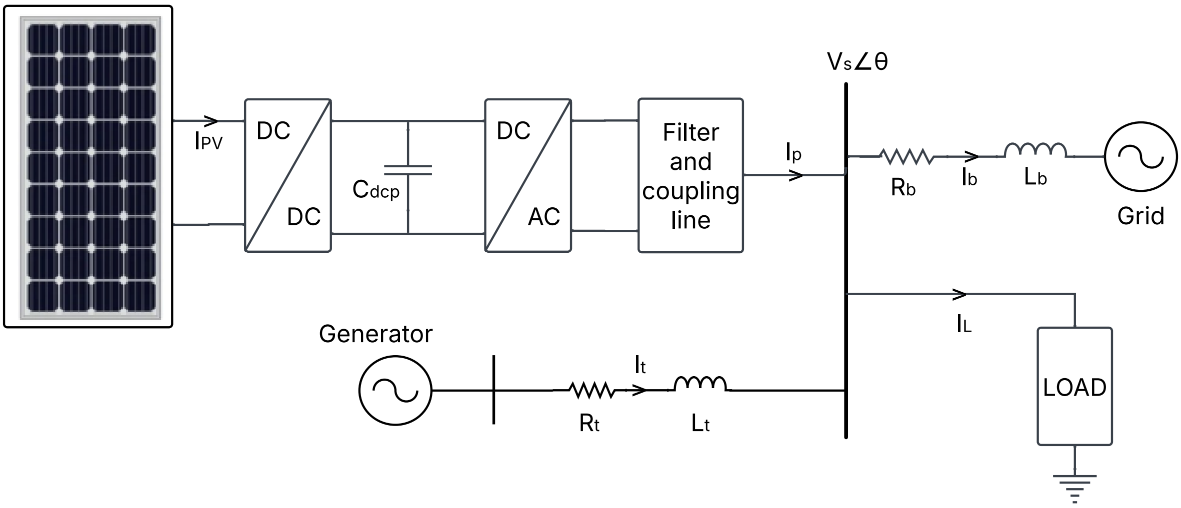

Fig. 4.2 Generator and PV connected to grid

Figure 4.1 shows a multimachine AC power system containing a synchronous generator, a PV generator and an integrated load connect to the power grid, all tied to a common bus with voltage V_s. The dynamics of the synchronous generator and PV system are detailed in sections 3.2 and 3.5 respectively. Note that the dynamic models of both generation units incorporate the components of V_s along the d-q axes (V_{sd}, V_{sq}). To achieve a closed-form representation of the composite state model, V_{sd} and V_{sq} must be expressed in terms of the selected system states.

Applying Kirchhoff's Current Law (KCL) at the common bus V_s gives:

$$i_t + i_p = i_b + i_L$$

Where, i_t, i_p, i_b, i_L are the generator output current, PV output current, grid current and load current respectively.

Taking d-q components this gives the following equations,

$$i_{td} + i_{pd} = i_{bd} + i_{Ld} \tag{4.1}$$

$$i_{tq} + i_{pq} = i_{bq} + i_{Lq} \tag{4.2}$$

The next stage is to express the non-state current ($i_{td}, i_{tq}, i_{bd}, i_{bq}, i_{Ld}, i_{Lq}$) as a function of V_{sd} and V_{sq}.

Generator output and Photovoltaic current components i_{td}, i_{tq}, i_{pd} and i_{pq} have already expressed as a function of V_{sd} and V_{sq} and are given in (3.1.7), (3.1.8), (3.4.14) and (3.4.15) respectively.

Load Current:

The load at the grid is modeled as an admittance $Y = g - jb$

The load current is given as $I_L = V_s Y$

$$i_{Ld} + j i_{Lq} = \left(V_{sd} + jV_{sq}\right)(g - jb)$$

Equating real and imaginary parts, we get

$$i_{Ld} = gV_{sd} + bV_{sq} \tag{4.3}$$

$$i_{Lq} = gV_{sq} - bV_{sd} \tag{4.4}$$

Grid Current:

From the figure 4.1 the main grid current i_b is given as

$$i_b = \frac{V_s - V_b}{r_b + jx_b}$$

$$i_{bd} + j i_{bq} = \frac{V_{sd} + jV_{sq} - (V_b \sin\delta + jV_b \cos\delta)}{r_b + jx_b}$$

Equating real and imaginary parts, we get

$$i_{bd} = \frac{\left(V_{sq} - V_b \sin\delta\right) r_b + \left(V_{sq} - V_b \cos\delta\right) x_b}{r_b^2 + x_b^2} \tag{4.5}$$

$$i_{bq} = \frac{\left(V_{sq} - V_b \cos\delta\right) r_b + \left(V_{sq} - V_b \sin\delta\right) x_b}{r_b^2 + x_b^2} \tag{4.6}$$

Finally substituting (i_{td}, i_{bd}, i_{Ld}) in (4.1) and solving for bus voltage components V_{sd} and V_{sq} as,

$$i_{pd} + i_{td} = i_{bd} + i_{Ld}$$

$$i_{pd} + \frac{-r_t V_{sd} + (e_q' - V_{sq})x_2}{z_1} = \frac{(V_{sq} - V_b \sin\delta)r_b + (V_{sq} - V_b \cos\delta)x_b}{z_b} + gV_{sd} + bV_{sq}$$

Where, $z_1 = r_t^2 + x_1 x_2$ and $z_2 = r_b^2 + x_b^2$

$$[gz_b z_1 + z_1 r_b + r_t z_b]V_{sd} + [bz_b z_1 + x_b z_1 + x_2 z_b]V_{sq} = z_b z_1 i_{pd} + z_b e_q' x_2 + V_b \cos\delta x_b z_1 + V_b \sin\delta r_b z_1 \quad (4.7)$$

Substituting (3.1.8), (4.4) and (4.6) in the above equation

$$i_{tq} + i_{pq} = i_{bq} + i_{Lq}$$

$$i_{pq} + \frac{V_{sd} z_1 - r_t^2 V_{sd} + r_t(e_q' - V_{sq})x_2}{x_2 z_1} = \frac{(V_{sq} - V_b \cos\delta)r_b + (V_{sq} - V_b \sin\delta)x_b}{z_b} \quad (4.8)$$

On simplifying the above, we get,

$$-[x_b x_2 z_1 + bz_b x_2 z_1 + z_1 z_b - r_t^2 z_b]V_{sd} + x_2[gz_b z_1 + z_1 r_b + r_t z_b]V_{sq} = z_b z_1 x_2 i_{pq} + r_t z_b e_q' x_2 + V_b \cos\delta r_b z_1 x_2 - \sin\delta x_b x_2 z_1 \quad (4.9)$$

