

**ANALYSIS OF PV FED VIRTUAL
SYNCHRONOUS GENERATOR CONNECTED TO
GRID**

A PROJECT REPORT

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CERTIFICATE

This is to certify that the report entitled ‘**Analysis of PV fed Virtual Synchronous Generator Connected to Grid**’ submitted by **Amjatha Salim** to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electrical and Electronics Engineering is a bonafide record of the project work carried out by her under our guidance and supervision. This project report in any form has not been submitted to any other University or Institute for any purpose.

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ABSTRACT

The power industry is currently experiencing a notable transition from a centralised power generation model to a distributed generation approach, accompanied by the implementation of smart grid technologies. The aforementioned transition is primarily motivated by the imperative to mitigate energy deficiencies and environmental concerns, thereby prompting a concentrated emphasis on renewable energy sources, electric vehicles, and energy storage systems. Solar grid integration, a process that entails the integration of solar photovoltaic (PV) power into the national utility grid, has gained widespread adoption on a global scale. This can be attributed to the rising need for environmentally friendly energy sources and the expanding capacity of solar power installations. Electronic inverters are commonly employed to establish a connection between distributed generators (DG) that rely on renewable energy sources and the primary power system. This is due to their advantageous characteristics, such as rapid response time and adaptable control capabilities. Nevertheless, electronic inverters exhibit a deficiency in terms of inertia and damping properties, which consequently leads to instability issues when faced with faults or disturbances. In order to address this particular obstacle, a novel control technique known as Virtual Synchronous Machine (VSM) has been devised. The Virtual Synchronous Machine (VSM) replicates the dynamic properties of synchronous machines, thereby enhancing the stability of the system. The objective of this project is to incorporate photovoltaic (PV) systems into the electrical grid utilising the Virtual Synchronous Machine (VSM) technique. Additionally, the project aims to examine the performance of the integrated system under different scenarios, including variations in irradiance levels and the occurrence of faults.

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Abbreviations and Notations

1. RES: Renewable Energy Sources
2. PV : Photovoltaic
3. MPPT : Maximum Power Point Tracking
4. PWM :Pulse Width Modulation
5. VSM : Virtual Synchronous Machine
6. DG : Distributed Generator
7. PO : Pertrub and Observe
8. IIDERs: Inverter Interfaced Distributed Energy Resources
9. VSI : Voltage Source Inverter
10. SM : Synchronous Machines
11. DMG : Droop Control-based Micro Hydro Generators
12. VSMG : Variable Speed Micro Hydro Generators

Chapter 1

Introduction

1.1 General Background

Power systems have changed significantly in recent years, moving from centralised to distributed generation models, then to smart grids. The shift towards renewable energy integration with power grids has been propelled by the growing usage of power electronic converters in linking different renewable energy sources, energy storage systems, electric vehicles, and other associated devices to the grids. The observed trend is a reaction to the current energy crisis and increasing apprehensions regarding the environment. This has resulted in a heightened focus on incorporating renewable energy sources, electric vehicles, and energy storage systems into power systems.

When distributed generation constitutes a small portion of the total grid capacity, its effect on the stability of the power system is typically insignificant. Nevertheless, with the escalation in the deployment of Distributed Generators (DGs), specific obstacles emerge. One of the primary obstacles is the insufficient supply of inertia and damping to the power grid, which may make it vulnerable to power oscillations and system failures. The incorporation of renewable energy sources is a pivotal matter of concern in the field of energy, as their increasing penetration into the power

system may have an adverse effect on power system stability. The emergence of inverter-dominant microgrids has been proposed as a potential solution to tackle these challenges. The notable increase and amalgamation of inverter-interfaced distributed energy resources (IIDERs) can be ascribed to this phenomenon. Maintaining an appropriate and effective level of control is of utmost importance in microgrids. The Intermediate Inverter System (IIERDs) has the capability to function in two distinct modes, namely isolated and grid-connected modes. The isolated mode requires voltage-controlled working conditions, while the grid-connected mode requires current-controlled working conditions. Consequently, a revision to the inverter controller is necessary during the switch between these modes. In either case, the power controller functions as the external control loop.

The droop control technique is a commonly used method for power regulation. This methodology involves the integration of control loops for regulating frequency and voltage. The droop characteristics pertain to the involvement of active and/or reactive powers, which necessitate potential readjustment based on the connecting lines and system conditions. The absence of stability in the reconfiguration and modification of the controller presents a disadvantageous characteristic, especially in enabling the plug-and-play capability of the inverters. It is imperative to develop a universal controller for voltage source inverters (VSIs) that enables their functioning in both islanded and grid-connected modes, without requiring any controller reconfiguration.

The implementation of a universal controller for Voltage Source Inverters (VSIs) would yield multiple advantages. Initially, it would augment the pliability and adjustability of the inverter systems in diverse operational situations. Enabling the IIERDs to integrate into the power system would be facilitated by the capacity to transition smoothly between islanded and grid-connected modes without requiring any reconfiguration. This would enable a higher level of efficiency and dependability in the functioning of the microgrids, irrespective of the operational mode.

Furthermore, the implementation of a universal controller could streamline the

installation and upkeep of inverter systems. The avoidance of controller reconfiguration during mode transitions results in decreased system complexity and reduced likelihood of failure points. The implementation of this technology optimises the installation procedure and facilitates the incorporation or substitution of inverters in the microgrid, while minimising the interference with the system's global performance.

Moreover, the implementation of a universal controller would enhance the stability of the power system. Through the implementation of a smooth mode transition, the controller can effectively regulate voltage and frequency, thereby preserving the stability of both the microgrid and the interconnected power system. Maintaining system stability is of utmost importance, especially in the context of high-penetration renewable energy sources, as variations in power generation can exert a substantial influence on the system's stability.

In summary, the prevailing pattern in power systems is observing a shift from a centralised generation paradigm to a distributed generation paradigm, and ultimately to intelligent grids. The transition towards integrating diverse renewable energy sources, electric vehicles, energy storage systems, and associated devices into power grids is primarily propelled by the growing usage of power electronic converters. The increasing prevalence of distributed generation, specifically from renewable sources, presents obstacles to the stability of the power system. The appearance of microgrids that are dominated by inverters underscores the necessity for effective regulation, wherein a ubiquitous controller for voltage source inverters (VSIs) is imperative. The implementation of a controller with the characteristics would facilitate smooth functioning in both islanded and grid-connected modes, thereby augmenting adaptability, streamlining deployment, and bolstering the stability of the power system

1.2 VIRTUAL SYNCHRONOUS MACHINE

Due to the massive infrastructure of the current public power system, which is one of the greatest human-made apparatuses in the world, it is not conceivable to completely reconstruct the power system from scratch. It is advisable to concentrate on the efficient control of loads and supplies linked to power electronic converters while following the basic principles of modern power systems.

Synchronous machines (SMs) are widely acknowledged for their inherent capability to attain synchronisation with the power supply or other SMs without necessitating external communication. For more than a century, the innate ability to facilitate the organic growth and operation of power systems has been observed. It is recommended to adopt an architecture that effectively utilises the SM synchronisation mechanism in future power systems to ensure smooth integration and interaction with a diverse range of generators and loads. This methodology obviates the necessity of a communication network in the lower stratum of the power grid, wherein all entities can participate in reciprocal interaction.

The communication functions within this architecture are executed via control mechanisms. Measurements of voltage or frequency at the local level are employed, and control algorithms are implemented based on the fundamental synchronisation mechanism of synchronous machines. Through the removal of low-level controls within the communication infrastructure of a smart grid, attention can be redirected towards high-level functionalities such as the supervision of data, administration, and energy market operations.

The proposed design enables the conversion of conventional and distributed energy resources (DERs) and a significant portion of loads into virtual energy storage systems, which are known as virtual synchronous machines (VSMs). The Virtual Synchronous Machines (VSMs) exhibit autonomous collaboration and contribute towards enhancing the stability of the power system, thereby enabling it to operate independently. The design is accompanied by two distinct technological implementation approaches: the synchronverter technology and the robust droop control

technology.

It is crucial to emphasise that the utilisation of power converters in the role of variable speed machines (VSMs) leverages their benefits, including swift response time and flexible controllability. The objective is not to duplicate traditional synchronous machines with complete accuracy, as this would lead to slow reactions because of their increased inertia. The emphasis lies in utilising the advantages of power converters to create a stronger, dependable, and resistant electrical grid.

Through the implementation of this methodology, the power grid can reap the advantages of the adaptable operation and regulation abilities of power converters, while simultaneously utilising the stability and synchronisation characteristics of synchronous machines. The amalgamation of two technologies results in a hybrid approach that optimises the electricity system's ability to adapt to varying conditions and disruptions.

The utilisation of Vector Space Models (VSMs) presents various benefits. Primarily, it facilitates enhanced assimilation of renewable energy sources and dispersed generation, as they can efficiently engage in system stability and regulation. Moreover, Variable Speed Motors (VSMs) have the potential to aid in frequency regulation and offer supplementary services, thereby improving the overall dependability and efficiency of the power grid.

Moreover, the architecture that relies on Vector Space Models (VSMs) diminishes the dependence on centralised communication networks, which are vulnerable to interruptions and cybersecurity threats. The emphasis is redirected towards localised control mechanisms, which aim to decrease the intricacy and susceptibility of the communication infrastructure, while guaranteeing the stability and efficacy of the power system.

Conclusively, the reconstruction of the entire power system is deemed impractical. It is recommended to optimise the management of loads and supplies that are connected to power electronic converters by utilising the synchronisation mech-

anism of synchronous machines. The implementation of virtual synchronous machines (VSMs) can lead to improved stability, reliability, and resilience in the power system. This is due to the utilisation of power converters and the synchronisation capabilities of synchronous machines. This methodology facilitates a highly adaptable and reactive electrical system that can effectively incorporate sustainable energy sources, dispersed power generation, and diverse loads, while diminishing dependence on centralised communication infrastructures.

Chapter 2

Literature Survey

2.1 Introduction

This chapter presents a comprehensive account of the prior research conducted on similar subjects.

2.2 Dynamic Analysis and Model Order Reduction of Virtual Synchronous Machine Based Microgrid

In recent years, there has been a notable surge in interest surrounding microgrids. These self-contained power systems have the capability to function autonomously or in conjunction with the primary grid. This attention stems from their perceived capacity to bolster grid resilience, integrate renewable energy sources, and enhance energy efficiency. Numerous control strategies and technologies are currently being investigated to enhance the efficiency and dependability of microgrid operations. The Virtual Synchronous Machine (VSM) technology is considered a viable solution for microgrid control. The primary objective of this research is to construct a small signal model for microgrids utilising VSM technology. The aim

of this study is to examine and contrast the unique characteristics of microgrid systems that are based on Variable Speed Micro Hydro Generators (VSMG) and Droop control-based Micro Hydro Generators (DMG)[2]. The comparison entails the examination of the static stability and dynamic response of these systems in both the frequency and time domains. The VSMG system utilises Voltage Source Matrix Converter technology, which facilitates improved performance during transient periods and swift return to a stable state in reaction to local load fluctuations. This technology presents certain benefits in comparison to conventional DMG systems that heavily depend on droop control mechanisms. The objective of this study is to gain insights into the dynamic characteristics of VSMG and DMG systems through a comparative analysis. Additionally, the study aims to elucidate the advantages and disadvantages of each system under various operating conditions and load disturbances. The present study involves an analysis of the behaviour exhibited by VSMG and DMG systems under different frequency and voltage conditions, as well as their capacity to sustain consistent operation during transient events. A comprehensive understanding of the performance of these systems is achieved by evaluating both steady-state and dynamic responses. The findings derived from this analysis make a valuable contribution to the current body of knowledge regarding the properties and behaviour of VSMG systems. They highlight the favourable attributes of VSMG systems, particularly in relation to their transient response and stability. The findings of the study underscore the potential advantages of incorporating VSMG technology into microgrid applications. Vibration-suppressed magnetic gear (VSMG) systems possess enhanced transient response and stability characteristics, rendering them highly suitable for facilitating the functioning of microgrids. This suitability is particularly evident in situations involving the utilisation of renewable energy sources characterised by variable output, such as micro hydro generators. This study provides a valuable resource for power system engineers, researchers, and industry professionals involved in the advancement and application of advanced control techniques for microgrid systems. The study makes a valuable contribution to the ongoing endeavours aimed at optimising the operation of microgrids and improving their overall performance by elucidating the unique characteristics and

benefits of VSMG systems. The study offers significant findings regarding the potential of VSM technology in enhancing the stability and dependability of microgrid systems. This, in turn, facilitates the integration of renewable energy sources and aids in the transition towards a more sustainable and resilient power grid. Finally, the comparison analysis carried out in this paper concentrates on examining the dynamic properties of VSMG and DMG systems in microgrids. The research emphasises the beneficial characteristics of VSMG systems, specifically their improved transient response and stability. The study makes a significant contribution to the development and adoption of advanced control methodologies for microgrid systems by offering valuable insights into the performance of VSMG systems and their potential advantages in microgrid applications.

