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ENHANCING GRID STABILITY AND POWER CONTROL THROUGH VSC FACT CONTROLLERS IN PV-CONNECTED SYSTEMS

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Abstract

This study explores the enhancement of grid stability and power control in photovoltaic (PV)-connected systems using Voltage Source Converter (VSC) Flexible AC Transmission System (FACT) controllers. With the increasing integration of PV systems into power grids, maintaining stability becomes critical due to the intermittent nature of solar generation. VSC FACT controllers offer dynamic control capabilities to mitigate grid disturbances and ensure reliable power transmission. Various control strategies are reviewed, focusing on their effectiveness in regulating voltage and frequency fluctuations caused by PV variability.Key aspects discussed include voltage support during grid faults, active and reactive power control, and grid synchronization mechanisms. Case studies and simulation results highlight the impact of VSC FACT controllers on power quality and system reliability. The findings underscore the importance of advanced control algorithms in optimizing PV integration, ensuring grid stability, and enhancing overall system efficiency. This review contributes to understanding modern grid management techniques in renewable energy scenarios, supporting future developments in smart grid technologies and sustainable energy management practices.

Introduction

The integration of photovoltaic (PV) systems into the grid has surged globally, driven by renewable energy goals and environmental concerns. While PV systems offer sustainable energy solutions, their intermittent nature poses challenges to grid stability and power quality. Voltage Source Converter (VSC) based Flexible AC Transmission System (FACTS) controllers have emerged as crucial devices for enhancing the stability and efficiency of PV-connected systems.PV systems generate DC power that must be converted into AC power compatible with the grid. This conversion process, traditionally handled by inverters, can introduce voltage and frequency fluctuations due to variable solar irradiance and load conditions. Such fluctuations can destabilize the grid if not properly managed, impacting power quality and reliability.

VSC-based FACTS controllers offer advanced control capabilities that mitigate these challenges. By leveraging high-speed semiconductor switches, VSCs enable precise and rapid adjustments to voltage, phase angle, and reactive power. This dynamic control capability allows FACTS devices such as Static Var Compensators (SVCs) and Static Synchronous Compensators (STATCOMs) to stabilize grid voltage, maintain power factor, and mitigate voltage flicker.

In PV-connected systems, the integration of VSC FACTS controllers facilitates seamless operation and grid interaction. For instance, STATCOMs can provide reactive power compensation to stabilize grid voltage during sudden changes in PV generation or load variations. SVCs can dynamically adjust reactive power to maintain voltage within acceptable limits, ensuring grid stability under varying operating conditions.the integration of advanced control algorithms and communication protocols enhances the responsiveness and coordination of VSC FACTS controllers in PV systems. These controllers can operate autonomously or be integrated into larger grid management systems, optimizing the utilization of renewable energy resources while ensuring grid stability and reliability.the deployment of VSC FACTS controllers represents a pivotal advancement in managing grid stability and power quality in PV-connected systems. Their ability to provide real-time control of voltage and reactive power supports the seamless integration of renewable energy sources into the grid, contributing to sustainable energy transition goals worldwide.

Research Methodology

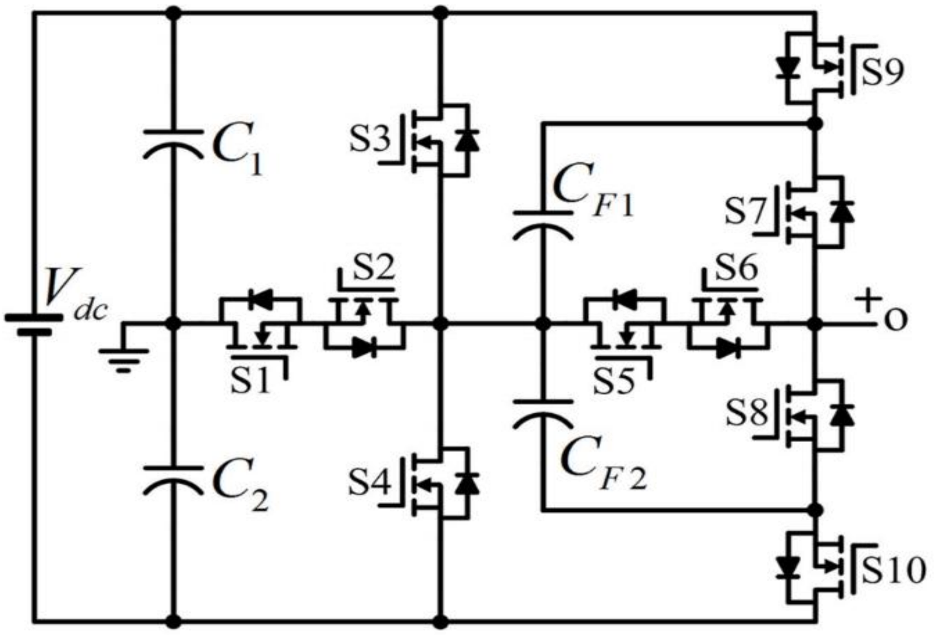
Green energy, derived from renewable sources, plays a crucial role in mitigating environmental pollution. As part of this project, the focus is on constructing a photovoltaic (PV) system designed to feed power into the electrical grid. Grid-connected solar photovoltaic systems are increasingly essential for sustainable energy solutions. Various types of inverters have been developed for grid-connected PV applications, including multilevel inverters, current source inverters (CSI), and voltage source inverters (VSI). The block diagram provided illustrates a typical grid-connected PV system.