On solving equations (4.7) and (4.9) we get

$$V_{sq} = Di_{pd} + Ee_q' + Fi_{pq} + GV_b \quad (4.10)$$

$$V_{sd} = \frac{1}{A}\left[z_b z_1 i_{pd} + z_b x_2 e_q' + V_b z_1(r_b \sin\delta + x_b \cos\delta) - BV_{sq}\right] \quad (4.11)$$

Where $A = [gz_b z_1 + z_1 r_b + r_t z_b]$

$B = [bz_b z_1 + x_b z_1 + x_2 z_b]$ and

$$C = [x_b x_2 z_1 + b z_b x_2 z_1 + z_1 z_b - r_t^2 z_b]$$

$$Den = BC + A^2 x_2$$

$$D = \frac{1}{Den} C z_b z_1$$

$$E = \frac{1}{Den} (C z_b x_2 + z_b x_2 r_t A)$$

$$F = \frac{1}{Den} (A x_2 z_1 z_b)$$

$$G = \frac{1}{Den} [z_1 C (r_b \sin\delta + x_b \cos\delta) + A x_2 z_1 (r_b \cos\delta - x_b \sin\delta)] \quad (4.12)$$

The values of V_{sd} and V_{sq} are substituted in the differential equations of the component models to get the closed form equation

$$\dot{X} = f[X, u] \quad (4.13)$$

Where the state vector X is given as

$$X = [\delta, \omega, e'_d, e'_q, E_{fd}, i_{pfd}, i_{pfq}, i_{pd}, i_{pq}, V_{cpd}, V_{cpq}, i_{pv}, V_{dcp}]$$

The control u is given as $U = [m_p]$

4.2 Linearized model of Generator and PV system

Repeating the procedure for the linearized component system models, the state model for the integrated generator, PV, load and the grid system is obtained by expressing the linearized grid voltage components along d-q axis $(\Delta V_{sd}, \Delta V_{sq})$ in terms of chosen states.

From (4.10) and (4.11) the grid voltage components are given as

$$V_{sq} = D i_{pd} + E e'_q + F i_{pq} + \frac{1}{Den} [z_1 C (r_b \sin\delta + x_b \cos\delta) + A x_2 z_1 (r_b \cos\delta - x_b \sin\delta)] V_b$$

$$V_{sd} = \frac{1}{A} [z_b z_1 i_{pd} + z_b x_2 e'_q + V_b z_1 (r_b \sin\delta + x_b \cos\delta) - B V_{sq}]$$

On differentiating V_{sq} we get,

$$\Delta V_{sq} = D\Delta i_{pd} + E\Delta e'_q + F\Delta i_{pq}$$

$$+V_b[\frac{1}{Den}[z_1 C(r_b \cos\delta_0 - x_b \sin\delta_0) - Ax_2 z_1(r_b \sin\delta_0 + x_b \cos\delta_0)]\Delta\delta$$

$$\Delta V_{sq} = D\Delta i_{pd} + E\Delta e'_q + F\Delta i_{pq} + G_1\Delta\delta \tag{4.14}$$

Where, $G_1 = V_b[\frac{1}{Den}[z_1 C(r_b \cos\delta_0 - x_b \sin\delta_0) - Ax_2 z_1(r_b \sin\delta_0 + x_b \cos\delta_0)]$

Similarly, on differentiating V_{sd} and substituting the value of ΔV_{sq} we get,

$$\Delta V_{sd} = \frac{1}{A}\big[z_b z_1 \Delta i_{pd} + z_b x_2 \Delta e'_q + V_b z_1(r_b \cos\delta_0 - x_b \sin\delta_0)\Delta\delta - B(D\Delta i_{pd} + E\Delta e'_q +$$

$$F\Delta i_{pq} + G_1\Delta\delta)\big]$$

$$\Delta V_{sd} = A_1\Delta i_{pd} + B_1\Delta i_{pq} + C_1\Delta e'_q + D_1\Delta\delta \tag{4.15}$$

Where $A_1 = \frac{1}{A}(z_b z_1 - B \cdot D)$,

$B_1 = \frac{1}{A}(-B \cdot F)$,

$C_1 = \frac{1}{A}(z_b x_2 - B \cdot E)$,

$D_1 = \frac{1}{A}(z_1 V_b(r_b \cos\delta_0 - x_b \sin\delta_0) - B \cdot G_1)$

The values of ΔV_{sd} and ΔV_{sq} are substituted in the linearized differential equations of the component models to get the closed form equation.

$$\big[\Delta\dot{X}_{GP}\big] = [A_{Gen-PV}]_{12\times12}[\Delta X_{GP}] + [B_P]_{12\times2}[\Delta U_P]$$

Where $[X_{GP}] = \big[\delta \;\; \omega \;\; e'_q \;\; E_{fd} \;\; i_{pv} \;\; V_{dcp} \;\; i_{pfd} \;\; i_{pfq} \;\; i_{pd} \;\; i_{pq} \;\; V_{cpd} \;\; V_{cpq}\big]^T$ (4.16)

$$A_{Gen-PV} = \begin{bmatrix} (A_{GG})_{4\times4} & (A_{GP})_{4\times8} \\ (A_{GG})_{8\times4} & (A_{pp})_{8\times8} \end{bmatrix}_{12\times12}$$

$$[\Delta U_P] = [\Delta m_p]$$

The sub matrix A_{GG} represents the system matrix of the generator and is given as,

$$A_{GG} = \begin{bmatrix} 0 & \omega_0 & 0 & 0 \\ -\frac{P_{e1}}{2H} & 0 & -\frac{P_{e3}}{2H} & 0 \\ -\frac{(x_d - x'_d)i_{d1}}{T'_{d0}} & 0 & -\frac{(x_d - x'_d)i_{d3}}{T'_{d0}} & \frac{1}{T'_{d0}} \\ \frac{k_a}{T_a}V_{t1} & 0 & \frac{k_a}{T_a}V_{t3} & -\frac{1}{T_a} \end{bmatrix}$$