2.3 A Comprehensive VSM Control Strategy Designed for Unbalanced Grids

The article presents an innovative approach known as VISMA (Virtual Synchronous Machine model for Asymmetric systems), which employs the Virtual Synchronous Machine (VSM) model for the purpose of controlling unbalanced three-phase systems. This study aims to analyse the operational efficiency of a rectifier in asymmetrical three-phase systems and explores the difficulties encountered when attempting to regulate these systems using conventional methodologies[3]. In systems characterised by imbalances, where the amplitudes and/or phases of the three phases differ, conventional control techniques may encounter difficulties in effectively regulating the system. The challenge at hand is effectively tackled by the VISMA method, as outlined in this article, through the integration of a filter that possesses intricate coefficients. The utilisation of this filter facilitates the examination and segregation of sequences that exhibit positive and negative attributes, constituting the fundamental elements of the asymmetrical system. A significant consideration in unbalanced systems pertains to the manifestation of double frequency ripples during the transmission of active and reactive power. The analysis of these ripples

has been conducted within the context of an asymmetrical power system, leading to their identification as the underlying cause of asymmetry in three-phase electrical current and oscillation in direct current voltage. Through the process of analysis and comprehension of these undulations, the article offers valuable perspectives on the underlying constituents that contribute to the instability and fluctuation of the system. The VISMA method proposed in this study extensively depends on the application of the complex coefficient filter. The segregation of positive and negative sequences has a notable impact on system complexity, facilitating the adoption of a control strategy that is both more efficient and effective. The process of sequence separation facilitates the independent regulation of the positive and negative sequence components by the control system, leading to improved system performance and stability. The article provides empirical evidence that supports the efficacy of the VISMA technique in the regulation of unbalanced three-phase systems, with a specific focus on its application in rectifier functionality. The proposed method enhances system efficiency and control by utilising the complex coefficient filter to effectively separate sequences and alleviate double frequency ripples. The findings derived from this research make a significant contribution to the comprehension and advancement of control methodologies for asymmetrical power grids, offering valuable insights for practitioners and academics in this particular domain. The VISMA technique presents several benefits in the regulation of unbalanced three-phase systems. The precise segregation of positive and negative sequences facilitates meticulous regulation of individual components, thereby minimising the impact of asymmetry. This results in enhanced system stability and performance. Moreover, the decrease in system complexity enables the application of control strategies, enhancing their efficiency and effectiveness in the management of asymmetrical systems. The implications of the findings in this study have significant ramifications for diverse applications within the power industry. Asymmetrical systems are frequently encountered in practical situations, and precise regulation of these systems is essential for the preservation of system stability and the maximisation of performance. The utilisation of the VISMA technique presents a potential solution for mitigating the issues related to unbalanced three-phase systems. This technique

holds promise in terms of facilitating the development of more effective control strategies and enhancing overall system efficiency. Using the Virtual Synchronous Machine (VSM) concept, the article's conclusion introduces the VISMA technique for controlling unbalanced three-phase systems. The control and stability of asymmetrical systems are enhanced by the implementation of a complex coefficient filter within the VISMA method, which effectively segregates positive and negative sequences. The findings of the research demonstrate the effectiveness of this method within the domain of rectifier functionality. The research findings presented in this study make a valuable contribution to the advancement of control methodologies for asymmetrical power grids. These insights offer meaningful perspectives for professionals and scholars working in this specific field of study. The utilisation of the VISMA technique holds promise for enhancing the domain of power system control, facilitating the optimisation of unbalanced three-phase systems through improved efficiency and precision.

2.4 A Virtual Synchronous Machine implementation for distributed control of power converters in Smart Grids

The article offers a concise summary of the current state of development of the Vector Space Model (VSM) and concentrates on a particular implementation of the VSM, along with its corresponding mathematical framework. The primary focus of this study is to conduct a stability analysis of the VSM (Variable Speed Motor) system. This analysis entails investigating the eigenvalues and their sensitivities to system parameters. By doing so, we aim to gain a deeper understanding of the dynamic behaviour and stability properties of the system.

When designing a Vector Space Model (VSM), it is crucial to prioritise the maintenance of system stability. Stability analysis entails the examination of the eigenvalues of a model that represents small signals, as well as the exploration of

the sensitivities of these eigenvalues to changes in system parameters. Through the evaluation of eigenvalues and their sensitivities, scientists can acquire a more profound comprehension of the stability characteristics and dynamic reaction of the system.

The article presents the incorporation of a swing equation simulation into the VSM (Virtual Synchronous Machine) implementation. The swing equation is a mathematical formulation that describes the rotor dynamics of a synchronous generator. It plays a pivotal role in precisely capturing the behaviour of the VSM system. Moreover, the article makes mention of cascaded voltage and current controllers, which are integral elements of the VSM implementation.

By conducting an analysis of eigenvalues and their parametric sensitivities, the objective of this article is to augment comprehension regarding the dynamic behaviour and stability properties of the VSM system. This analysis offers significant scientific insights regarding the performance and resilience of the VSM implementation, thereby aiding in its future development and optimisation.

The findings and observations elucidated in the article serve to enhance the continuous progress of Variable Speed Motor (VSM) technology. By incorporating a particular implementation and conducting an analysis of its stability properties, the article contributes to the existing knowledge base regarding VSM (Vector Space Model) systems. This information holds significant value for scientists and engineers engaged in the advancement and enhancement of Voltage Source Converter-based Static Synchronous Compensator (VSM) technologies.

The ongoing advancement and refinement of VSM (Voltage Stability Monitoring) systems play a crucial role in numerous applications within the realm of power systems. The utilisation of VSM technology presents various benefits, including the augmentation of power quality, the amplification of control capabilities, and the facilitation of the integration of renewable energy sources. The article enhances our understanding of stability analysis and the dynamic behaviour of the VSM (Virtual Synchronous Machine) system, thereby contributing to the optimisation and

progress of VSM systems in various power system applications.

In general, the article functions as a valuable resource for researchers and practitioners who are interested in VSM (Value Stream Mapping) technology. The text describes a particular instantiation of the Vector Space Model (VSM), explores the corresponding mathematical structure, and emphasises the significance of conducting stability analysis. The results of this study enhance our comprehension and advancement of VSM (Virtual Synchronous Machine) systems, empowering researchers to maximise their efficiency, improve their reliability, and broaden their utilisation in the domain of power systems.

2.5 Comparison of Methods for Implementing Virtual Synchronous Machine on Inverters

The primary objective of this study is to examine the utilisation of the Variable Inductance Synchronous Motor Algorithm (VISMA) on an inverter using two distinct methodologies. The objective of this study is to analyse and contrast the static and dynamic characteristics of the system while it is functioning in conjunction with a rigid grid. Furthermore, an analysis is conducted to assess the practicality of integrating both VISMA methodologies into an autonomous power grid.

The article presents a novel methodology for the implementation of the Virtual Synchronous Machine Algorithm (VISMA) on a Pulse Width Modulation (PWM) controlled inverter. This methodology entails the application of two separate models: a current-to-voltage converter and a voltage-to-current converter. These models facilitate the control of the inverter's functioning and streamline the application of VISMA principles.

One notable benefit of VISMA implementations lies in their capacity to operate independently in an islanded condition, wherein the inverter can function autonomously without dependence on the main power grid. This underscores the

capacity of self-sustaining power networks or microgrids to produce electricity in a sustainable manner, even in the absence of connection to the primary grid.

The utilisation of a current-to-voltage model results in a significant enhancement in the precision of voltage measurements. The meticulous control of electric current and its subsequent transformation into voltage contributes to the stability and dependability of the voltage output. This phenomenon enhances the stability and efficiency of the power supply, which is of paramount importance for a multitude of applications.

The article concludes by presenting a concise overview of the results and significance of the VISMA implementation on the pulse-width modulation-controlled inverter. The methodologies presented in this study provide significant insights into the potential applications of Voltage-Source Inverter-based Model Predictive Control (VISMA) in the regulation of inverters and the facilitation of autonomous power grids. The objective of this study is to enhance the domain of control algorithms and techniques in order to enhance the effectiveness of power systems, particularly in islanded or autonomous grid configurations.

The implications of the study's findings hold significant importance within the domain of power systems and grid operation. The VISMA approach offers a potential solution for improving the efficiency and dependability of inverters, particularly in situations where they operate independently. The capacity to function autonomously from the primary power grid presents opportunities for self-sustaining power networks, thereby mitigating reliance on centralised power generation and enhancing the overall power system's resilience.

The integration of VISMA into power systems presents numerous advantages. First and foremost, this technology facilitates accurate voltage regulation, thereby guaranteeing a reliable and uniform provision of electrical power. This aspect is of utmost importance, especially in contexts involving sensitive applications, as variations in voltage can result in adverse consequences. Furthermore, the capacity to operate independently in islanded mode significantly strengthens the robustness of

the power system, enabling it to sustain operations even in the event of disturbances or blackouts in the primary grid. In conclusion, the implementation of VISMA plays a significant role in promoting the progress of control algorithms and techniques, thereby fostering innovation within the realm of power systems engineering.

The feasibility of integrating VISMA into self-sustaining power grids is a promising proposition. These networks possess the capacity to facilitate the integration of renewable energy sources and mitigate carbon emissions. By integrating localised generation sources, such as solar panels or wind turbines, into microgrids equipped with VISMA-controlled inverters, communities can reduce their dependence on power generation derived from fossil fuels and attain a greater degree of energy self-sufficiency.

Furthermore, the ongoing optimisation of power systems is supported by the advancements in control algorithms and techniques enabled by VISMA. VISMA has the potential to optimise the utilisation of renewable energy resources, minimise energy wastage, and improve the overall performance of systems by enhancing the efficiency and reliability of inverters. The aspect holds significant importance within the framework of transitioning towards a sustainable and ecologically conscious energy industry.

In essence, the article introduces a novel methodology for the implementation of VISMA on an inverter that is governed by pulse width modulation. The statement emphasises the capacity of VISMA implementations to function independently in isolated scenarios, enhance voltage accuracy, and contribute to the advancement of self-sustaining power grids. The implications of the study's findings are relevant to the progress of control algorithms and techniques within the domain of power.

2.6 Conclusion

This section summarises the findings on the detailed study of the topics related to the proposed system. This literature survey helped to identify different

approaches to implement the related systems, their methodology, pros & cons of each approach etc.

Chapter 3

Methodology

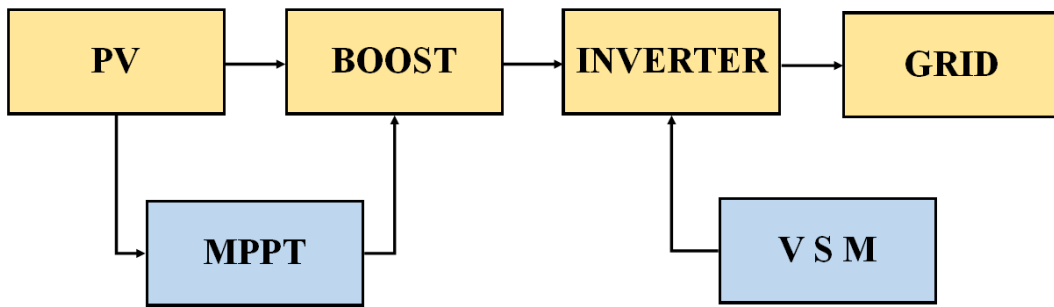


fig. 3.1: PV fed VSM

PV is integrated into the grid with the help of a boost converter and an inverter. The boost converter boosts the PV voltage and provides it to the inverter. The inverter converts the boost output which is DC to AC and provides it to the grid. MPPT technique is necessary in order to track the maximum power from PV. A VSM technique is employed here to provide better stability to the system.

3.1 Power Stage

The power stage of a three-phase LC filter-equipped voltage source inverter (VSI) is shown in Figure 3.2. The Voltage Source Inverter (VSI) is linked to an AC bus by means of interconnecting conductors and a three-phase switch (SW).

The VSI is connected to the grid via a three-phase circuit breaker, allowing it to function autonomously or in an interconnected state as per the user's needs.

The VSI (Voltage Source Inverter) is a device that is primarily designed to perform the conversion of electrical energy from direct current (DC) to three-phase alternating current (AC) or vice versa. The system comprises of three inverter legs that are regulated by pulse width modulation (PWM) techniques. The Pulse Width Modulation (PWM) control signal functions as a point of reference for the gate drive and PWM block located in the power stage.

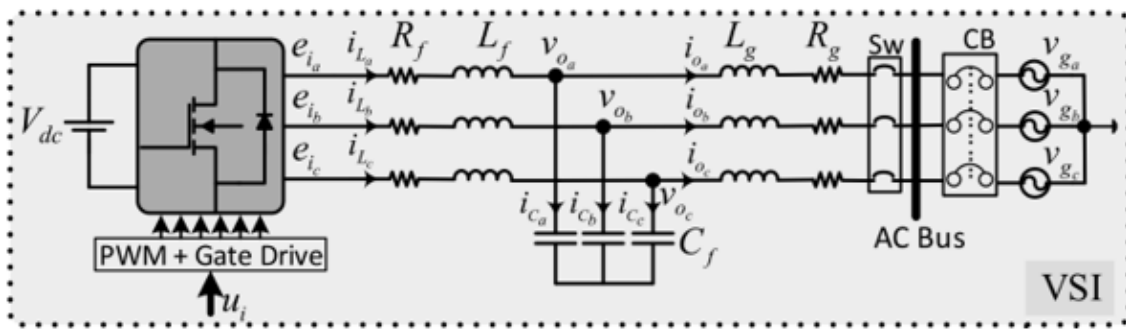


Fig. 3.2: Power stage of a three-phase VSI

To mitigate the effects of switching-induced voltage ripple and consequent current ripple, the system incorporates LC filters. The implementation of filters aids in the attenuation of voltage and current waveform distortions, thereby enhancing the power quality of the AC bus.

In the context of grid-connected operation, it is crucial to consider the grid impedance in the inductors (L_g) and their corresponding series resistance (R_g). This guarantees optimal functioning of the system in parallel with the grid. It is important to acknowledge that in this particular arrangement, the impedance of the grid is presumed to be infinitely large, leading to the creation of a "infinite bus" beyond the circuit breaker. This hypothesis streamlines the examination of the system's performance.