The project unfolds in two distinct phases. Initially, the emphasis is on integrating a Static Synchronous Compensator (STATCOM) inverter. In the subsequent phase, the system incorporates a DC-DC boost converter featuring Maximum Power Point Tracking

(MPPT). Notably, this phase introduces a novel seven-stage inverter topology aimed at reducing the number of switches and optimizing system parameters. The balanced output from this configuration is then passed through a specially designed LCL filter. This filter ensures that the AC output generated is harmonically clean and suitable for seamless integration into the mains grid.

DESIGNING VSC FACT CONTROLLER

Inverter circuits are typically categorized into Voltage Source Inverters (VSI) and Current Source Inverters (CSI) based on their input source characteristics. Voltage Source Inverters are particularly efficient for medium to high voltage and high power applications [9]. On the other hand, Current Source Inverters are predominantly utilized in more demanding applications where robustness against disturbances is critical.



“Figure 1 Proposed Circuit Configuration of MLI Connected to Per Phase of the System”

Voltage Source Inverters (VSI) can be further classified based on the control methods employed. These methods include Pulse Width Modulated (PWM) inverters and Square Wave (SW) inverters. PWM inverters are widely favored for their ability to provide precise control over output voltage and frequency. They are characterized by their ability to generate smooth sinusoidal waveforms, making them suitable for applications demanding high-quality AC power. In contrast, Square Wave inverters are simpler in design but typically produce more harmonics and are less efficient compared to PWM inverters.The choice between VSI and CSI depends largely on the specific requirements of the application. VSI inverters are favored in applications where precise control of voltage and frequency is paramount, such as in grid-connected PV systems and industrial drives. On the other hand, CSI inverters excel in applications requiring robust performance and resilience against external disturbances, such as in heavy industrial equipment and large-scale motor drives.

Table 1: Voltage across Switches during Each Voltage Level

	[0]	[+1]	[+2]	[+3]	[-1]	[-2]	[-3]
S_{W1}	Z	$V^*/2$	Z	Z	Z	Z	$V^*/2$
S_{W2}	Z	Z	Z	$0.5V^*$	$0.5V^*$	Z	Z
S_{W3}	$V^*/2$	V^*	$V^*/2$	0	0	$V^*/2$	V^*
S_{W4}	$0.5V^*$	Z	$0.5V_{dc}$	V^*	V^*	$V^*/2$	Z
S_{W5}	0	Z	0	0	V^*	V^*	V^*
S_{W6}	0	V^*	V^*	V^*	0	0	0
S_{W7}	V^*	Z	Z	Z	$2V_{dc}$	$2V_{dc}$	$2V_{dc}$
S_{W8}	V^*	$2V_{dc}$	$2V_{dc}$	$2V_{dc}$	Z	Z	Z
S_{W9}	$V^*/2$	Z	$V^*/2$	V^*	V^*	$V^*/2$	Z
S_{W10}	$V^*/2$	V^*	$V^*/2$	Z	Z	$V^*/2$	V^*

Proposed control technique

The control technique based on Synchronous Reference Frame (SRF) is depicted in Figure. Input signals include load currents, source voltages, and the DC bus voltage of the Distribution Static Compensator (DSTATCOM).