The sub matrix A_{pp} represents the system matrix of the PV system and is given as,

$$A_{pp} =$$

$$\begin{bmatrix} \frac{V_{pv}}{L_{dc}} & -\frac{(1-dc)}{L_{dc}} & 0 & 0 & 0 & 0 & 0 & 0 \\ \frac{(1-dc)}{C_{dc}} & 0 & -\frac{m_p\cos(\varphi_p)}{C_{dc}} & -\frac{m_p\sin(\varphi_p)}{C_{dc}} & 0 & 0 & 0 & 0 \\ 0 & \frac{\omega_0\, m_p\cos(\varphi_p)}{L_{pf}} & -\frac{\omega_0(R_{pf}+R_{pdr})}{L_{pf}} & \omega_0 & \frac{\omega_0\, R_{pdr}}{L_{pf}} & 0 & -\frac{\omega_0}{L_{pf}} & 0 \\ 0 & \frac{\omega_0\, m_p\sin(\varphi_p)}{L_{pf}} & -\omega_0 & -\frac{\omega_0(R_{pf}+R_{pdr})}{L_{pf}} & 0 & \frac{\omega_0}{L_{pf}}R_{pdr} & 0 & -\frac{\omega_0}{L_{pf}} \\ 0 & 0 & \frac{\omega_0\, R_{pdr}}{L_p} & 0 & -\frac{\omega_0(R_p+R_{pdr})}{L_p} & \omega_0 & \frac{\omega_0}{L_p} & 0 \\ 0 & 0 & 0 & \frac{\omega_0\, R_{pdr}}{L_p} & -\omega_0 & -\frac{\omega_0(R_p+R_{pdr})}{L_p} & 0 & \frac{\omega_0}{L_p} \\ 0 & 0 & \frac{\omega_0}{C_{pf}} & 0 & -\frac{\omega_0}{C_{pf}} & 0 & 0 & \omega_0 \\ 0 & 0 & 0 & \frac{\omega_0}{C_{pf}} & 0 & -\frac{\omega_0}{C_{pf}} & -\omega_0 & 0 \end{bmatrix}$$

The constants in the above matrices are given as

$$V_{pv} = -N_s\left[\frac{nV_T}{N_pI_{ph} - i_{pv} + N_pI_s} + \frac{R_s}{N_p}\right]$$

Chapter 5

Simulation Studies

This section will examine how the system's dynamic performance is affected by the integration of PV generation. The key parameters analyzed include generator speed deviations, relative rotor angles, and system stability under different operating conditions. Steady-state analysis of the system is performed to obtain the pre-fault (or pre-disturbance) states of the system. The load flow results of the hybrid system are given in Appendix A.

5.1 Impact of PV Dynamics

We aim to investigate how the integration of photovoltaic (PV) systems affects the dynamic behavior of the power network. As PV systems are different from conventional synchronous generators. We will focus on understanding how the dynamic characteristics of PV systems influence the overall system performance. By studying the system in different conditions, we want to see if the PV dynamics help to improve stability, reduce oscillations, and keep voltage and frequency steady, or if they cause any new problems that need fixing.

Figure 5.1 presents the generator speed deviations for Generator 1, Generator 2, and Generator 3 following a disturbance applied at t = 1.5 seconds. The comparison between the two cases; with and without PV integration, demonstrates the impact of photovoltaic (PV) to the system dynamic performance.

When PV is not integrated into the system, the generators show longer and stronger oscillations in their speed after a disturbance, meaning the system takes more time to become stable again. This happens because the system has weaker damping without PV. On the other hand, when PV is integrated, the speed deviations of the generators reduce much faster, showing that the system becomes stable more quickly. This better damping is mainly because the PV system provides only real power and does not supply reactive power. As a result, the power balance is easier to maintain during disturbances, and the generators are less stressed, allowing them to return to steady-state faster.

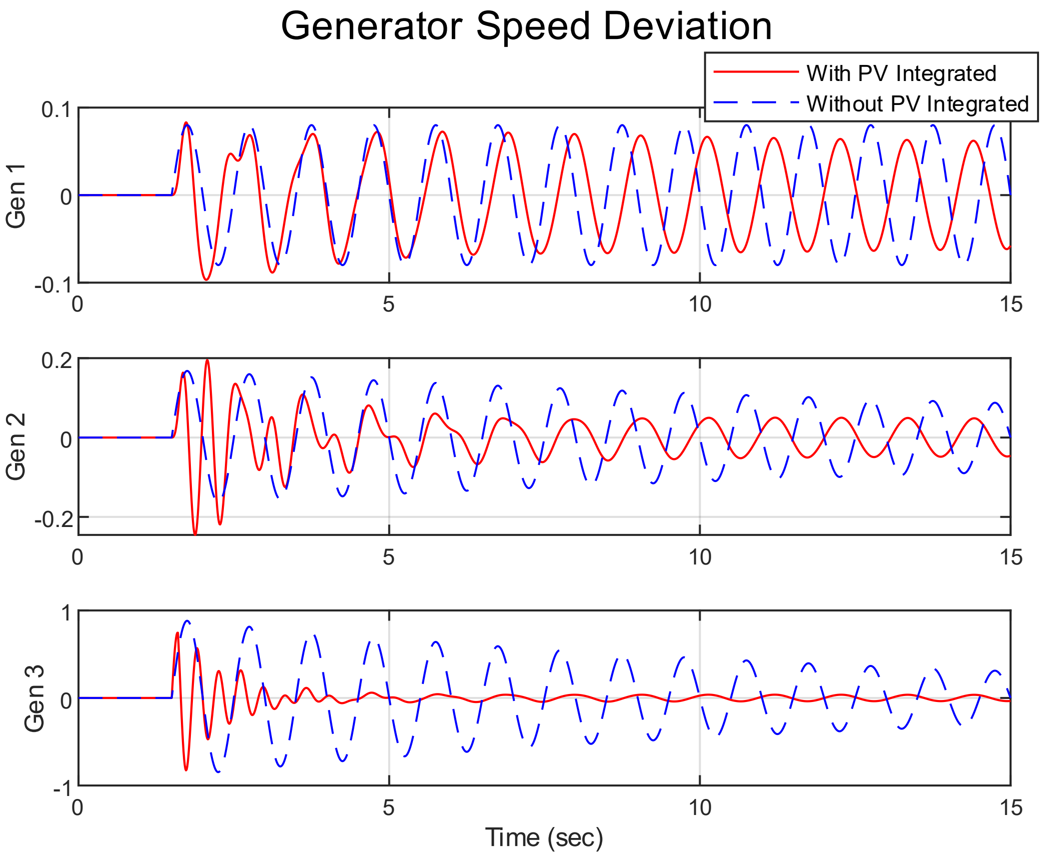

Fig 5.1: Speed Deviations with and without PV integrated

It is also evident that prior to the disturbance at 1.5 second, both systems were operating in synchronism, as indicated by the zero deviation in generator speeds. This confirms that the initial conditions were consistent across both cases.

5.1.1 Impact of PV input in the AC System

In this section, we analyze the influence of photovoltaic (PV) system dynamics on the transient response of a multimachine AC power system. The PV system was integrated into the existing network, and the system response was evaluated under three different PV power injection levels.

Figure 5.2 illustrates the speed deviation profiles of three generators (Gen1, Gen2, and Gen3) which we get from equation (3.1.2) over time following a disturbance. It is evident from the figure that the presence of PV contributes positively to system damping in all three scenarios. However, the degree of damping and the overall transient behavior vary significantly depending on the amount of PV power injected.