The power supply of the synchronverter is denoted by the circuit located on the left-hand side of the three capacitors, which encompasses the capacitors them-

selves. Under the assumption of minimal ripple, this particular segment of the circuit exhibits analogous behaviour to that of a synchronous generator (SG) that is linked in parallel with capacitors of identical specifications. While the diagram does not explicitly depict inductors (L_g), their inclusion can confer benefits in terms of achieving synchronisation and power regulation. The presence of an energy reservoir on the DC bus is crucial, despite its lack of explicit depiction in the diagram. The system's stability is maintained by an energy reservoir that absorbs power from both the primary motor and the rotating component of the synchronous generator (SG), thereby preventing any potential disruptions. The DC bus may experience power absorption surges that are directly proportional to the grid frequency derivative. The occurrence of surges is attributed to fluctuations in the grid frequency, and the presence of an energy reservoir aids in minimising their effect on the system.

The power stage of the three-phase voltage source inverter (VSI) with an LC filter facilitates the conversion of DC electrical energy to AC or vice versa, as illustrated in Figure 3.2. The utilisation of LC filters aids in mitigating voltage and current ripple, thereby augmenting the power quality delivered to the AC bus. The establishment of a connection to the electrical grid via a three-phase circuit breaker facilitates the possibility of operating autonomously or in an interconnected manner. The incorporation of inductors and an energy storage component facilitates the attainment of synchronisation, power regulation, and system stabilisation. Autonomous or interconnected state, contingent upon the user's discretion. The utilisation of a direct current to alternating current (DC-AC) converter, colloquially referred to as an inverter, holds significant importance in a multitude of scenarios where alternating current (AC) power is necessary but solely direct current (DC) power is accessible. Inverters find widespread application in various industries, including renewable energy systems, electric vehicles, uninterruptible power supplies (UPS), and numerous other sectors. A comprehensive understanding of the operation and constituent elements of an inverter is imperative for grasping its functionality and practical implementation.

The primary objective of an inverter is to facilitate the conversion of direct

current (DC) electrical energy into alternating current (AC) or vice versa. In the context of a DC-AC inverter, the input is derived from a direct current (DC) power source, such as a battery or a solar panel. The output, on the other hand, is characterised by an alternating current (AC) waveform, which can manifest as either a single-phase or three-phase configuration, depending on the specific operational needs. In contrast, an AC-DC inverter operates with an alternating current (AC) power source, commonly derived from the electrical grid, and produces a regulated direct current (DC) voltage as its output.

To accomplish the conversion process, an inverter is composed of three distinct inverter legs, with each leg being assigned the task of generating a single phase of the alternating current waveform. The regulation of these legs is achieved through the utilisation of pulse width modulation (PWM) technique, wherein the width of the pulses administered to the switching devices, such as insulated-gate bipolar transistors (IGBTs), is controlled. The manipulation of pulse width enables the regulation of both average output voltage and frequency, facilitating the precise and seamless production of the intended alternating current waveform.

One of the primary difficulties encountered in the operation of inverters is the existence of voltage and current fluctuations resulting from the switching behaviour of the Insulated-Gate Bipolar Transistors (IGBTs). The presence of these ripples has the potential to generate undesirable harmonics, thereby impacting the overall performance and efficiency of the system. In order to address this concern, the system incorporates LC filters. LC filters are composed of inductors (L) and capacitors (C) which collaborate to mitigate voltage and current fluctuations by effectively attenuating the waveform.

In the context of grid-connected operation, the inclusion of the inverter in the electrical grid necessitates careful consideration of the grid's impedance within the broader system. The inclusion of inductors (L_g) and their accompanying series resistance (R_g) serves to integrate the impedance of the grid into the system. The inclusion of this consideration is imperative due to the finite nature of the grid

impedance. Failing to account for it would lead to imprecise functioning of the inverter. By taking into consideration the impedance of the grid, the inverter is able to guarantee accurate synchronisation and power regulation, while simultaneously preserving stability and efficiency.

The power supply of the inverter, which is positioned on the left side of the capacitors within the circuit, exhibits similarities to a synchronous generator (SG) that is connected in parallel with capacitors of equal characteristics. While the inverter does not incorporate physical inductors (L_g), the inclusion of such components can offer benefits in terms of synchronisation and power regulation. The inductors, denoted as L_g , serve to model the impedance of the stator windings within an idealised synchronous generator.

$$v = -(R_f i) - \frac{d\phi}{dt} = -(R_f i) - L_f \frac{di}{dt} + e$$

Within the confines of the circuit, the voltage across the capacitor is directly associated with the terminal voltage (v) of the hypothetical synchronous generator. Furthermore, the inductance L_f and resistance R_f parameters associated with the inductors positioned on the left side symbolise the impedance characteristics of the stator windings within the hypothetical synchronous generator. The parameters exert a substantial influence on the overall behaviour and performance of the inverter. The rotational motion of the theoretical rotor within the synchronous generator results in the generation of a counter electromotive force (EMF), denoted as e_a , e_b , and e_c . The attainment of accurate control in manipulating these signals can pose a challenge, albeit one that is generally attainable due to their high-frequency characteristics. To achieve the desired value of e , it is necessary to regulate the switches within the inverter to ensure that the mean values of e_a , e_b , and e_c during a switching period align with the desired value. The regulation is achieved through the utilisation of conventional Pulse Width Modulation (PWM) techniques, wherein the pulse widths of the switching signals are modified to attain the intended output waveform. $e = M_f i_f \theta \sin \theta - M_f \frac{di_f}{dt} \cos \theta$ The appropriate selection of filtering capacitors C is crucial, as it determines the resonant frequency $\frac{1}{\sqrt{L_f C}}$ that should

be approximately equilent to $\sqrt{\omega_n \omega_f}$. Here, ω_n represents the nominal angular frequency of the grid voltage, while ω_f is the angular switching frequency employed for switching on and off the switches. Although the figure depicts insulated-gate bipolar transistors (IGBTs), alternative power semiconductors can also be utilised. This resonant frequency is of utmost importance as it serves to eliminate undesirable harmonics and maintain the seamless functioning of the system. Through a meticulous process of capacitor selection, the inverter can attain an optimal level of performance while simultaneously mitigating potential complications associated with voltage and current ripples.

The illustration portrays the use of insulated-gate bipolar transistors (IGBTs) as the power semiconductors in the inverter. However, it is worth noting that alternative power semiconductor devices may also be employed, depending on the specific demands of the application. The devices encompassed in this category consist of MOSFETs (Metal-Oxide-Semiconductor Field-Effect Transistors), thyristors, and various other sophisticated power electronic components. The selection of power semiconductors is contingent upon various factors, including but not limited to switching speed, power handling capabilities, efficiency, and cost considerations.

A DC-AC inverter plays a crucial role in diverse applications that necessitate the transformation of DC electrical energy into AC current, or vice versa. The efficient conversion of power while ensuring stability and accuracy can be achieved through the application of pulse width modulation (PWM) techniques in conjunction with LC filters to mitigate voltage and current ripples. The inclusion of the impedance of the electrical grid via the utilisation of inductors, coupled with the consideration of the parameters associated with a hypothetical synchronous generator, facilitates the attainment of synchronisation and the regulation of power. The optimal performance and efficient operation of the inverter system are ensured through the careful selection of filtering capacitors and power semiconductors.

3.2 Virtual Synchronous Machine

A Virtual Synchronous Machine (VSM) is a control paradigm that allows power electronic converters, like inverters, to replicate the characteristics of a conventional synchronous machine. It plays a pivotal role in power systems and the integration of renewable energy by offering stability and capabilities that support the grid.

When establishing a connection between an inverter and a power grid, a fundamental goal is to achieve synchronisation between the inverter's output and the voltage and frequency of the grid. The process of synchronisation guarantees a seamless and dependable transmission of energy, thereby upholding the stability and effectiveness of the power grid. Synchronous machines are commonly employed as generators in conventional power plants, exhibiting crucial attributes such as inertia, voltage regulation, and frequency control.

The VSM control algorithm facilitates the emulation of the dynamics and traits of a synchronous machine by an inverter. Through the implementation of this control scheme, the inverter is able to actively regulate its active and reactive power output, thereby establishing a stable connection with the grid. The control algorithm perpetually observes the grid voltage and frequency, and modifies the inverter's output correspondingly to uphold synchronisation. Through the utilisation of the Vector Space Model (VSM) control algorithm, inverters have the capability to replicate the grid-supporting functionalities exhibited by synchronous machines. This facilitates the effective incorporation of sustainable energy sources, such as solar or wind, into the electrical grid. Furthermore, it aids in the preservation of stability, power integrity, and system robustness amidst the variability of renewable energy generation.

The VSM control algorithm is commonly formulated with the objective of facilitating a smooth and uninterrupted switch between grid-connected and islanded (stand-alone) operational modes. In the scenario of islanded mode, wherein the connection to the grid is severed, the Voltage Source Management (VSM) control algorithm enables the inverter to uphold consistent voltage and frequency levels.

This ensures a dependable and self-sufficient power provision to the nearby loads.

Furthermore, the implementation of VSM (Virtual Synchronous Machine) control has the potential to enhance the active involvement of renewable energy sources in providing ancillary services to the grid. Ancillary services encompass vital functions such as frequency regulation, voltage support, and system restoration, which are imperative for upholding the overall stability of the power grid. Through the replication of synchronous machine behaviour, inverters equipped with Virtual Synchronous Machine (VSM) technology have the capability to actively participate in providing ancillary services. This active involvement serves to improve the flexibility and dependability of the power system.

Chapter 4

PV Integration

The optimisation of power output is of utmost importance in enhancing the efficiency and performance of photovoltaic (PV) systems. One of the primary methodologies employed to accomplish this objective is known as Maximum Power Point Tracking (MPPT). This response aims to provide a comprehensive analysis of the concept of Maximum Power Point Tracking (MPPT), its significance within Photovoltaic (PV) systems, and the pivotal role played by DC-DC converters in the extraction of the maximum available power.

The field of photovoltaics has emerged as a highly efficient and promising method for generating renewable energy. In light of the global challenges arising from the depletion of conventional power resources and the environmental consequences associated with traditional energy generation, the necessity for alternative energy sources becomes increasingly evident. Solar energy possesses significant potential owing to its abundant and freely accessible nature.

Photovoltaic (PV) modules, comprising interconnected solar cells, produce direct current (DC) electricity upon exposure to sunlight. Nevertheless, it is uncommon for a photovoltaic (PV) module to operate at its maximum power point (MPP) during regular circumstances. The maximum power point (MPP) is defined as the specific combination of voltage and current at which the module exhibits its highest

power output. To fully exploit the capabilities of photovoltaic (PV) modules, it is imperative to employ tracking mechanisms and operate them at their maximum power point (MPP).

The photovoltaic (PV) array, consisting of multiple PV modules, functions as an unregulated direct current (DC) power source. Prior to connecting the photovoltaic (PV) array to the grid or a load, it is necessary to ensure that the array is appropriately conditioned in order to maximise power extraction. MPPT techniques are employed in this context. The photovoltaic (PV) modules' electrical working point is effectively modified by the Maximum Power Point Tracking (MPPT) technology, allowing them to produce the highest power possible.

The Maximum Power Point Tracking (MPPT) technique holds significant importance in photovoltaic (PV) systems due to various compelling reasons. Initially, the proposed approach aims to optimise the power output of the photovoltaic (PV) array, irrespective of variations in temperature and radiation conditions. The power output of photovoltaic (PV) modules can experience fluctuations due to variations in solar irradiance, which can occur at different times of the day and under diverse weather conditions. The incorporation of Maximum Power Point Tracking (MPPT) within photovoltaic (PV) systems ensures the attainment of optimal efficiency through continuous monitoring and adjustment of the operating point to sustain the Maximum Power Point (MPP).

Furthermore, Maximum Power Point Tracking (MPPT) serves to mitigate fluctuations in the electrical characteristics of the load. The impedance characteristics of the electrical load connected to a photovoltaic (PV) system can vary, thereby influencing the efficiency of power transfer. The utilisation of Maximum Power Point Tracking (MPPT) in photovoltaic (PV) systems allows for the dynamic adjustment of the operating point of the PV modules. This capability enables the system to effectively adapt and optimise power delivery to the load by maximising the power output.

In order to achieve maximum power point tracking (MPPT), a direct current-

direct current (DC-DC) converter is utilised at the output of the photovoltaic (PV) array. The primary function of the DC-DC converter is to optimise power transfer from the photovoltaic (PV) module to the load, ensuring maximum power output. The device serves as a mediator between the photovoltaic (PV) array and the load, facilitating effective power conversion and regulation. Various types of DC-DC converters, including buck converters, boost converters, and buck-boost converters, can be employed based on the specific voltage demands of the load.

The operation of the DC-DC converter involves the manipulation of the duty cycle, defined as the proportion of time during which the switch is on relative to the entire switching period. By manipulating the duty cycle, the converter has the ability to alter the load impedance perceived by the photovoltaic (PV) array in an efficient manner. Impedance matching facilitates the optimisation of power extraction from the photovoltaic (PV) module and its subsequent transfer to the load.

It is crucial to acknowledge that MPPT does not function as a mechanical tracking system that physically alters the orientation of PV modules to directly align with the sun. In contrast, Maximum Power Point Tracking (MPPT) relies on electronic control and monitoring techniques to consistently track and modify the operating point of the modules. The implementation of this electronic system guarantees the optimisation of PV modules' power output, eliminating the necessity for manual repositioning.