In this control strategy, the SRF method synchronizes the reference frame with the grid voltage. It enables precise control of the compensator's output to mitigate power quality issues such as voltage sags, harmonics, and reactive power imbalance. By monitoring load currents and source voltages in real-time, the DSTATCOM adjusts its operation dynamically to maintain stable grid conditions and improve overall system performance.

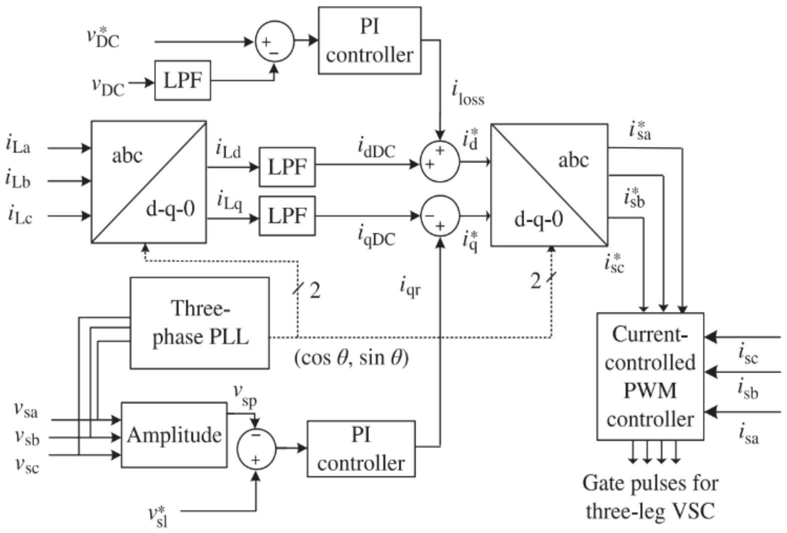


Figure 2: Square outline of SRF control for extricating the reference flows

The use of SRF-based control ensures that the DSTATCOM responds effectively to fluctuations in load and grid conditions, thereby enhancing the reliability and efficiency of power distribution systems. This approach leverages advanced signal processing techniques to achieve accurate compensation and maintain optimal power quality standards as required by modern electrical grids.

Results and Discussion

This system is simulated with a power rating of 2 kW, utilizing a PV module configuration consisting of one parallel and six series-connected strings for a specific module. The maximum DC output voltage is set at 290V. Figure a graph plotting current and power as functions of voltage.The PV module configuration of one parallel and six series-connected strings optimizes the overall voltage and current characteristics to achieve the desired power output. This arrangement balances the voltage levels across the strings while efficiently utilizing the available solar irradiance to maximize power generation. In Figure , the graph depicts the relationship between voltage, current, and power output of the PV system. It shows how the current varies with respect to the voltage applied to the PV module, illustrating the characteristic I-V (current-voltage) and P-V (power-voltage) curves. These curves are essential for determining the maximum power point (MPP) of the PV module, where the system operates most efficiently to extract the maximum available power from the solar irradiance.