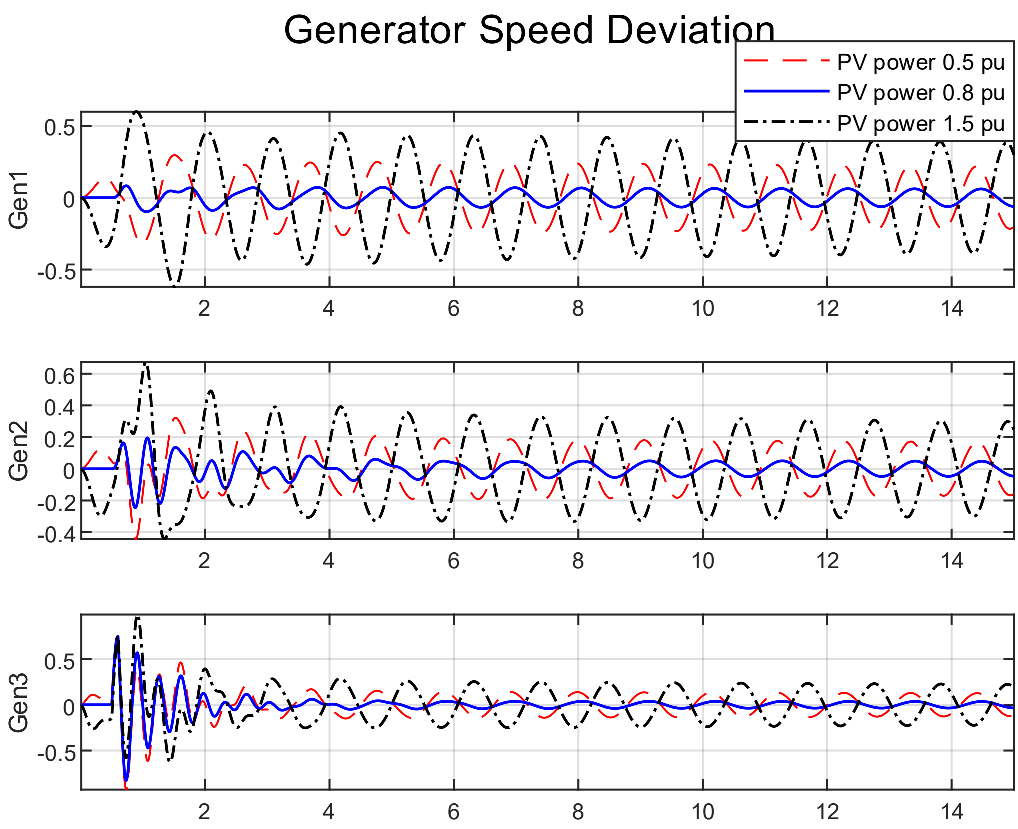

Fig 5.2: Speed Deviations of generators in different PV power

The results demonstrate that with 0.5 pu PV power (red dashed line), the system shows moderate oscillatory behavior, and the damping is noticeable. At 1.5 pu PV power (black dash-dotted line), the system experiences increased oscillations and reduced damping capability. This excessive power injection may contribute to destabilizing the dynamic response due to the mismatch with the system's optimal operating condition.

The most stable and desirable performance is observed at 0.8 pu PV power (solid blue line). In this case, all three generators exhibit well-damped oscillations with minimal overshoot and rapid settling. This behavior aligns with our load flow analysis, which indicated that 0.8 pu is an optimal operating point for PV power injection in this configuration. At this level, the PV system enhances the damping without introducing additional dynamic stress into the network.

5.1.2 Impact of AC-PV Control

In the earlier analysis, it was shown from both load flow studies and transient response results that setting the photovoltaic (PV) system output to 0.8 pu gives the best operating condition for system stability. In this section, the effect of incorporating proportional-integral (PI) controllers is investigated. The study is conducted individually for Generator 1 and Generator 2 under three different scenarios.

Initially, the PV system was integrated into the AC network without any additional control mechanisms. The simulation results from equation (3.1.2), presented in Figure 5.3(a) and Figure 5.4(a), demonstrate that the PV integration alone significantly improves the damping of oscillations compared to the baseline case.

A PI controller was applied only to the exciter system $\left(U_{ref} - V_{t1} + controller\right)$ of the generator which we have used in equation (3.1.4), while the PV system continued to operate without any dynamic control. As shown in Figure 5.3(b) and Figure 5.4(b), the exciter control initially enhanced the transient stability. However, due to a mismatch between the exciter action and the natural stabilizing effect of the PV system, instability arose after a certain period, leading to unstable scenario over time.

Finally, a coordinated control strategy was implemented where the same PI controller was applied to both the generator exciter and the PV system. The controller equation for PV system

$(m_p + controller)$ was derived from (3.3.7). The results, shown in Figure 5.3(c) and Figure 5.4(c), indicate a substantial improvement in damping, with significantly reduced oscillations and enhanced overall transient stability. The consistent observed across both Generator 1 and Generator 2 confirms the effectiveness of the AC-PV coordinated control strategy in enhancing system performance under transient conditions.