In order to maximise the power production of PV systems, MPPT is an essential approach in the field of photovoltaics. The utilisation of Maximum Power Point Tracking (MPPT) technology allows for the continuous monitoring and optimisation of photovoltaic (PV) modules at their Maximum Power Point (MPP). This enables the PV system to efficiently extract the maximum amount of available power, irrespective of variations in temperature, radiation conditions, and load characteristics. The utilisation of DC-DC converters in conjunction with maximum power point tracking (MPPT)

4.1 P&O MPPT

Maximum power point tracking (MPPT) in photovoltaic (PV) systems is frequently accomplished using the perturb and observe (P&O) methodology. The algorithm functions by monitoring the power output of the photovoltaic (PV) array and implementing small perturbations, either increasing or decreasing, to the voltage or current of the array. The PO algorithm initiates by inducing a minor perturbation to the system, resulting in an alteration in the power output of the solar module. If the power exhibits an increase due to the perturbation, the algorithm will proceed to perturb in the same direction. Through this process, it progressively converges toward the maximum power point.

Once the maximum power is attained, the power at the subsequent moment initiates a decline. At this juncture, the algorithm initiates a reversal of the perturbation direction in order to retrace its steps toward the peak power point. The phenomenon of oscillation occurring near the maximum point arises when the system achieves a state of equilibrium.

In order to maintain minimal power fluctuation throughout the oscillatory procedure, the perturbation magnitude is maintained at a significantly diminutive level. Through the implementation of iterative modifications and ongoing observation of the power generation, the algorithm is able to adaptively follow the Maximum Power Point (MPP) in response to fluctuations in environmental factors. It is imperative to acknowledge that the Perturb and Observe (P&O) algorithm serves as a straightforward and widely utilized Maximum PowerPoint Tracking (MPPT) technique. Nevertheless, it is important to acknowledge that there may be certain limitations associated with this phenomenon. In instances where there are multiple peaks or rapidly fluctuating irradiance levels, the system has the capability to oscillate around the Maximum Power Point (MPP). Moreover, in the event that the magnitude of the perturbation is excessively large, it can result in overshooting or prolonged tracking duration. The flowchart of execution is shown in Figure 4.1

In general, the Perturb and Observe (P&O) algorithm offers a relatively simple

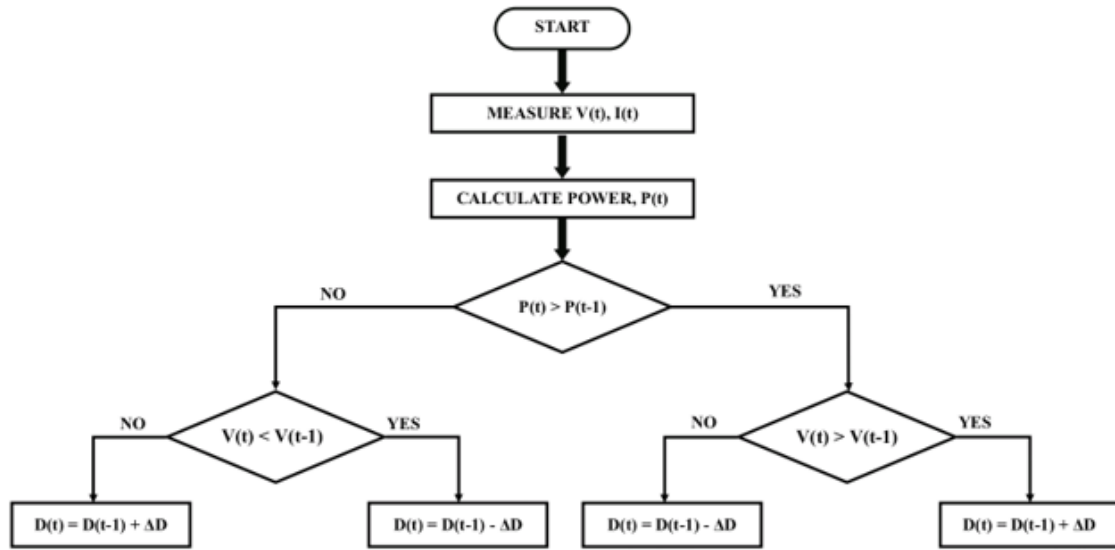


fig. 4.1: P&O Algorithm

and efficient method for Maximum PowerPoint Tracking (MPPT) by systematically perturbing the system and analyzing the resulting variations in power generation.

The Perturb and Observe Maximum Power Point Tracking (P&O MPPT) algorithm is employed to continuously monitor and adjust the operating point of a photovoltaic system to maximise the power output at the Maximum Power Point (MPP). The process is accomplished by monitoring and measuring both the electrical power and voltage. The graph depicting the irradiance curve is presented in Figure 4.2. Based on the observations, it is evident that there exists a specific voltage at which the maximum power point is achieved. Any voltage beyond this point results in a decrease in power output.

By comparing the current values of power and voltage with their respective previous values, one can determine the change in power and voltage. Using these two values, we can analyse various scenarios such as a positive change in power and voltage, a positive change in power but a negative change in voltage, a negative change in power but a positive change in voltage, and both voltage and power experiencing negative changes. Based on the observed variations in power and voltage measurements, it is possible to monitor the specific location and determine

the corresponding duty cycle. If the decrease in power is negative and the decrease in voltage is also negative, it indicates a shift toward the left of the Power-Voltage profile. This implies that a specific duty cycle value must be assigned in order to achieve the Maximum Power Point (MPP). The duty cycle exhibits variability based on the position and yields the maximum power point (MPP).

4.2 PV Array Sizing

The PV size is selected according to the connected load in the grid. For example, if the connected load is 150KW then we need to design a PV system that produces power greater than 150KW. Irradiance is another important factor in solar power generation. We must first take into account the irradiance of the area where the system will be installed. Another factor to be considered is the panel generation factor. Calculating the panel generation factor is necessary to make up for environmental impacts,

Table 4.1: Panel generation factor

Desert Area	3.86
Land Area	3.43
Cloudy area (5-7 days/month)	3.00
Cloudy area (<10 days/month)	2.57

Peak panel power = Wh ÷ PGF, where PGF is the panel generation factor.

Maximum power,

$$P_M = V_M \times I_M$$

Calculate the number of modules to be connected in series and parallel,

$$N_S = V_{MA} / V_M$$

$$N_P = I_{MA} / I_M$$

For the simulation purpose, a 200W PV panel is selected and a string of 11 modules connected in series and 1 such string is connected in parallel, having a total power of 2300 W at maximum. With the help of an MPPT technique, we can track the

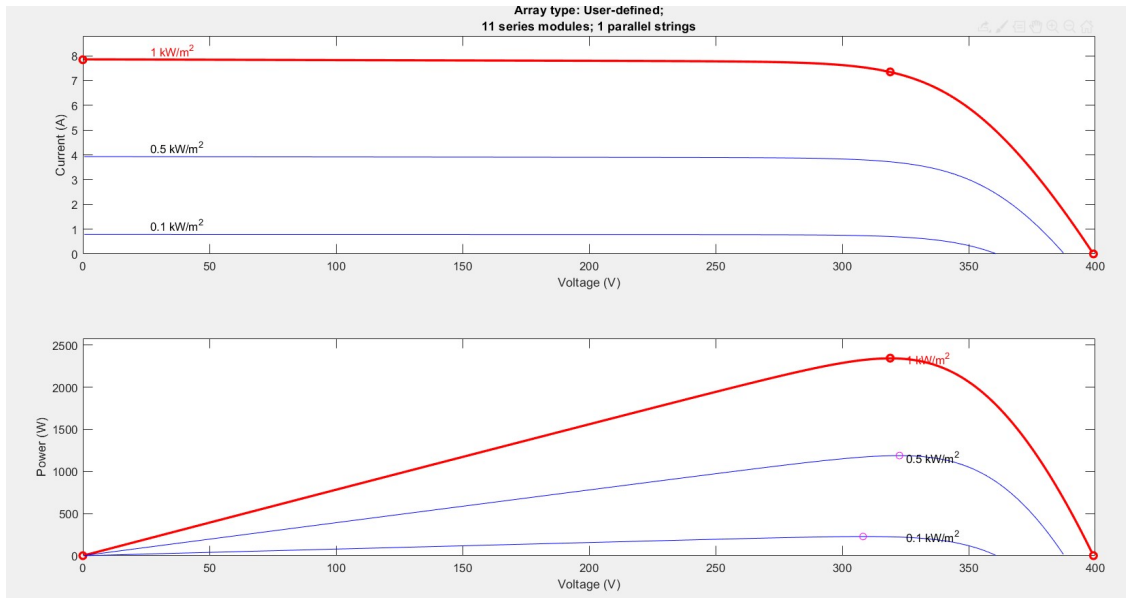


fig. 4.2: PV power and voltage profile with different irradiance

maximum power which is nearly 2000W. Fig.4.2 shows the power, current, and voltage profile with different irradiance for a 200W solar panel. The panel specifications are,

Open circuit voltage=36.3V

Short circuit current=7.84A

Voltage at MPP= 29V

Current at MPP= 7.35A

Fig.4.2 only shows when one series string is taken, we can take the no of series strings and parallel strings according to our bus voltage and current. From the fig, it's quite understandable that for every irradiance there is a maximum power point and it needs to be tracked.

4.3 Boost Converter

The Boost converter, alternatively known as a step-up converter, is an electronic circuit specifically engineered to augment the voltage level of a given power source. It is frequently employed in diverse applications wherein a greater voltage is necessitated than that which the input source furnishes. From the figure 4.3

converter consists of multiple essential elements, such as an input voltage source, a switch, an inductor, a diode, a capacitor, and a load resistor. By alternately activating and deactivating the switch, the Boost converter is able to control and stabilise the output voltage.

Upon closure of the switch, an electric current is established within the inductor, resulting in the accumulation of energy within its magnetic field. This phenomenon results in a gradual increase in the current flowing through the inductor. Conversely, in the open state, the inductor discharges its stored energy, while the diode facilitates the passage of current through the load resistor and capacitor.

One notable advantage of the Boost converter lies in its ability to achieve voltage amplification without relying on a transformer, in contrast to alternative approaches like step-down converters. This property renders it particularly advantageous in situations where a greater voltage magnitude is necessary, yet the utilisation of a transformer is impractical or undesirable.

The Boost converter functions by regulating the duty cycle, symbolised as D , which signifies the proportion of time the switch is turned on compared to the entire switching period. The duty cycle is a parameter that governs the duration for which the switch remains closed, thereby influencing the resultant level of output voltage. By manipulating the duty cycle, the Boost converter is capable of accurately controlling the output voltage in accordance with the specified requirements.

It is noteworthy that although the input current exhibits continuous flow, the average output current is observed to be lower than the average inductor current. This implies that the inductor facilitates the transfer of energy to the output during the switch's on-time, leading to an increase in the root mean square (rms) current flowing through the filter capacitor.

The photovoltaic (PV) system is linked to the boost converter and subsequently connected to the bus. The boost converter is responsible for increasing the voltage generated by the photovoltaic (PV) system and supplying it to the direct current

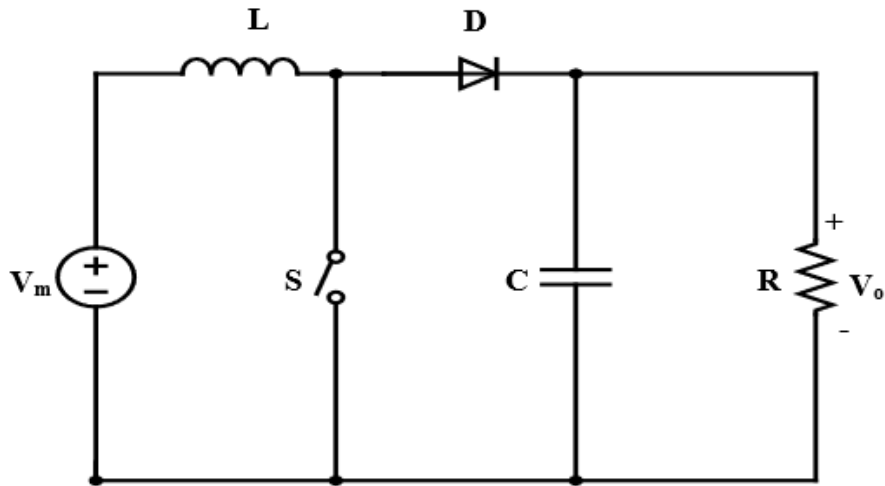


Fig. 4.3: Schematic representation of Boost converter

(DC) bus. The duty cycle of the boost converter can be determined by utilising the equation provided.

4.4 Design of Boost Converter

Desired output, $V_o=600V$

1. Selection of d

$$d_{min} = 1 - \frac{V_{in_min}}{V_o} = 0.625 \quad (4.1)$$

$$d_{max} = 1 - \frac{V_{in_max}}{V_o} = 0.5625 \quad (4.2)$$

Nominal d=0.6

2. Inductor Ripple Current, ΔI_L

$$\Delta I_L = (0.2 - 0.4) \times I_{out_max} \times \frac{V_o}{V_{in}} = 1.6 \quad (4.3)$$

3. Selection of L_{min}

$$\Delta I_L \geq \frac{d(1-d) \times V_o}{f_s \times L} \quad (4.4)$$

$$L_{min} = 26mH$$

4. Selection of Output capacitance

$$C_{out} = \frac{I_{out_max} \times d}{f_s \times \Delta V_o} = 250\mu F \quad (4.5)$$

Table 4.2: Boost Converter Parameters

Boost Converter Parameters	Parameter Values
Efficiency	0.9
Duty Cycle	0.53
Switching frequency	20 KHz
Inductor	0.15 mH
Capacitor	0.27 mF

Chapter 5

Simulation

5.1 Introduction

Matlab Simulink is used for simulation. The math computing environment and proprietary multi-paradigm computer language MATLAB were created by MathWorks. MATLAB is an acronym for "MATrix LABoratory." Matrix manipulation, function and data plotting, algorithm implementation, user interface creation, and interfacing with other programming languages are all possible with MATLAB.