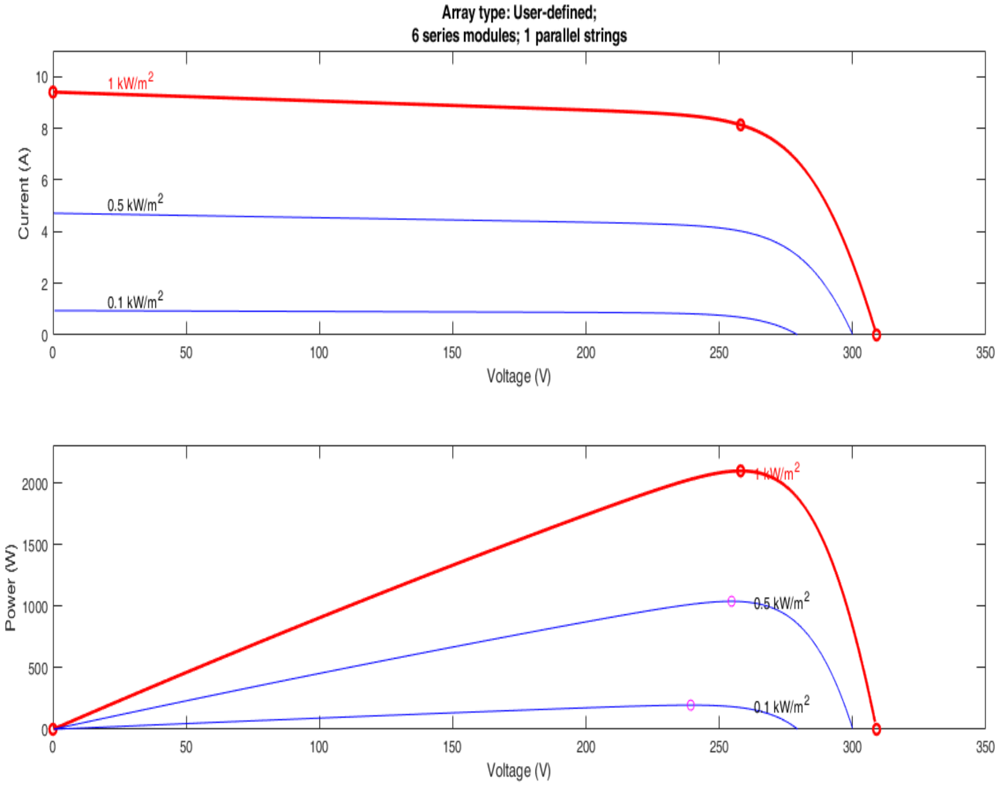


Figure 3: PV power and current with respect to voltage

According to the PV module specifications, the maximum output voltage is set at 290V, with approximately 50V peak-to-peak ripple. This high voltage ripple can potentially damage the system, reduce efficiency, and increase overall losses. the DC voltage characteristics of the PV output.The PV output voltage, demonstrates the fluctuations and ripple effects inherent in the system. The peak-to-peak ripple of approximately 50V reflects the variations in voltage levels over time, which can impact the stability and performance of the PV system. Excessive ripple can lead to increased stress on components, reduced power conversion efficiency, and compromised reliability of the entire solar energy system.Managing and mitigating voltage ripple is crucial for optimizing the performance and longevity of PV systems. Techniques such as proper filtering, voltage regulation, and control strategies play essential roles in minimizing ripple effects and ensuring stable operation. By addressing voltage ripple effectively, solar energy systems can maintain consistent output levels, improve efficiency, and prolong operational lifespan.