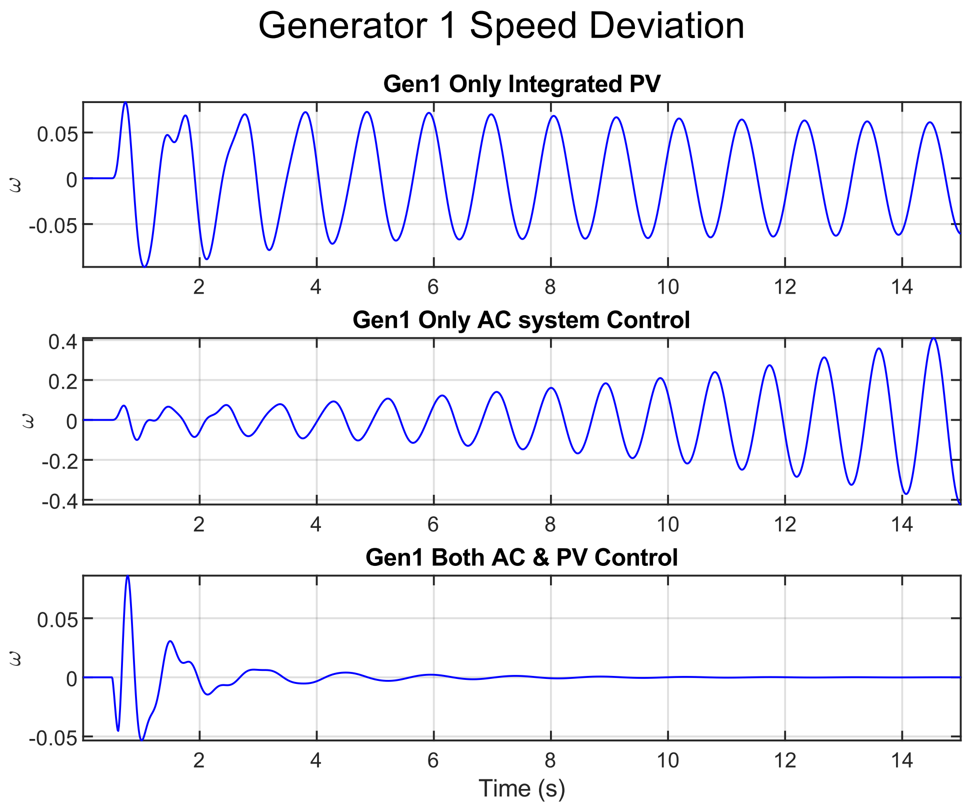

Fig 5.3: Gen 1 speed deviations in three different cases

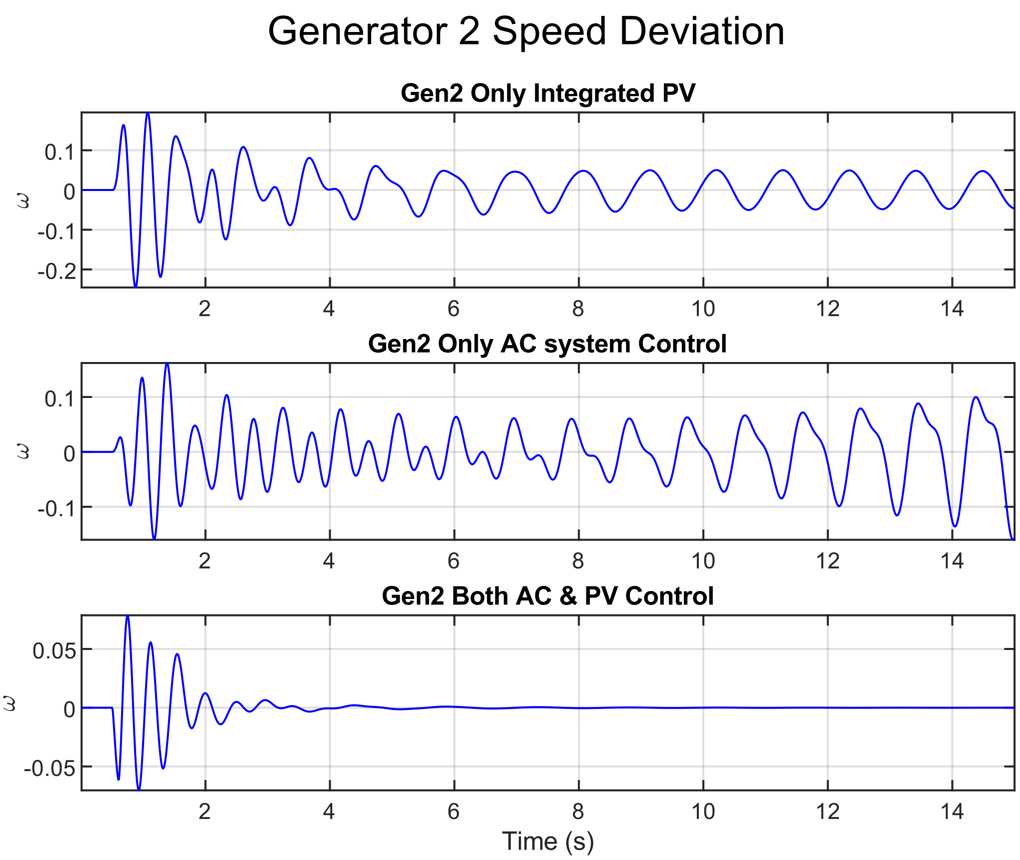

Fig 5.4: Gen 2 speed deviations in three different cases

The figure 5.5 below shows the impact of the PI controller on the speed deviations of all three generators. In each subplot, the response with and without the controller is compared. From the figure, it is evident that the application of the PI controller significantly improves the system's transient response. In the case without the PI controller (blue dashed line), all generators exhibit sustained oscillations and slower settling times following the disturbance. In contrast, when the PI controller is applied (solid red line), the oscillations are substantially damped, and the generators quickly stabilize to their steady-state operating points.

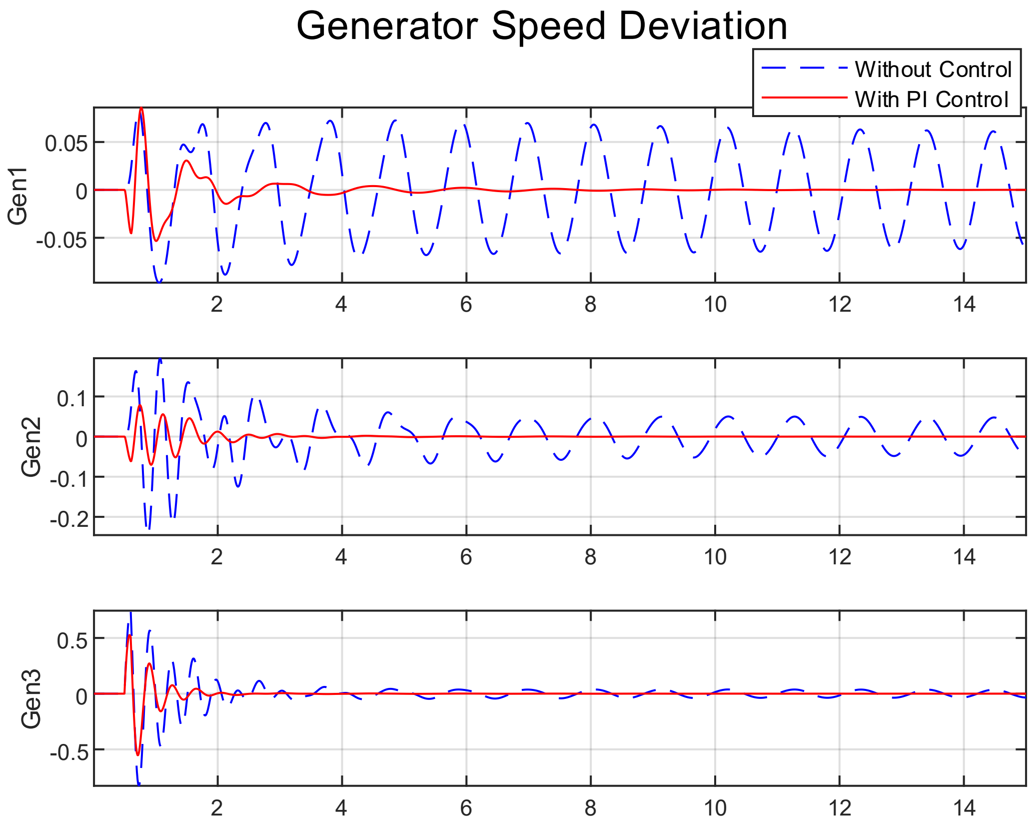

Fig 5.5: Generator speed deviations with and without controller

These results highlight that, while PV integration improves system dynamics to some extent, the addition of a proper control strategy, such as a PI controller, further enhances the stability and performance of the AC system.