Although MATLAB is mainly designed for numeric computation, symbolic computation capabilities are accessible through an optional toolbox that uses the MuPAD symbolic engine. Graphical multi-domain modelling and model-based design for embedded and dynamic systems are added by an additional package called Simulink.

5.2 Component Design

5.2.1 Active Power

DC voltage source :- 420V

5.2.2 Reactive Power

In conventional synchronous machines reactive power is related to peak voltage. By this E can be determined from the simulation (fig 5.2).

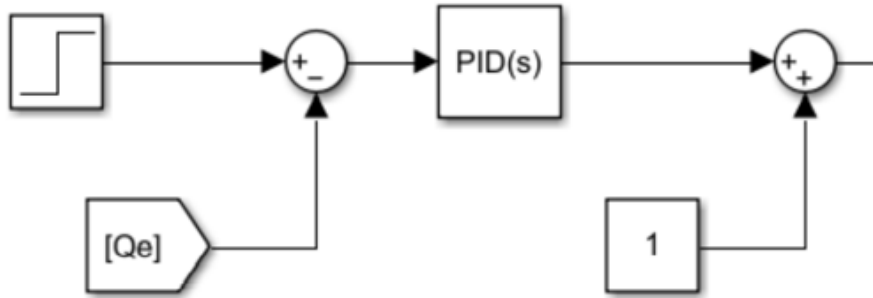


Fig. 5.2: Reactive Power Simulation Block

5.2.3 Lowpass Filter

Low pass filter used to determine the values of active and reactive power from instantaneous power it obtained by the simulation .It is necessary to convert this instantaneous power to average power.

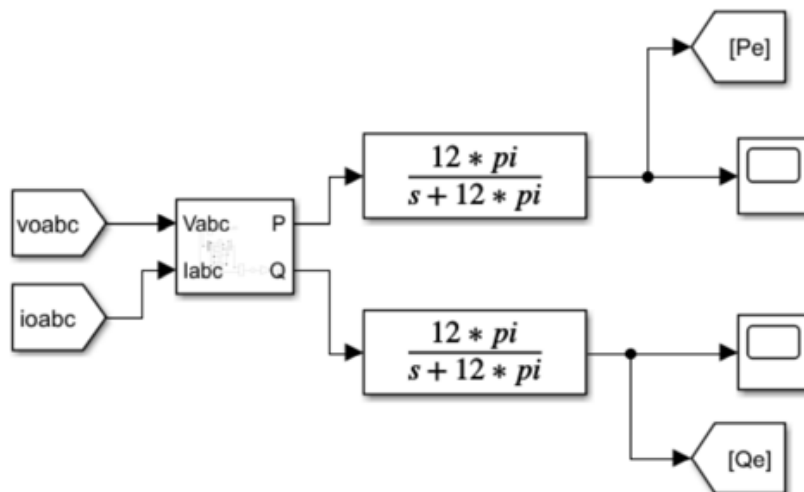


Fig. 5.3: Lowpass filter

$$\omega_c = \frac{1}{10^{th}} \text{ of fundamental frequency} \quad (5.3)$$

$$= \frac{1}{10} \times 2\pi \times 60 = 12\pi$$

By combining the active (fig 5.1) and reactive (fig 5.2) simulation block. We got a combined form (fig 5.4) for the use of power block of VSM.

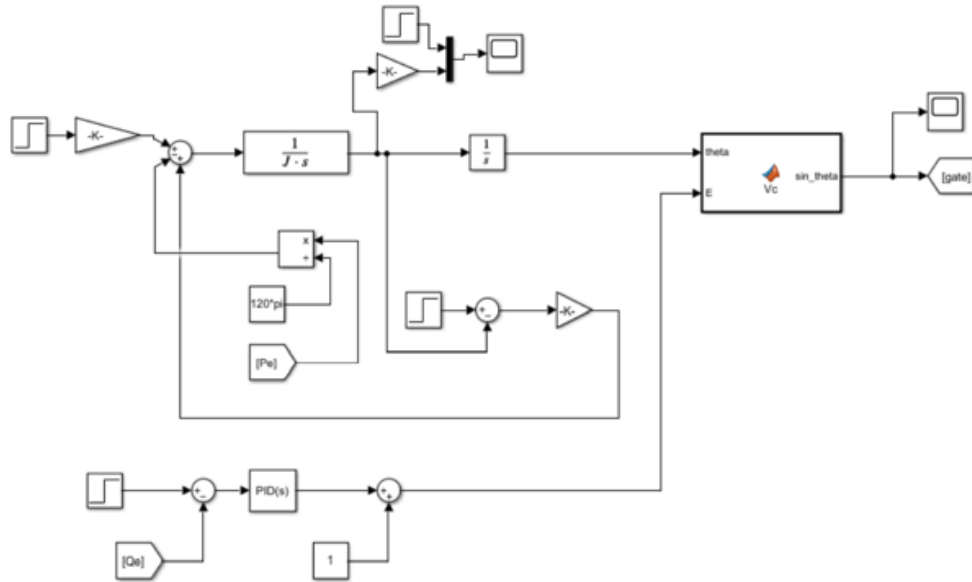


Fig. 5.4: Combined form of Active and Reactive powers

By analysing the simulation fig: 5.4 the values like E, θ and ω has obtained.

Table 5.1: System Parameters

System parameters	Parameter Values
Grid phase voltage	120v
Grid frequency	60 Hz
Filter resistance (R_f)	0.364 Ω
Filter inductance	2.5 mH
Filter capacitance (C_f)	10 μ F
Virtual inertia	0.0002 kgm^2
Nominal angular frequency (ω_n)	12 π rad/s

5.2.4 Power Part

Power part of VSM is obtained by combining the simulations and the required values.

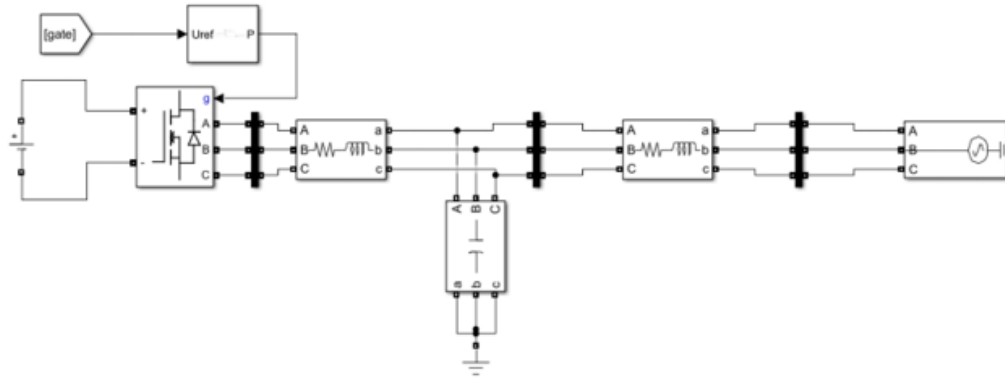


Fig. 5.5: Power part of VSM

5.3 PV MPPT Boost Converter

Now dc source is changed and pv panel is given as a source. The output of the PV is fed as the input to the boost converter which boosts the input voltage to required voltage i.e 600 V. The gate pulse from the P&O algorithm control the PWM generator of the Boost converter switch.

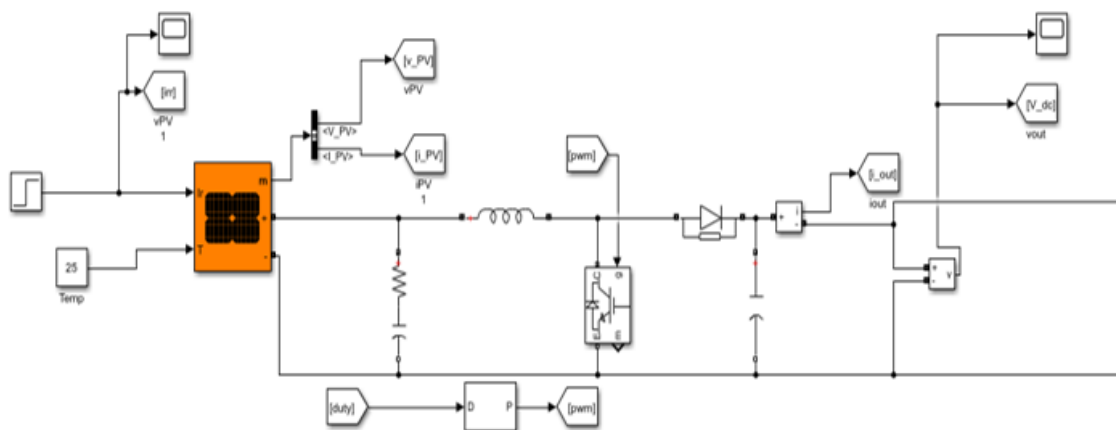


Fig. 5.6: PV MPPT Boost Converter

5.3.1 MPPT Control design

The PV module's output is always fluctuating. An MPPT is used with the DC-DC converter to get the maximum power out of the panel. The Matlab embedded block is then modified by adding the MPPT algorithm to create the MPPT block. The output of the MPPT, i.e the duty cycle is fed to the mosfet of the DC-DC boost converter, while the output of the PV module's current and voltage are passed into the Matlab embedded block.

The P-V curve's slope is picked up by the perturb and observe algorithm, and the P-V curve's extreme is utilized to find the MPP. For MPPT, this algorithm perturbs the operating voltage to ensure maximum power. The MPPT function block's output, a duty cycle, is passed to the PWM generator to produce the gate pulse for the boost converter's mosfet.

5.4 PV MPPT into Grid

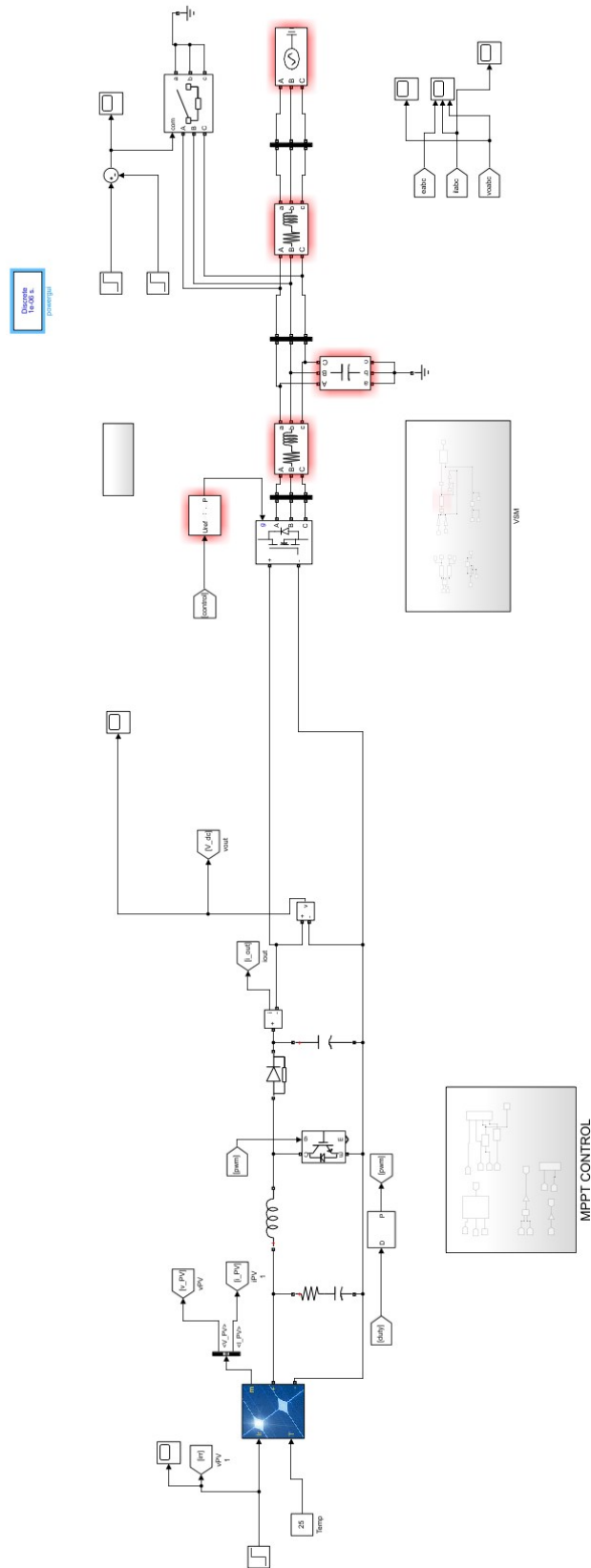


Fig. 5.7: PV MPPT into Grid

5.5 Conclusion

The simulation of the proposed system and modified system are carried out in Matlab and the results are compared.

Chapter 6

Results and Discussions

6.1 VSM in the grid without PV integration

Figure 6.1 to 6.5 shows the result when there is no PV integration into the grid, a DC source is connected there. Figure 6.1 and 6.2 shows the PCC voltage (voltage at the point of common coupling) and output current of VSM. In fig:6.3, the active power responses of the VSM for step changes in reference commands were observed. The active power reference is changed from 5KW to 10KW at $t=2s$. In Fig 6.4, the reactive power response of VSM for step changes in reference commands were observed. The reactive power reference is changed from 2000 VAR to 4000 VAR at $t=2s$. In Fig:6.5, the VSM successfully tracks the reference frequency of 60 Hz.