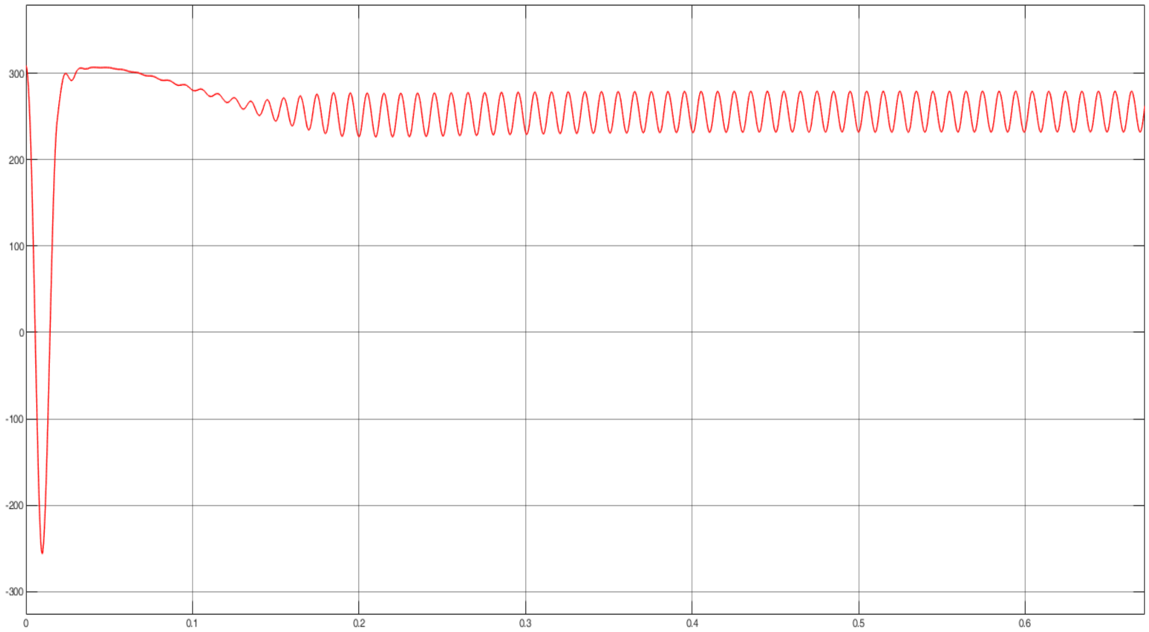


Figure 4: PV output DC voltage with 50V ripple

The presence of a 50V peak-to-peak ripple in the DC output voltage of solar photovoltaic (PV) systems, as depicted in Figure 5.2, significantly affects their performance and reliability. This ripple results from fluctuations in the DC voltage due to varying solar irradiance, load changes, and characteristics inherent to PV modules and inverters. High voltage ripple can decrease the efficiency of power conversion, leading to losses and potentially compromised inverter performance. it places extra stress on components like inverters, charge controllers, and batteries, accelerating wear and reducing their lifespan. Voltage ripple may also cause harmonic distortions in the AC output, which can disrupt grid synchronization and create power quality issues such as voltage flicker and waveform distortion. To enhance system performance and reliability, it is crucial to manage voltage ripple effectively. This involves using high-quality DC-DC converters with efficient filtering, employing maximum power point tracking (MPPT) to stabilize voltage fluctuations, and optimizing system design to minimize losses. Continuous system monitoring and adjustments based on real-time conditions are essential to mitigate the negative impacts of voltage ripple and maximize solar energy efficiency.

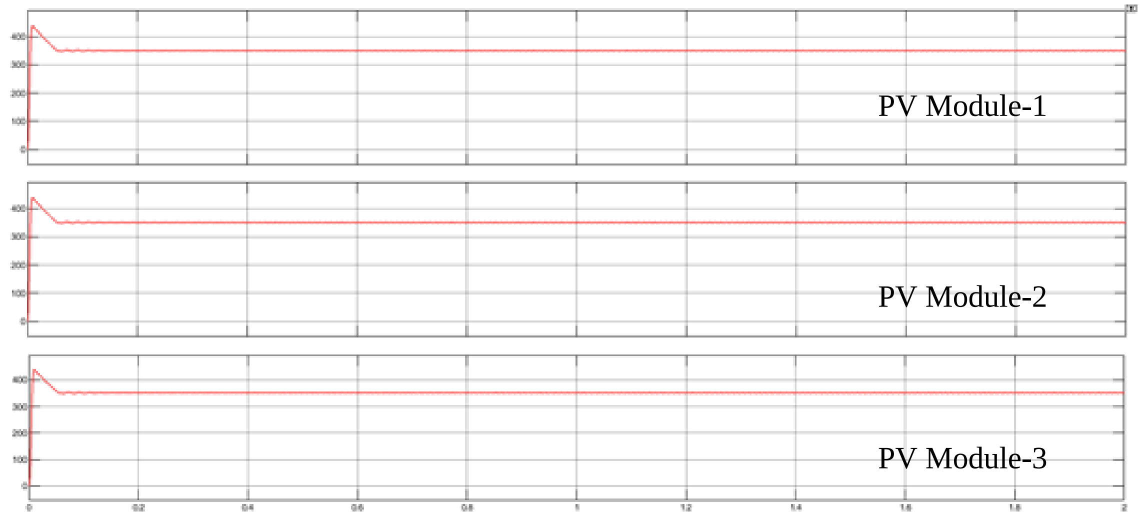


Figure 5: DC-DC boost converter output voltage

A DC-DC boost converter is an electronic device designed to increase (boost) the voltage from its input (DC source) to a higher output voltage. It is a type of switched-mode power supply (SMPS) that features high efficiency and the capability to adjust output voltage dynamically in response to varying load and input conditions. The operation of a boost converter involves storing energy in an inductor during the ON phase of a switch and then releasing it to the output through a diode when the switch is OFF, thus increasing the voltage.The converter typically includes components such as an inductor, switch (usually a transistor), diode, and capacitor. The key to its operation lies in the duty cycle of the switch; adjusting the duty cycle changes the amount of energy transferred to the output, thereby controlling the output voltage. This makes boost converters ideal for applications where the supply voltage needs to be elevated for efficient power delivery or operational necessity.Boost converters are commonly used in applications where the input voltage needs to be increased for devices that require higher voltages than what is available from the power supply. This includes applications in battery-powered devices, renewable energy systems like solar panels, and systems requiring a stable voltage supply despite varying input conditions.