5.2 AC system Stability

In this section, we are going to investigate the dynamic performance of the AC system under different operating conditions. First, we will study the rotor angle behavior to assess the ability of synchronous generators to maintain stability after disturbances. Then, we will analyze the frequency variations between AC generators to evaluate the system's frequency response and observe the impact of controllers on improving overall system stability.

5.2.1 Rotor Angle Study

Stability of the AC-DC system was investigated with and without PI control. The disturbance conditions studies were with a 10% torque pulse on generator 3 for 0.1 seconds. The relative rotor angles are computed with respect to Generator 1. The relative angle for Generator 2 is determined as $\delta_2 - \delta_1$, and for Generator 3, it is $\delta_3 - \delta_1$ highlighting the impact of the torque disturbance on rotor angle deviations which was used from equation (3.1.1). The fig 5.6 below illustrates the rotor angle responses under both conditions, one with a PI controller implemented in the system and one without the PI controller.

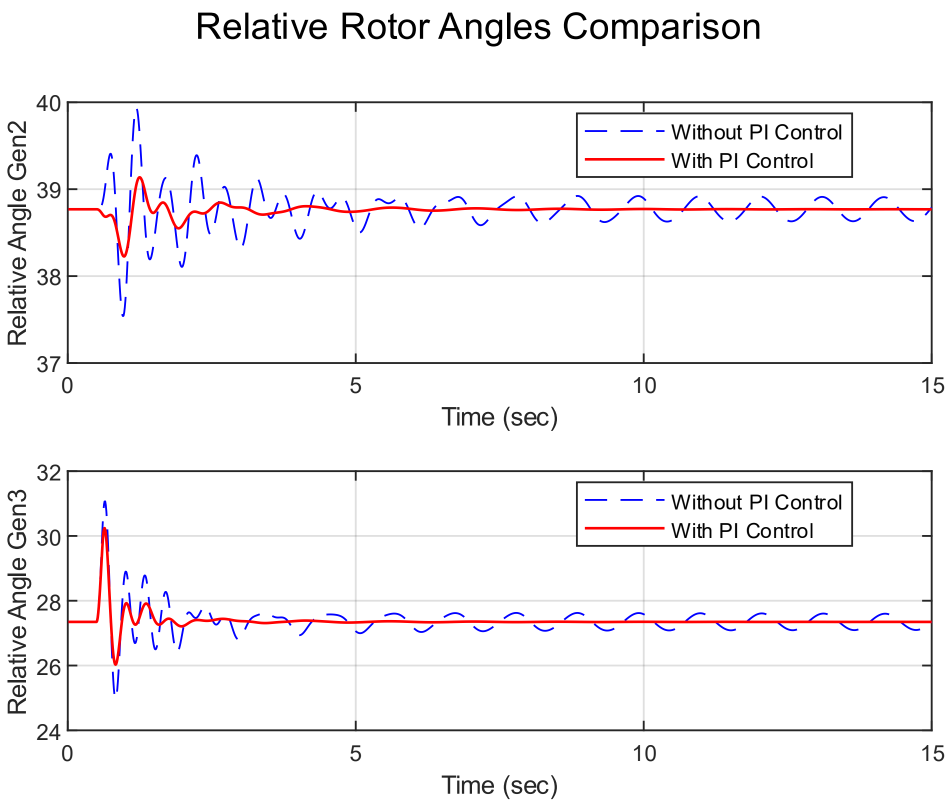

Fig. 5.6: Angle of Gen 2 and 3 with PI and without PI

From the obtained results shown in fig 5.6, the relative rotor angles of Generator 2 and Generator 3 initially exhibit oscillations after the disturbance, which gradually settle over time. The presence of oscillations indicates the transient response of the system, while the damping nature of these oscillations reflects the inherent stability of the system shown (blue dashed line).

To enhance the system's ability to damp oscillations and improve overall rotor angle stability, a PI controller has introduced. With the PI controller placed into the system, the rotor angle response of Generator 2 and Generator 3 show a significant improvement in damping, leading to faster stabilization compared to the uncontrolled case (red solid line). The initial disturbance still causes a deviation in the rotor angle, but the oscillations now decay much more rapidly, demonstrating the effectiveness of the control strategy. The smoother transition to steady-state operation indicates that the PI controller successfully enhances system stability.

5.2.1 Frequency variations between Generators

The variations of AC generator frequency with and without an excitation controller are illustrated in Fig. 5.7. The plots compare the frequency deviations ($\Delta\omega$) among different machines under two scenarios: without controller (dashed blue lines) and with controller (solid red lines). As observed, the inclusion of an excitation controller significantly enhances the damping characteristics of the system.

With the controller (solid red line), the frequency deviations are much smaller and the system stabilizes quickly. In the first plot ($\Delta\omega_1 - \Delta\omega_2$), the controller reduces both the amplitude and the settling time. In the second plot ($\Delta\omega_1 - \Delta\omega_3$), the improvement is even more noticeable, with faster damping of higher initial oscillations. Overall, the controller clearly improves system stability by reducing oscillations and helping the generators return to steady-state faster.