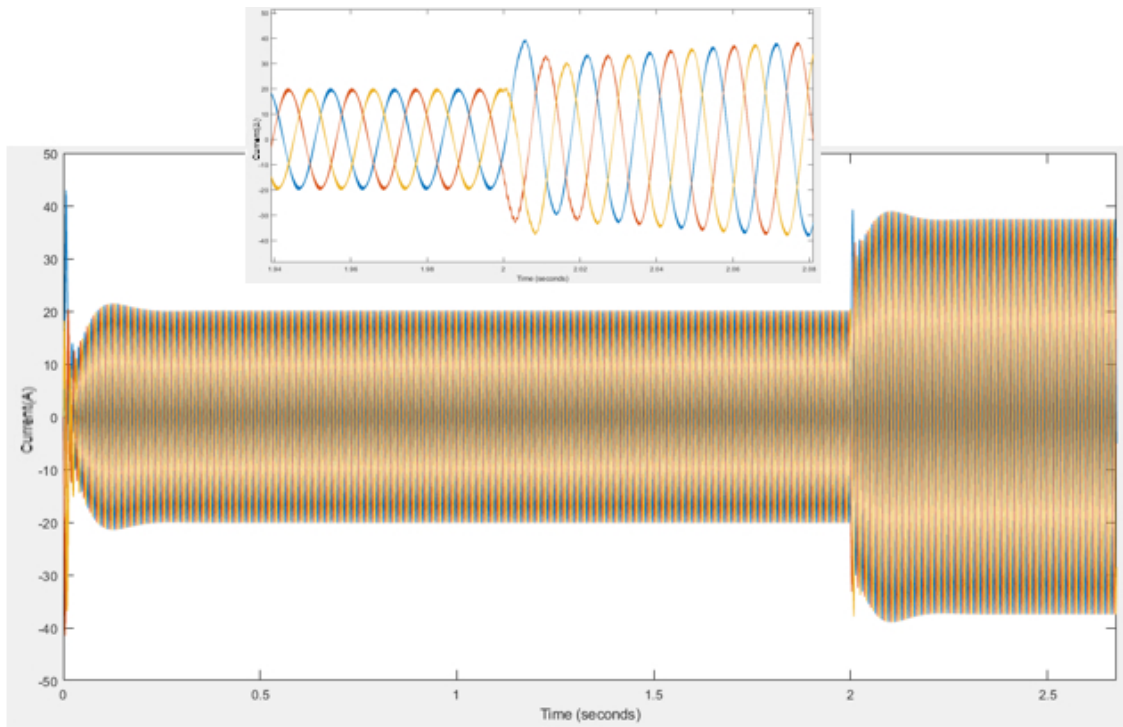


Fig. 6.1: Output current of VSM in abc reference frame.

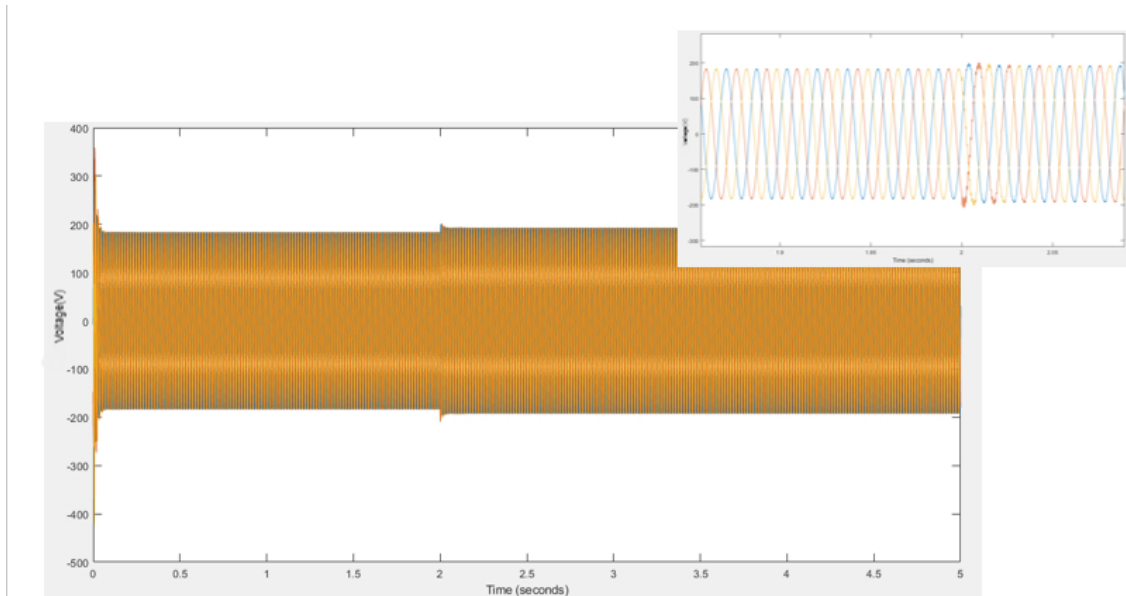


Fig. 6.2: PCC voltage in abc reference frame

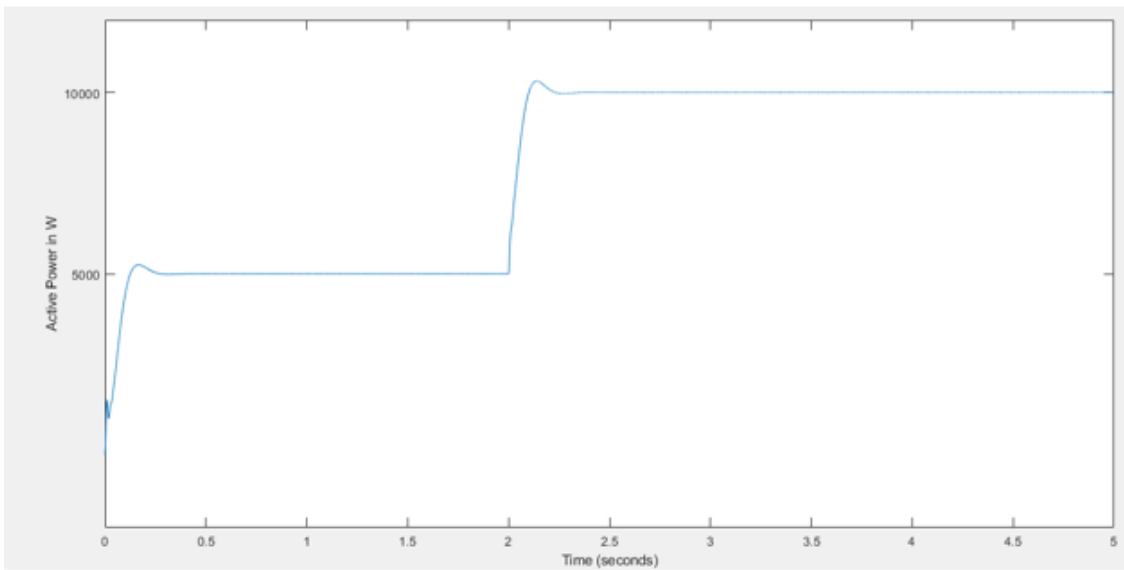


Fig. 6.3: Active Power Injected into Grid by VSM

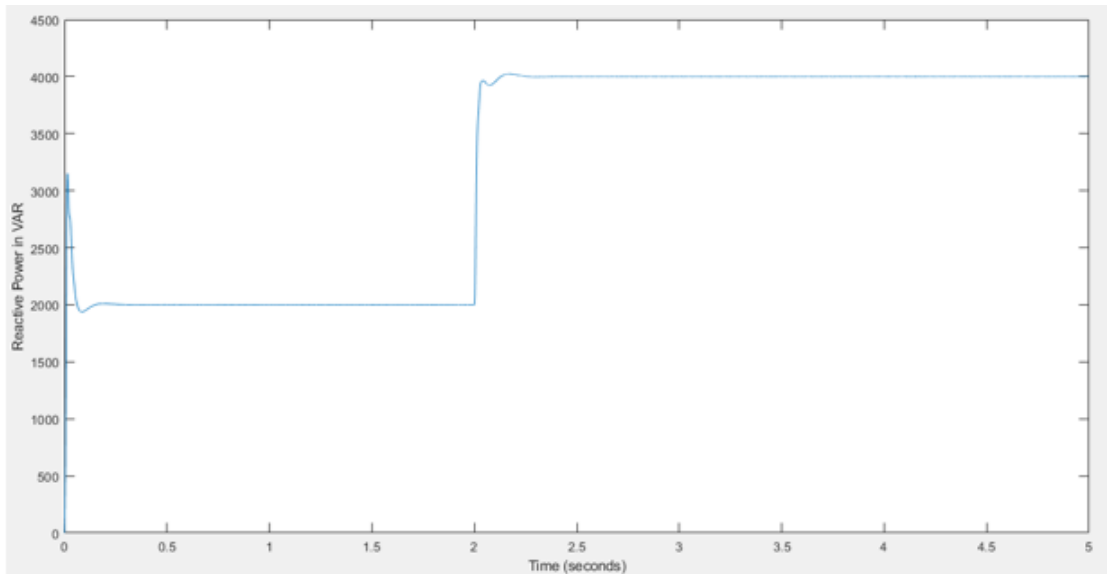


Fig. 6.4: Reactive Power Injected into Grid by VSM

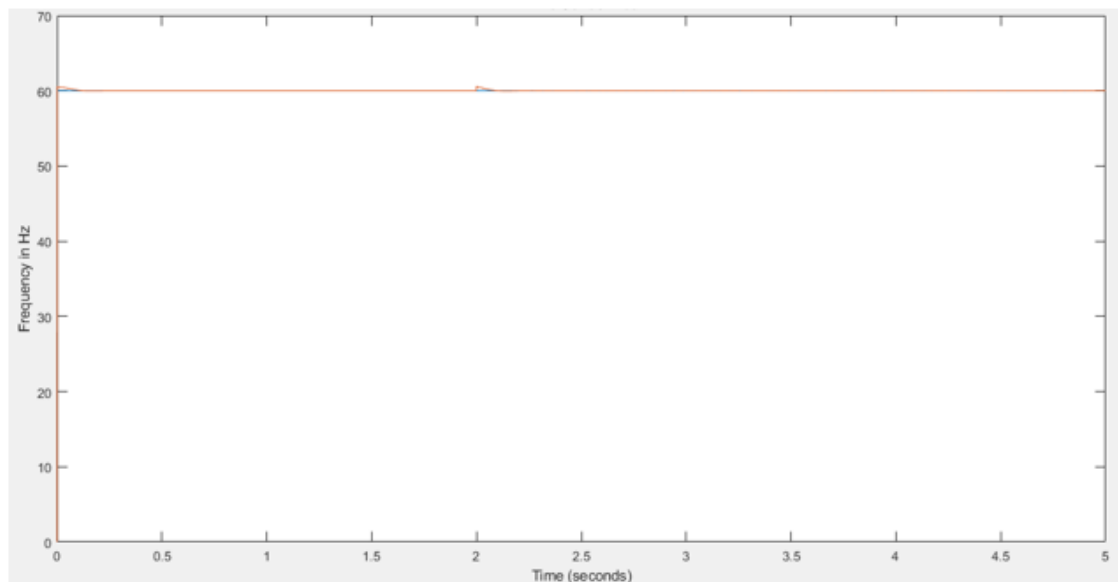


Fig. 6.5: Frequency of VSM Output Voltage

6.2 VSM in the grid with PV integration

PV is integrated into the grid with the help of a boost and inverter which is explained in earlier sections. The following results are obtained according to different conditions.

6.2.1 Case 1: Active and Reactive Power Responses with a constant irradiance

In this case, a constant irradiance of $1000W/m^2$ is provided to the system. A voltage of nearly 200V is obtained at the point of common coupling which is shown in figure 6.6. Figure 6.7 shows the three-phase current injected into the grid which is around 8A. In this condition, a 2000W active power and 500 VAR reactive power are injected into the grid in which both of them settle after a 0.7Seconds.

6.2.2 Case 2: Active and Reactive Power Responses by providing a step change in irradiance

In this case, a step change in irradiance is given to the system which is shown in Figure 6.10. From $t=0$ to $t=2$ Seconds a $500W/m^2$ irradiance is provided and after that, the irradiance is changed to $1000W/m^2$. In this condition, the active and reactive power obtained is shown in Fig 6.11 and 6.12. When a $500W/m^2$ irradiance is provided, the active power is around 1000W and it takes nearly 0.7 seconds to settle. After $t=2$ seconds the irradiance is changed to $1000W/m^2$ and the active power is changed to around 2000W after a small fluctuation of around 0.6 seconds. The same changes are also noticeable in reactive power response.

6.2.3 Case 3: Active and Reactive Power Responses by providing an irradiance curve

In this case, an irradiance curve is given to the system which is shown in Figure 6.14. Here in every second, the irradiance is changing. so our system needs to behave according to that change. There is no irradiance from $t=0$ to $t=0.5$ seconds,

after that, the irradiance increases with small fluctuations and it reaches maximum irradiance at $t=2$ to $t=2.5$ seconds. After that, the irradiance decreases and reaches zero at $t=3.8$ seconds. The active power response is similar to the irradiance curve with certain oscillations due to sudden irradiance change and its shown in Figure 6.15. From $t=0$ to $t=0.5$ S there are only oscillations in active power response because there is no irradiance provided but after $t=0.5$ seconds the irradiance increases and as a result the active power increases and reaches 2000W at maximum irradiance. But on the path to maximum power, it has so many small oscillations. Between $t=0.5$ and $t=1$ S there is a continuous fluctuation, it's because of the oscillation present in the irradiance curve, and after that the power response is similar to the irradiance curve. So we say that the system behaves properly to the sudden irradiance variations. The reactive power response is shown in Figure 6.16.