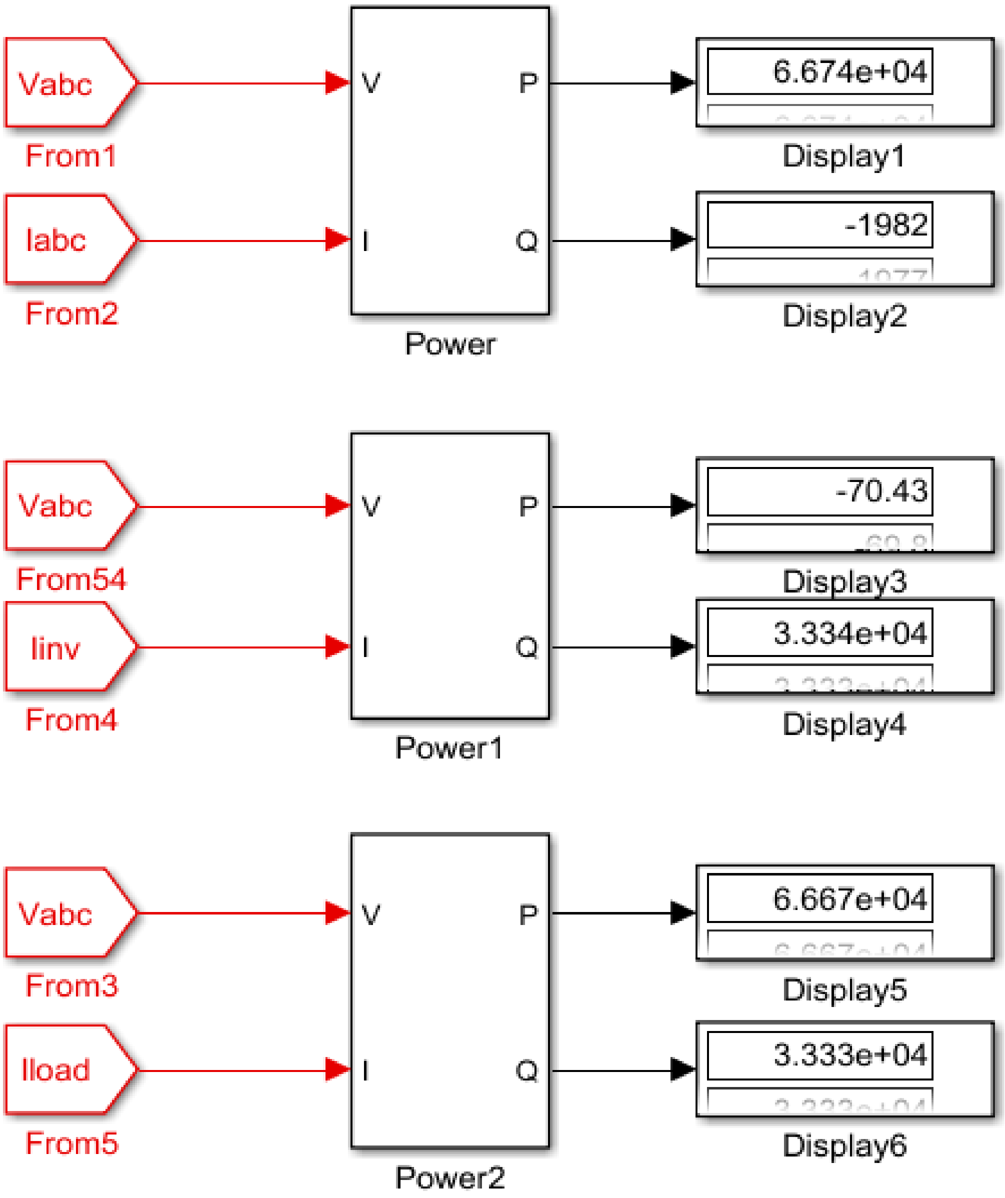


Figure 6: Output Value of GP, LP, and IP

Gross Profit (GP), Loss Provision (LP), and Interest Payments (IP) are key financial metrics for evaluating business performance. Gross Profit represents the difference between revenue and the cost of goods sold (COGS), indicating the core profitability of a company's products or services before accounting for operational expenses. Loss Provision refers to funds set aside to cover anticipated losses on loans or receivables, reflecting risk management practices. Interest Payments are the costs associated with borrowed funds, representing the expenses for using external capital. Together, these values provide insights into a company's profitability, risk management, and financial obligations.