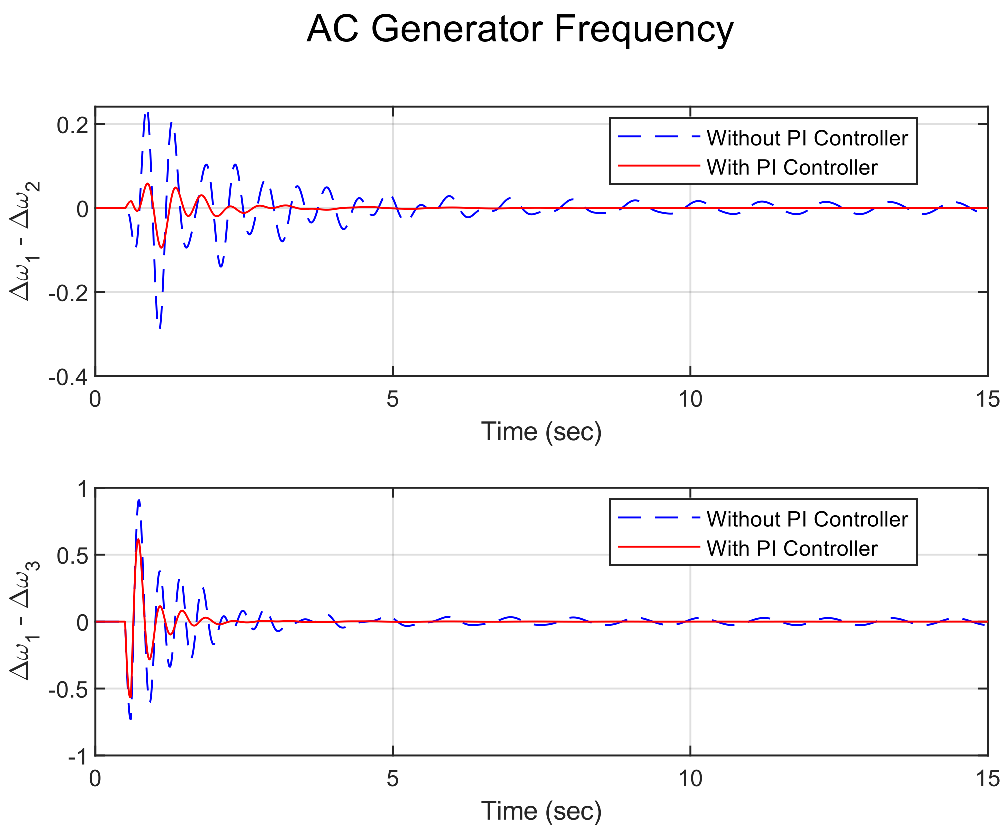

Fig. 5.7: Frequency variations of AC generators with and without controller

5.3 Simulations with Terminal Voltages

The terminal voltage response of the system was analyzed to evaluate the impact of the control strategy under different operating conditions. For this purpose, the terminal voltages of all three generators from equation (3.1.4a) were observed and compared for two scenarios: one with the control system implemented and one without it. The fig 5.8 below illustrates the voltage deviations of the generators in both cases.

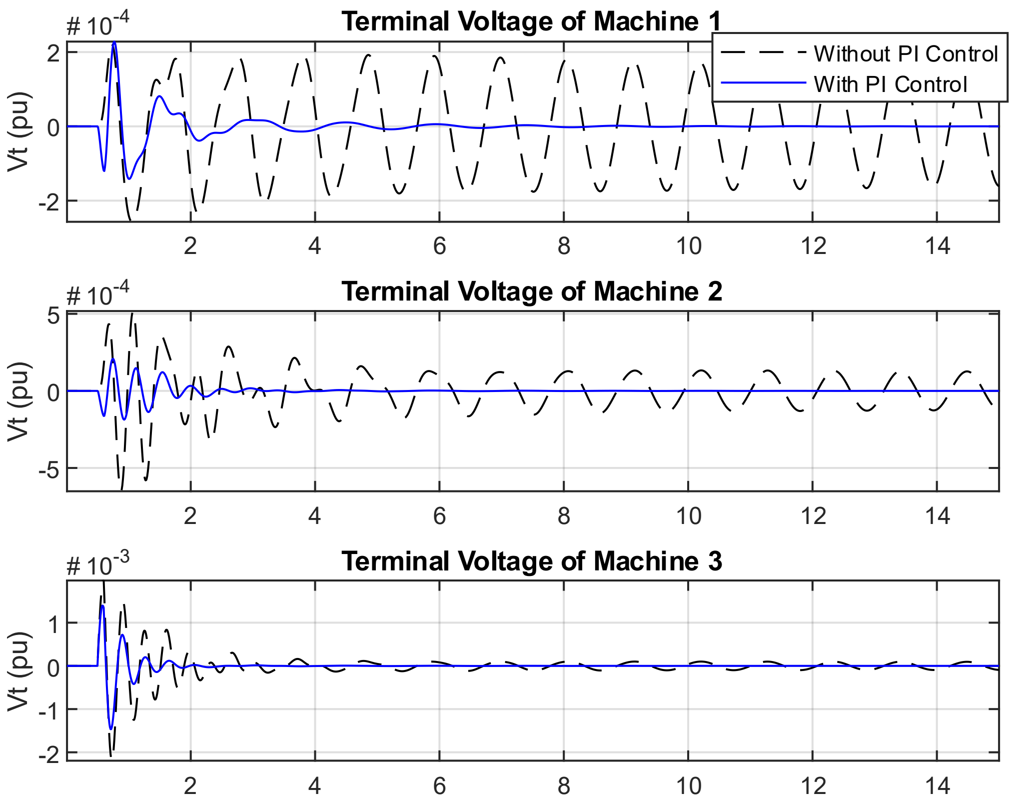

Fig. 5.8: Terminal Voltages of AC generators with and without controller

Without control, the generators exhibit noticeable voltage fluctuations, with slower damping and longer settling times after the disturbance. This indicates that the system struggles to maintain stable voltage levels when operating without any control measures. In contrast, when the control system is applied, the voltage responses show significant improvement. The oscillations are reduced, and the system stabilizes more quickly, demonstrating improved voltage regulation across all three generators. This comparison in shown fig 5.8 highlights the effectiveness of the control strategy in maintaining terminal voltage stability under transient conditions.

5.4 Simulations with Voltage Dips

To simulate an extreme scenario of three phase fault, the terminal voltage of Machine 4 was examined. The analysis focuses on the network's ability to maintain stability, manage reactive power.

Table 1: Load flow result while Three Phase Fault

Bus	Terminal Voltage	Angle	P	Q
1	1.04	0	99.03	62.53
2	1.025	0.0227	105	33.83
3	1.005	-0.0580	50	29.59
4	0.96	-0.1536	80	6.18
5	0.95	-0.1419	0	0
6	0.9867	-0.0831	0	0
7	1.0111	-0.0471	0	0
8	0.9871	-0.0843	0	0
9	1.0098	-0.0281	0	0
10	0.9906	-0.0831	0	0
11	0.9568	-0.1536	0	0
12	0.9506	-0.1658	0	0

When comparing the load flow results during a three-phase fault condition with the initial base case scenario (where generator 4 operated at nominal voltage), several notable trends emerge. The system behavior shows that the voltage at this terminal remains relatively close to its original value. This stability at terminal 4 is complemented by relatively steady voltage levels at neighboring buses, including Buses 5, 11, and 12, though these voltages appear to have slightly decreased compared to the base condition, likely due to the fault-induced stress on the system.

The active power distribution reveals a concentration of generation at terminal 1 through 4, while other buses show no active power contribution, indicating a redistribution or isolation effect caused by the fault. Specifically, Terminal 1 maintains a significant power injection role, suggesting a compensatory action to stabilize the network. Reactive power levels are similarly concentrated in the main generator terminal, while most other terminals reflect a lack of reactive power flow, which may indicate reduced local demand or supply paths due to fault clearing procedures. Overall, the system continues to operate in a controlled manner during the fault, with voltage levels remaining within acceptable limits and power flow adapting to ensure continuity.