6.2.4 Case 4: Performance of VSM under LLLG fault at its terminals

Here a three-phase symmetrical fault (LLLG fault) is simulated at the terminals of the VSM and its performance is analyzed. A fault is given in between $t=2$ to $t=2.3$ S to the system, the active and reactive power response obtained is shown in figures 6.17 and 6.18. Here the irradiance is constant so the active and reactive power is also constant, but at $t=2$ seconds the fault occurs and both the active and reactive power varies and the system becomes unstable. At $t= 2.3$ S the fault is cleared and both the active and reactive power tries to come back to their previous value. It takes almost 0.4 seconds to come into its stable condition after the fault is cleared. When the fault occurred the frequency also varied but when the fault cleared, It can be seen that the VSM successfully tracks the reference frequency of 60Hz which is shown in figure 6.19.

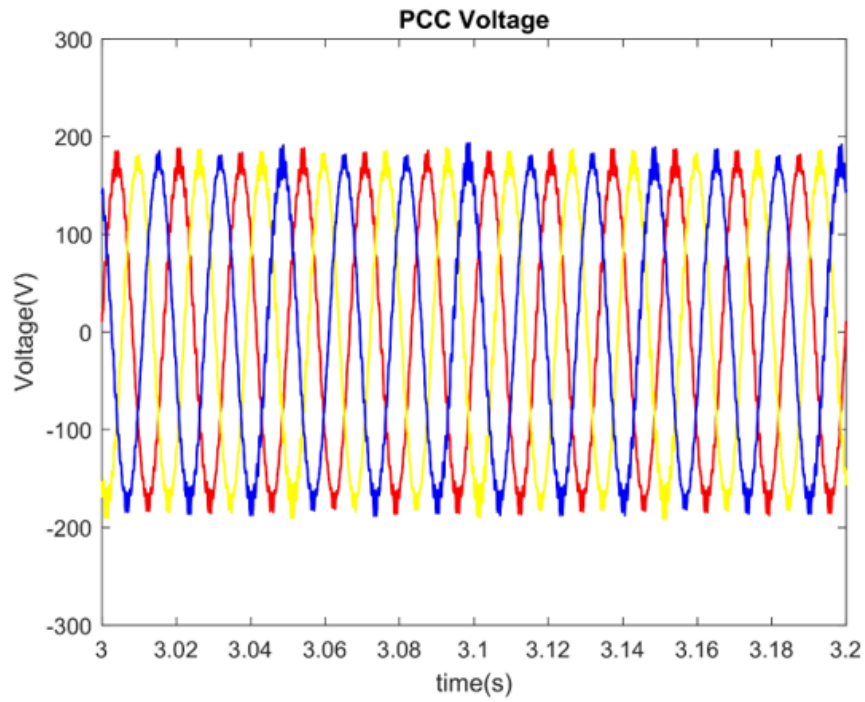


Fig. 6.6: Voltage at Point of Common Coupling

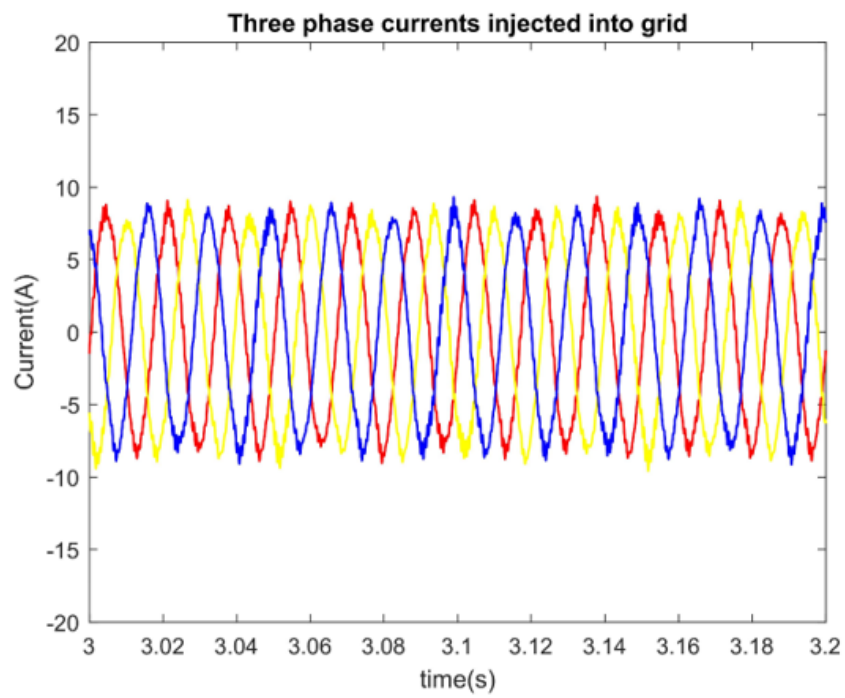


Fig. 6.7: Three Phase Current Injected into the Grid

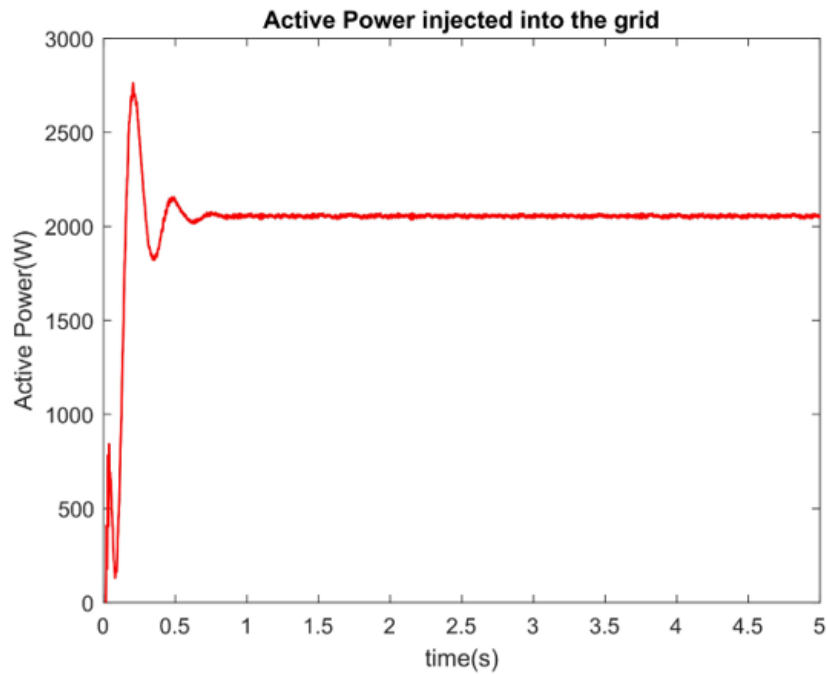


Fig. 6.8: Active Power Injected into Grid

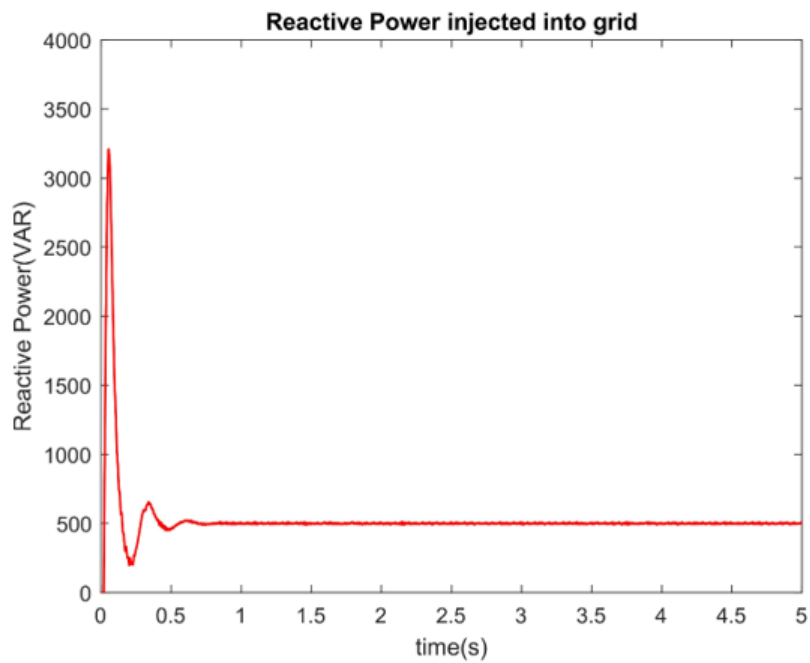


Fig. 6.9: Reactive Power Injected into Grid

6.3 Results with Step Change in Irradiance

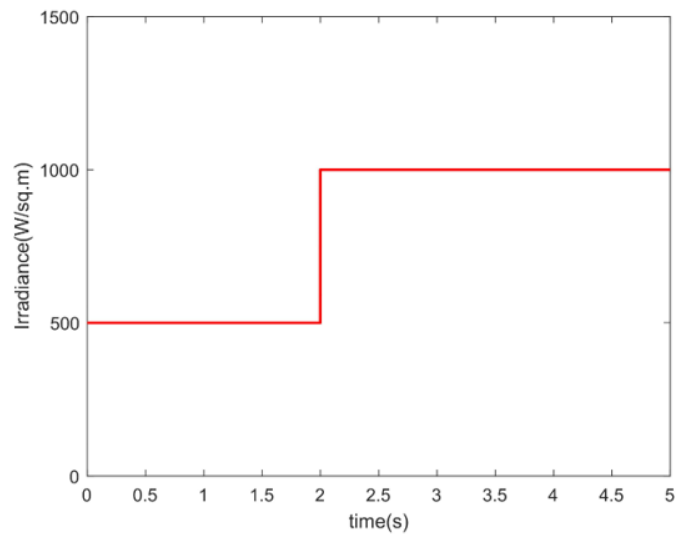


Fig. 6.10: Step Change in Irradiance

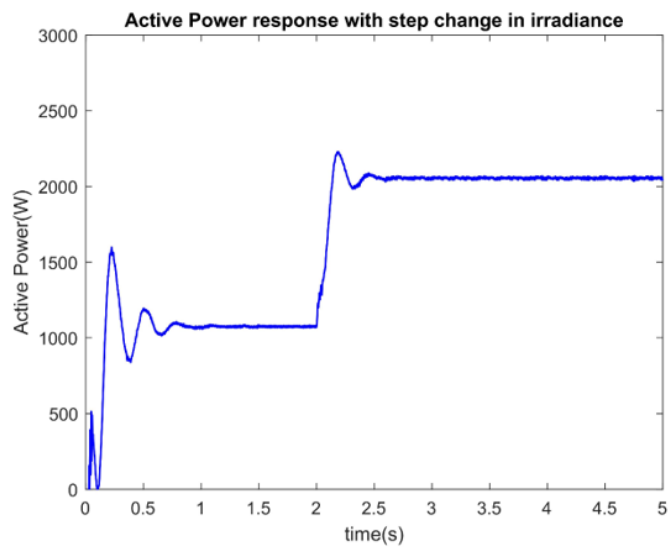


Fig. 6.11: Active Power Response with Step Change in Irradiance

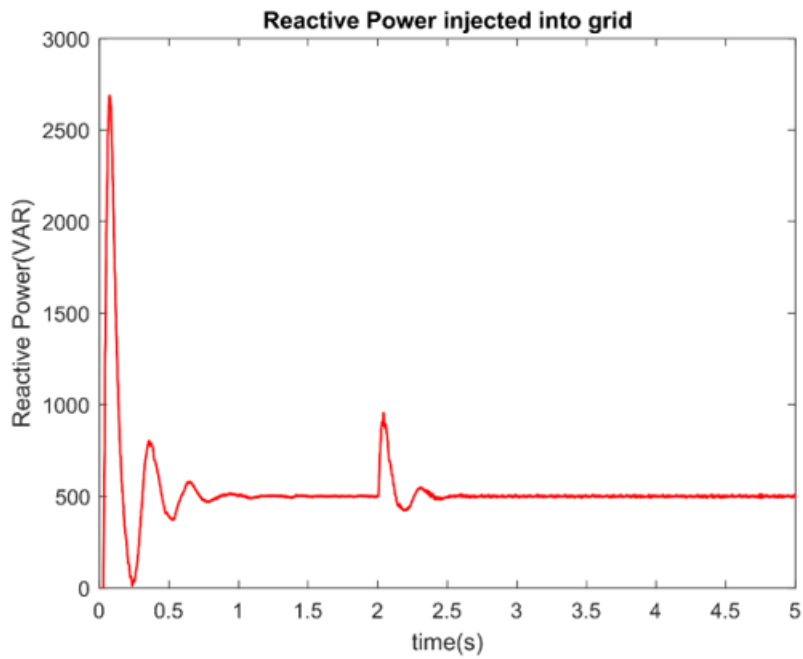


Fig. 6.12: Reactive Power Response with Step Change in Irradiance

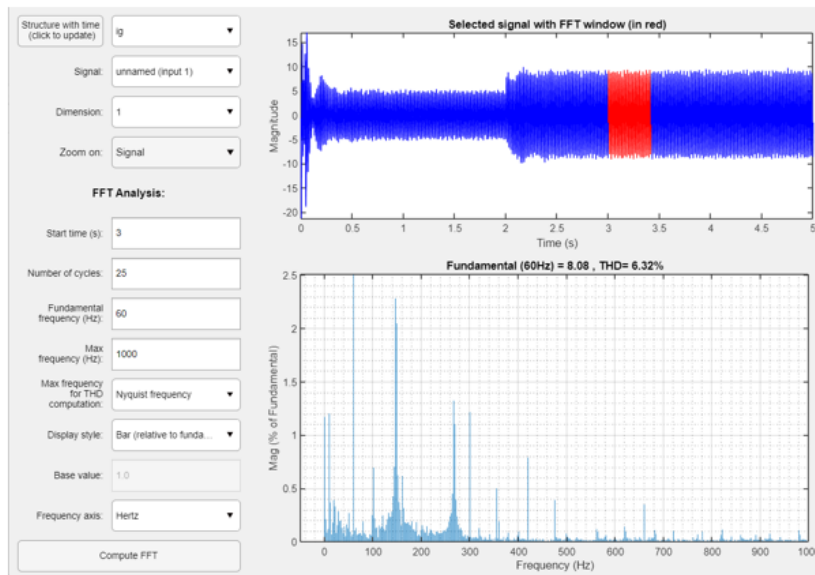


Fig. 6.13: THD in Current

