Harmonic Voltage Control in Distributed Generation Systems Using Optimal Switching Vector Strategy

Mr. B. Ramu[1], Ms. K. Krupa Jyothi[2], Ms. P. Ganga Bhavani[3], Mr. P. Nagendra[4], Mr. N. Rama Narayana[5]

*Corresponding Author: Mr. B. Ramu, Email: ramubanadar0511@gmail.com

[1]Currently pursuing the final year of Bachelor of Technology in Electrical and Electronics Engineering, Sir C R Reddy of Engineering, India-534007
Email: ramubandaruo511@gmail.com

[2]Currently pursuing the final year of Bachelor of Technology in Electrical and Electronics Engineering, Sir C R Reddy of Engineering, India-534007
Email: krupakatepalli3@gmail.com

[3]Currently pursuing the final year of Bachelor of Technology in Electrical and Electronics Engineering, Sir C R Reddy of Engineering, India-534007
Email: pamulagangabhavani@gmail.com

[4]Currently pursuing the final yea Bachelor of Technology in Electrical and Electronics Engineering, Sir C R Reddy of Engineering, India-534007 Email: pvdnagendra@gmail.com

[5]Assistant Professor in Department of Electrical and Electronics Engineering, Sir C R Reddy College of Engineering, India-534007
Email: ramanarayana1@gmail.com

ABSTRACT

The increasing integration of distributed generation (DG) systems in modern power grids has highlighted the importance of maintaining power quality and ensuring efficient voltage control. Harmonic voltage distortion, caused by non-linear loads and inverter-based DG sources, is a key challenge. This paper presents an innovative approach for harmonic voltage control in DG systems using an Optimal Switching Vector Strategy (OSVS). The proposed strategy leverages advanced control algorithms to optimize the switching of power electronic devices, such as inverters, to reduce harmonic distortion and maintain a stable voltage profile. By minimizing harmonic components in the system, the OSVS enhances power quality, improves voltage regulation, and ensures efficient operation of DG systems. The effectiveness of the approach is demonstrated through simulation studies, showing significant reductions in harmonic voltage and improved performance under varying load conditions. The results confirm that the OSVS is a promising solution for harmonic voltage control, ensuring reliable and stable operation of DG systems in modern power networks.

Keyword:- *Distributed generation (DG), optimal switching vector (OSV), harmonics, power quality, voltage source.*

1. INTRODUCTION

With increased penetration of renewable power and the nonlinear loads in the distributed generation (DG) systems, increased power quality concerns are exhibited in the active distribution networks, especially the challenges associated with the current and voltage harmonics in the system. The control logic exploits the property of an optimal-switchingvector controller, i.e., accurate output voltage tracking. Simulations results demonstrate the effectiveness of the controller, to suppress grid current harmonics and load voltage harmonics in grid-interfaced (GI) and off-grid modes [1]. An increased dissemination of distributed energy resources (DERs) has led to shift in paradigm toward the decentralized generation of electricity. The energy industry is moving into a new era of smart grids, which encourage distributed generation (DG) systems with a reliable, resilient, and responsive control structure [2]. The smart grid concept encourages a decentralized network structure that enhances reliability and performance of the grid, reduces undesirable environmental impacts by incorporating renewable energy sources, and facilitates customer–operator power producer real-time interactions [3]. To promote future resilient power grids with a flexible control structure, different power quality standards are formulated. In many practical applications, the distributed power network contains a substantial number of harmonics when nonlinear loads located in the network. These background harmonics make the output current of grid-connected inverter distorted, which imposes difficulty in satisfying the stringent grid standards, such as [4]. Different research works are reported in the past decade for power quality improvement in gridinterfaced (GI) DERs, both for single-phase and three-phase DERs. These are broadly classified into two categories— selective methods for harmonic mitigation [5]–[8] and nonselective methods [9]–[13]. The selective harmonic mitigation techniques generally use multiple proportional-integral (PI) regulators in rotating frame, individually for each harmonic, thereby involving dq transformations. Some methods, like those in [5] and [8], use multiple resonant controllers at the fundamental frequency and harmonic frequencies, either in stationary or rotating frame.

In the selective harmonic compensation control for harmonic current rejection, the reference currents are modified to provide information about the prominent harmonics present in the load current. These methods are computationally more intensive and are sensitive to variations in the system fundamental frequency. Moreover, commonly used proportional-resonant (PR) controllers or PI controllers are based on harmonic compensators to eliminate the steadystate error and compensate selective grid harmonics. In such cases, the current loop needs a wide enough band width to cover the resonant frequencies of controller. Otherwise, the system may become unstable[13].Moreover, these resonant filters, designed for a particular frequency, can accurately compensate harmonics only with a known utility grid frequency. In the case of varying the grid frequency, the tracking performance of the current is degraded. Thus, variable grid frequency can contribute to significant performance degradation of the harmonic mitigation for grid interactive systems. The nonselective approaches generally use hysteresis controllers [9]–[11], dead-beat controllers [12], and the repetitive controllers[13],[14].