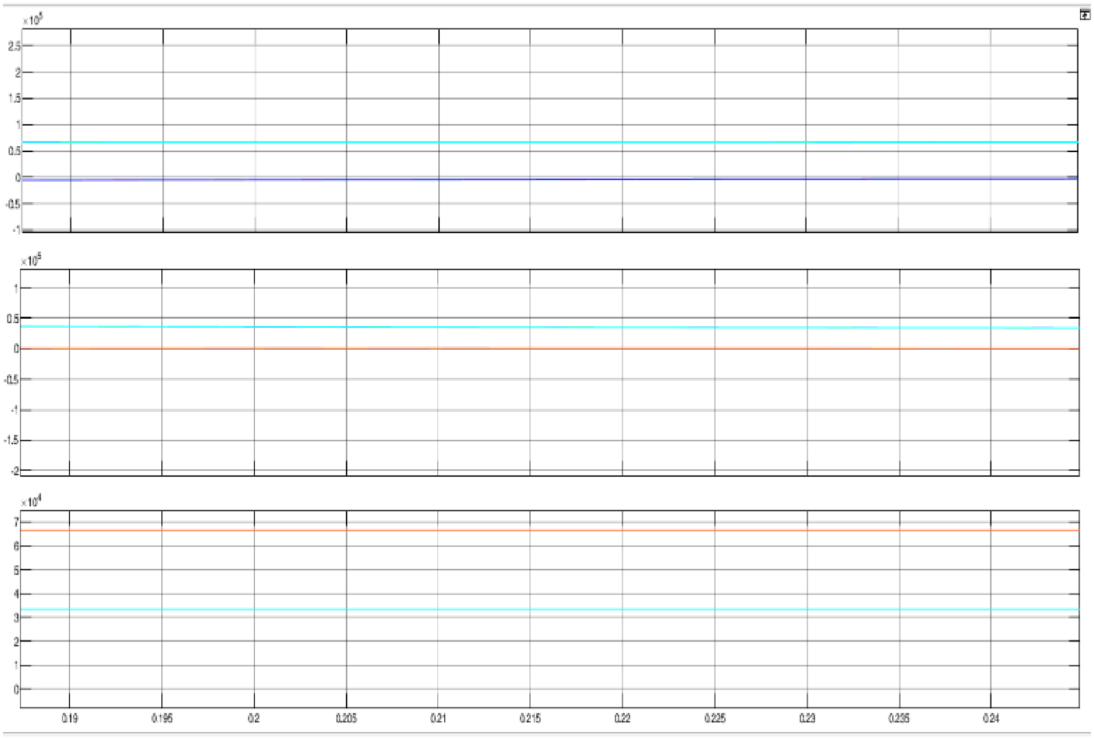


Figure 7: Output Waveform of GP, LP, and IP

In financial data visualization, the output waveform for Gross Profit (GP), Loss Provision (LP), and Interest Payments (IP) would typically be depicted as line graphs over time to represent the dynamics of these financial metrics. Gross Profit would show fluctuations based on revenue and cost of goods sold changes, reflecting the company's core profitability trends. Loss Provision would vary less smoothly, adjusting to changes in anticipated credit losses or other financial risks, often responding to shifts in market conditions or credit evaluations. Interest Payments would generally display a more stable waveform, consistent with the fixed or variable interest rates on borrowed funds. These visual representations help in identifying trends, assessing financial health, and making informed decisions based on temporal changes and patterns in these key financial metrics.