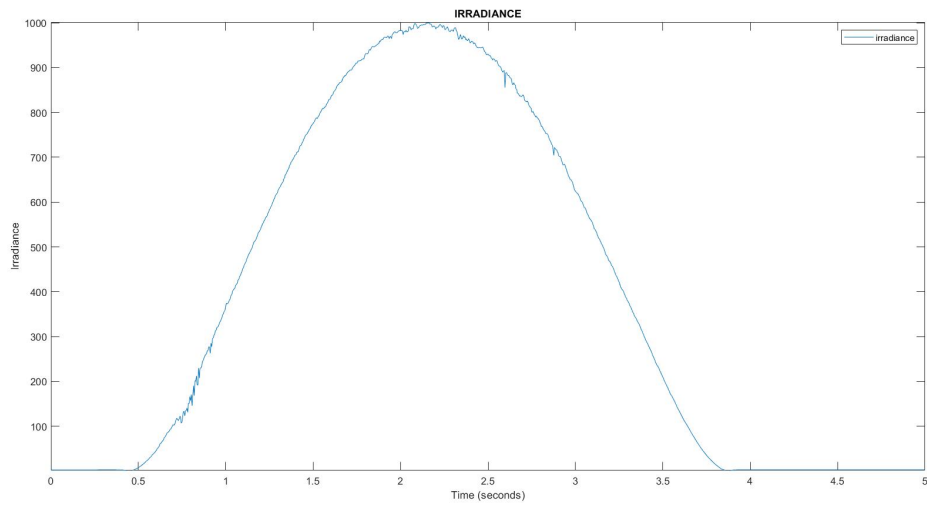


Fig. 6.14: Irradiance curve

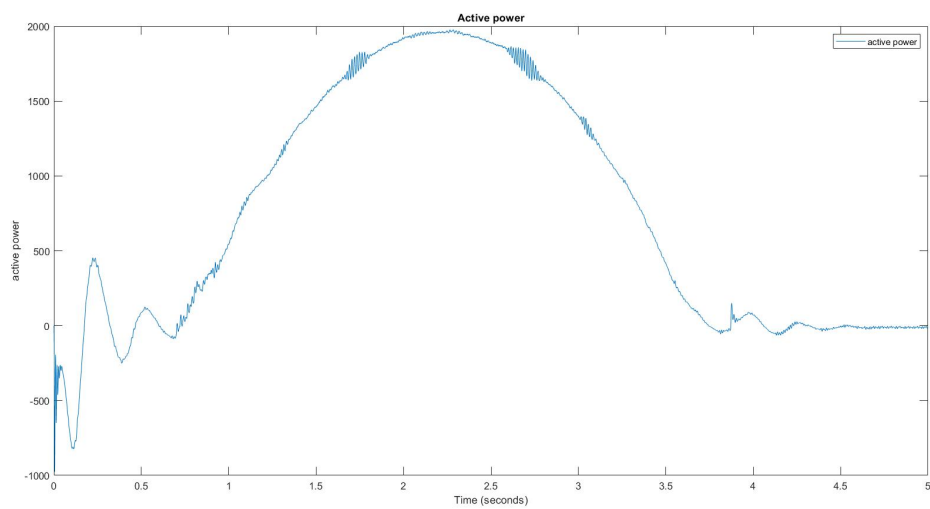


Fig. 6.15: Active power response with irradiance curve

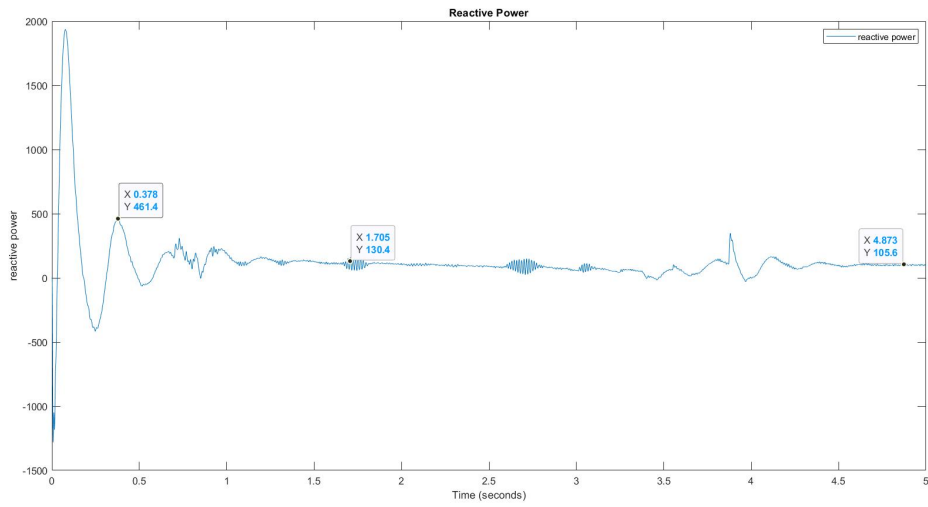


Fig. 6.16: Reactive power response with irradiance curve

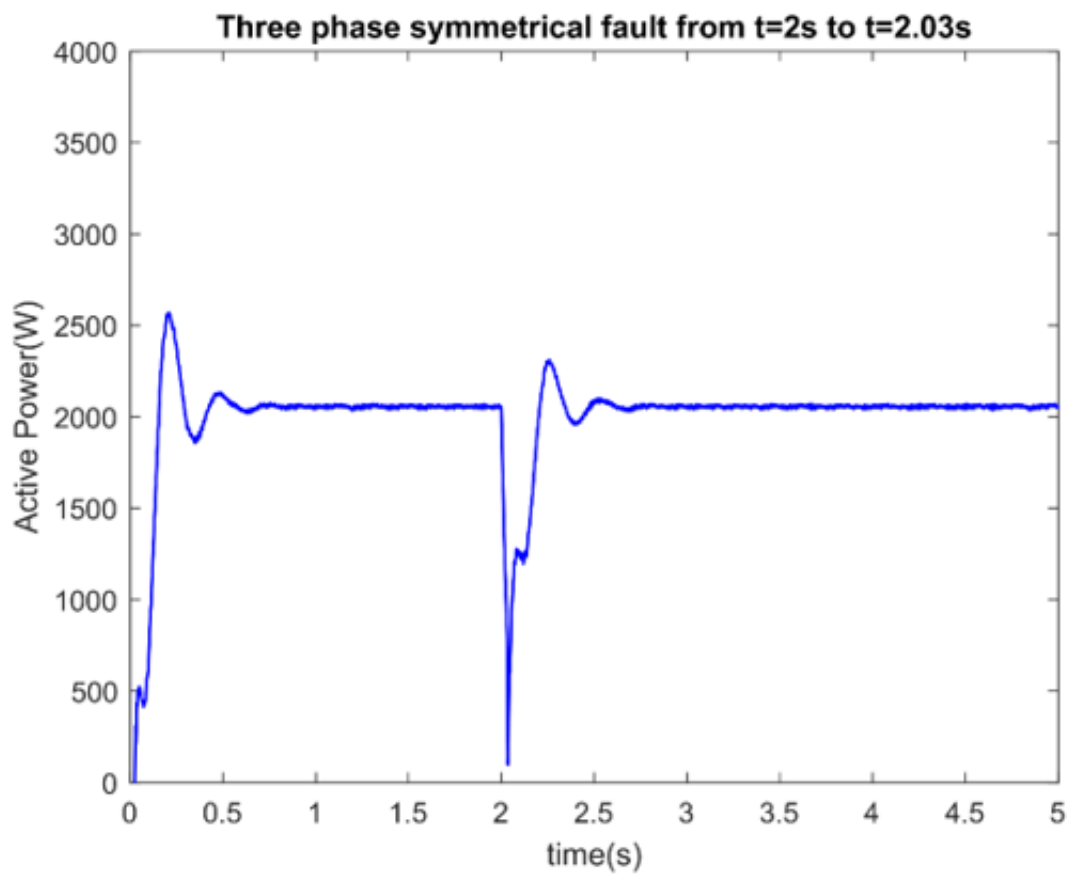


Fig. 6.17: Active Power Injected during Fault

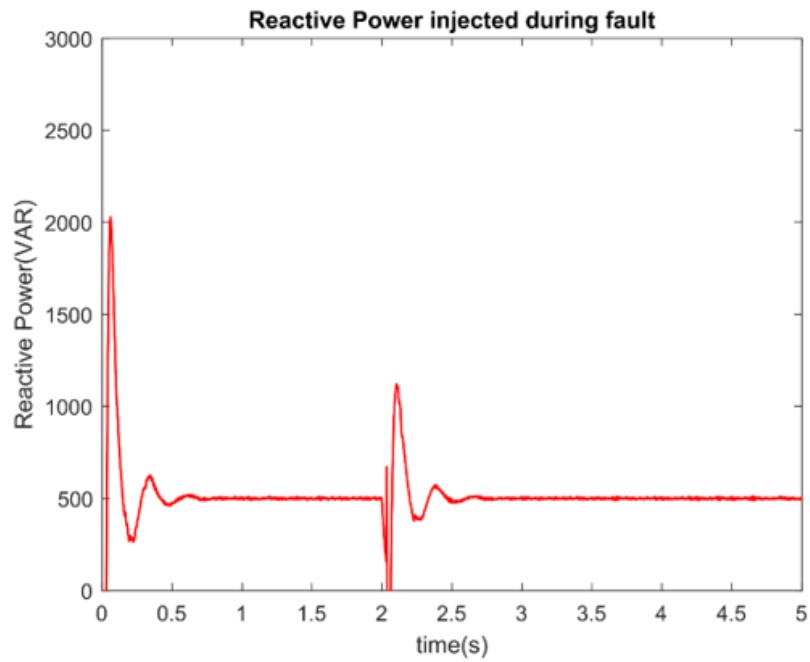


Fig. 6.18: Reactive Power Injected during Fault

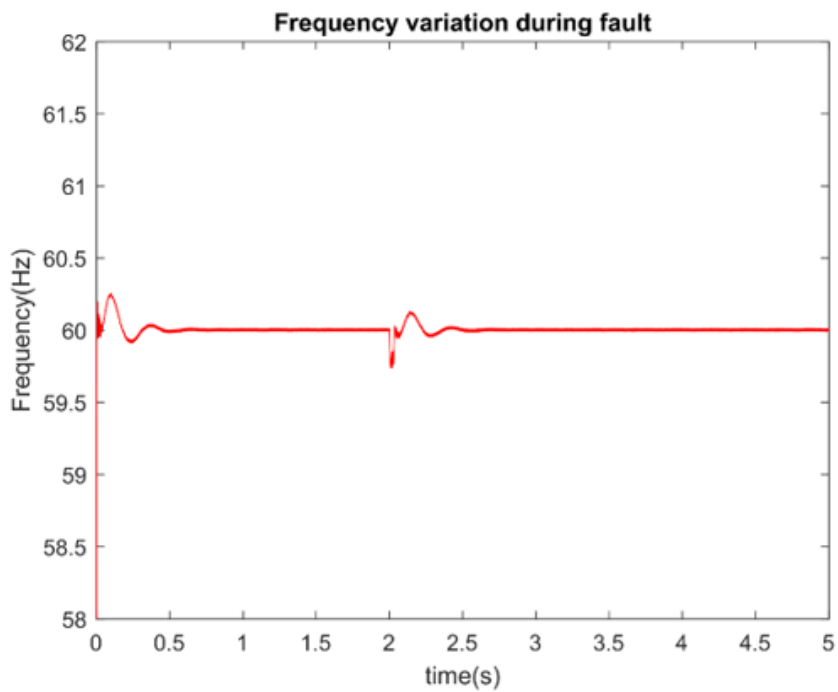


Fig. 6.19: Frequency Variation during Fault

Chapter 7

Conclusion

This project is about a simulation model of a PV-integrated grid-connected virtual synchronous machine. Initially, a dc voltage source is connected to the grid which has a VSM, and the corresponding results are obtained and studied. The VSM successfully tracks the active and reactive power reference commands and also the reference frequency of 60 Hz. Instead of a DC source a PV is integrated into the system and the system behavior is analysed for different conditions such as constant irradiance, stepped irradiance, irradiance curve, and fault. For the irradiance change whether its stepped or continuously varying the system behaves properly to the providing irradiance. When an irradiance curve is provided the active power response is almost similar to the shape of that curve. A 3-phase symmetrical fault is simulated at the terminals of the VSM and its performance is analysed. Its seen that, after the fault is cleared the active power and reactive power values reach their previous value(value before fault) and also the VSM successfully tracks the reference frequency of 60Hz.

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