Chapter 6

Conclusions

6.1 Summary and Discussion

This work presents the dynamic modeling and analysis of a multimachine power system integrated with a photovoltaic (PV) generating unit. Both nonlinear and linear dynamic models of individual components, including synchronous generators and the PV system, were developed. A major contribution of this thesis is the development of an extended dynamic model, in which the conventional third-order synchronous generator model was expanded into a fifth-order form. This enhancement allows for a more accurate representation of internal generator dynamics and their impact on system behavior. Furthermore, this work uniquely investigates the dynamic performance of an AC multimachine system with integrated PV generation under various disturbance conditions. This study offers new insights into the role of renewable generation in supporting conventional grid systems, particularly under transient and dynamic operating conditions. The dynamic interactions between these components were studied through multiple case studies, with a particular focus on the effects of PV integration and system disturbances on overall stability.

Transient stability was assessed under various disturbance scenarios, such as sudden changes in load and generation. The AC system with the integration of the PV system was examined under different operating conditions, and the results consistently demonstrated that its integration had a stabilizing effect on the system. One of the major reasons for that is, PV does not inject reactive power, whereas this only provides real power to the system. Furthermore, the study investigated key aspects of AC system dynamics, including rotor angle stability, frequency deviation among synchronous machines, and voltage dips, to evaluate synchronization and dynamic performance.

To improve the stability of the system, control strategies were applied and tested. A proportional-integral (PI) controller was designed and tuned to reduce speed fluctuations and suppress oscillations, which helped maintain synchronization between the generators. In addition, the effect of the excitation system response and the modulation index of the PV inverter was studied.

Integration of PV into the multimachine system itself has shown a positive impact on overall system performance. The results showed that the amount of real power injected from the PV into the system, the transient stability of the overall system could be significantly improved. To conclude that adding PV not only supports the grid but also improves the stability and performance of the multimachine system.

6.2 Future Studies

Based on the findings and limitations of this study, the following recommendations are proposed for further research:

- Standalone Operation of the System: This study focuses on grid-connected mode. Future work can explore islanded operation, emphasizing autonomous power balancing using energy storage systems like batteries, supercapacitors, or SMES to enhance stability.
- Advanced Control Strategies: While PI controllers are used here, future studies could investigate alternatives such as MPC, SMC, or AI-based adaptive controllers to improve transient response and robustness.
- Integration of Additional Renewable Sources: This study focuses on the integration of PV systems with an AC multimachine system. Future research can explore hybrid

renewable energy systems, including wind power and other distributed generation sources, to assess their impact on transient and small-signal stability.

These recommendations can serve as a foundation for future research to further enhance the stability and reliability of power systems with high renewable energy penetration.

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Appendix.

Table 2 Generation and load data (from load flow solution)

Bus				Load		Generator	
no	type	Voltage	Angle	P_L, MW	Q_L, Mvar	P_g, MW	Q_g, Mvar
1	Slack	1.0400	0	0	0	18.95	56.61
2	Gen	1.0250	0.0968	0	0	105	33.28
3	Gen	1.0050	0.0524	0	0	50	25.63
4	Gen	0.9750	0.1039	0	0	80	11.42
5	Load	0.9565	-0.0130	110	80	0	0
6	Load	0.9883	0.0070	52.5	25	0	0
7	Load	1.0128	-0.0090	0	0	0	0
8	Load	0.9870	-0.0266	80	40	0	0
9	Load	1.0101	0.0461	0	0	0	0
10	Load	0.9926	0.0274	0	0	0	0
11	Load	0.9700	0.0616	0	0	0	0
12	Load	0.9640	0.0497	10	5	0	0

Table 3 Generation and load data for the base case (Systems base MVA is 100)

Bus				Load		Generator	
no	type	Voltage	Angle	P_L, MW	Q_L,	P_g, MW	Q_g,
1	Slack	1.04	0	0	0	0	0
2	Gen	1.025	0	0	0	105	0
3	Gen	1.025	0	0	0	50	0
4	Gen	1.015	0	0	0	60	0
5	Load	1	0	110	80	0	0
6	Load	1	0	52.5	25	0	0
7	Load	1	0	0	0	0	0
8	Load	1	0	80	40	0	0
9	Load	1	0	0	0	0	0
10	Load	1	0	0	0	0	0
11	Load	1	0	0	0	0	0
12	Load	1	0	10	5	0	0

Table 4 Line data.

Bus From	Bus To	R (pu)	X (pu)	½ B (pu)
1	7	0	0.05	0
2	9	0	0.05	0
3	10	0	0.05	0
4	11	0	0.05	0
11	12	0.018	0.35/3	0.0175
11	5	0.009	0.40/4	0.035
5	10	0.009	0.35/3	0.035
10	6	0.009	0.27/2	0.035
6	9	0.009	0.43/4	0.035
9	8	0.009	0.33/3	0.049
8	7	0	0.4/3	0.035
7	5	0.009	0.4/3	0.035

Table 5 Generator data

Generator	**1**	**2**	**3**	**4**
Direct axis synchronous reactance, X_d	0.1460	0.8953	1.3125	1.3125
Quadrature axis synchronous reactance, X_q	0.0969	0.8645	1.2578	1.2578
Direct axis transient reactance, X_d'	0.0608	0.1198	0.1813	0.1813
Quadrature axis transient reactance, X_q'	0.0969	0.1969	0.25	0.25
Inertia constant, H	23.64	6.4	3.01	3.01
Direct axis transient open-circuit time constant, T_{d0}'	8.96	6.00	5.89	5.89
Quad axis transient open-circuit time constant, T_{q0}'	0.31	0.535	0.6	0.6
AVR (Automatic Voltage Regulator) gain, K_a	100	100	100	100
AVR time constant, T_a	0.01	0.01	0.01	0.01
Stator resistance, R_s	0	0	0	0
Exciter constant, K_E	1	1	1	1
Exciter time constant, T_E	0.314	0.314	0.314	0.314
Stabilizer gain, K_F	0.063	0.063	0.063	0.063
Stabilizer time constant, T_F	0.35	0.35	0.35	0.35

Table 6 Generation and load data for the base case (from load flow solution)

Bus				Load		Generator	
no	type	Voltage	Angle	P_L, MW	Q_L,	P_g, MW	Q_g,
1	Slack	1.0400	0	0	0	18.95	56.61
2	Gen	1.0250	0.0968	0	0	105	33.28
3	Gen	1.0050	0.0524	0	0	50	25.63
4	Gen	0.9750	0.1039	0	0	80	11.42
5	Load	0.9565	-0.0130	110	80	0	0
6	Load	0.9883	0.0070	52.5	25	0	0
7	Load	1.0128	-0.0090	0	0	0	0
8	Load	0.9870	-0.0266	80	40	0	0
9	Load	1.0101	0.0461	0	0	0	0
10	Load	0.9926	0.0274	0	0	0	0
11	Load	0.9700	0.0616	0	0	0	0
12	Load	0.9640	0.0497	10	5	0	0