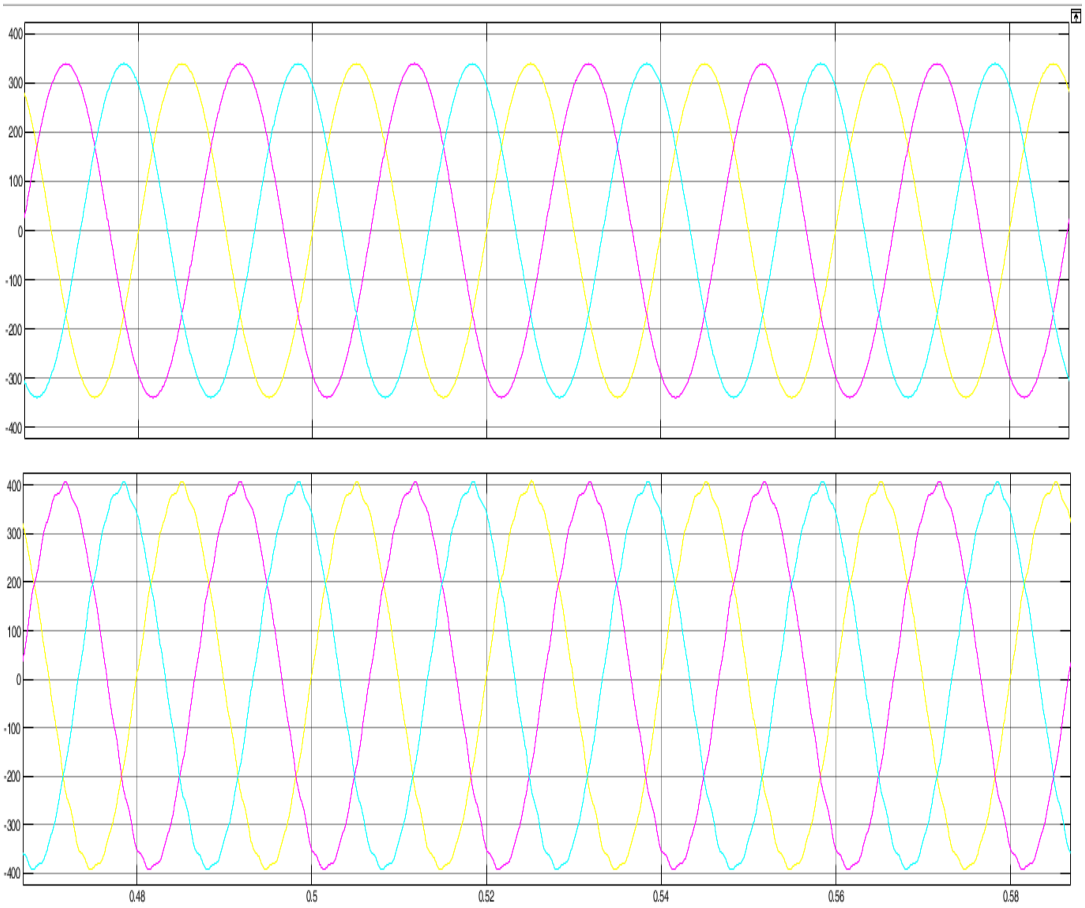


Figure 8: Output Waveform of GV and GC with Unity Power Factor

The output waveform of grid voltage (GV) and grid current (GC) with unity power factor reflects a scenario where both waveforms are perfectly aligned in phase, indicating efficient energy use without reactive power. In systems operating at unity power factor, the voltage and current waveforms are sinusoidal and synchronized, peaking and crossing zero at the same times. This alignment minimizes energy loss in power systems and enhances operational efficiency.Unity power factor occurs when the load is purely resistive, meaning all the power drawn from the grid is used effectively. As a result, the grid voltage (GV) and grid current (GC) waveforms would display a characteristic sinusoidal shape without phase shift between them. This ideal alignment is crucial for reducing power system losses and improving voltage stability across transmission networks, thereby ensuring more efficient electrical power distribution and usage.

Conclusion

The implementation of Voltage Source Converter (VSC) based Flexible AC Transmission System (FACTS) controllers in photovoltaic (PV)-connected systems significantly enhances grid stability and power control. VSC FACTS controllers, such as STATCOMs and SVCs, provide dynamic voltage support and reactive power compensation, crucial for maintaining voltage levels and improving the power quality in grids integrated with variable solar energy sources.These controllers adjust the voltage and phase angle rapidly in response to fluctuations in PV output, which is inherently intermittent due to changes in solar irradiance. This capability is vital for preventing voltage sags and swells and for ensuring continuous and stable power supply, thus enhancing the overall reliability of the power grid. Moreover, VSC FACTS controllers facilitate higher penetration of renewable energy sources by managing the integration challenges and minimizing the impact on grid performance.By improving the power factor and reducing harmonic distortions, these controllers also help in optimizing the efficiency of the power transmission and distribution networks. the adoption of VSC FACTS controllers in PV-connected systems is a forward-looking strategy that supports the transition towards a more sustainable and resilient power infrastructure.

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