The power quality improvement in the distribution system using the hysteresis current control techniques are widely reported, which have used an indirect current control technique, where the grid current is controlled by feeding only the fundamental component of local load currents. For instance, in [9]–[11], the local load currents are sensed and the fundamental component of the load current is extracted, and accordingly, the reference grid currents are generated. The reference grid currents are compared with the grid currents and passed through a hysteresis current controller. These algorithms are successful in achieving harmonic current elimination; however, the point of common coupling (PCC) load current measurements are not readily available all the time. Moreover, the use of hysteresis indirect current control is undesirable accounting to its variable switching frequency. A comprehensive review of different harmonic mitigation techniques is reported in [15].

In majority, industrial applications, hysteresis current controllers are avoided, and reference voltage based pulse width modulated inverters are preferred [10], [16]. However, in voltage controlled inverters, in order to modify the inverter reference voltages to include harmonic reference voltages, the conventional methods employ multiple PR controllers. For example, He et. al. [17] have used the cascaded voltage and current control schemes for harmonic output voltage control in DG-based systems with multiple proportional resonant (PR) controllers for different harmonics, to establish harmonic output voltage control, which is computationally intensive. The system performance with PR controllers is degraded under variation of the system frequency as it provides infinite gain at selected harmonic frequencies. The nonideal implementation of infinite gains could cause series of instability issues for GI DG systems [18].To over come these issues, in this article, a harmonic controller for a three-phase voltage-controlled inverter is contemplated. In contrast to the conventional harmonic current control techniques, this new strategy is capable of being appended in any voltage-controlled inverter system, without causing stability issues. It means that the harmonic compensation algorithm becomes a subset of any voltage-reference-driven inverter systems, and it is possible to be switched-ON or switched-OFF at the convenience of the operator. This controller facilitates direct harmonic voltage control, where it neither uses cascaded voltage/current control loops nor PI/PR regulators.

It uses an OSV controller [19], which is based on finite future samples of input. It explicitly uses the system model to produce control action that describes the desired system behaviour. Thus, the OSV controller for power electronic device facilitates easier practical implementation. Here, the system identification is performed in a certain way by modeling the system through state-space equations, thereafter, transforming the continuous state-space model to discrete domain. Model identification serves in estimating the future control samples. Out of the future samples thus computed, only the first prediction is applied to the plant. After predicting the future control samples, a minimization criterion is used to generate the control signal. Different minimization criteria for an OSV controller are described in [19] and this article uses quadratic cost function minimization to compute the future control samples. The OSV controller for voltage controlled inverters has been used in the past research work [21]–[23], where the output voltages of an inverter are strictly governed by the minimization criterion, however, this property is not fully explored for reference harmonic voltage injection. This article explores this property to formulate a generalized algorithm, which voluntarily injects harmonic grid voltages, to improve power quality in the grid-connected and off-grid DG systems

2. OBJECTIVES

1. Analyze Harmonic Generation in DG Systems

   • Study the causes and effects of voltage harmonics due to power electronics in DG.

   • Evaluate Total Harmonic Distortion (THD) under various DG operating conditions.

2. Develop an Optimal Switching Vector Strategy (OSVS)

   • Design a control algorithm based on Space Vector Pulse Width Modulation (SVPWM) to optimize inverter switching.
   • Minimize harmonic content while maintaining efficient power conversion.

3. Simulate the Proposed Control Strategy

   • Implement the OSVS model in MATLAB/SIMULINK to test its performance.

   • Compare results with conventional switching techniques.

4. Validate Harmonic Voltage Control Performance

   • Measure voltage and current harmonics before and after applying OSVS.

5. Enhance System Efficiency and Reliability

   • Reduce switching losses and improve power factor.

   • Ensure stable voltage regulation under dynamic load and generation conditions.

3. PROPOSED METHOD

3.1 Overview of the Proposed Harmonic Voltage Control Strategy

To address the limitations of traditional harmonic compensation techniques in distributed generation (DG) systems, this study proposes an Optimal Switching Vector (OSV) control strategy for voltage-controlled DG inverters. The OSV-based approach provides a computationally efficient and adaptive method for harmonic voltage control by eliminating the need for Proportional-Integral (PI) or Proportional-Resonant (PR) controllers. It ensures precise voltage tracking, enhances power quality.

3.2 System Configuration

The proposed control strategy is designed for a three -phase voltage-source inverter (VSI) in a DG system. The VSI interfaces with the power grid and supplies nonlinear loads, which introduce harmonics into the system. The system consists of:

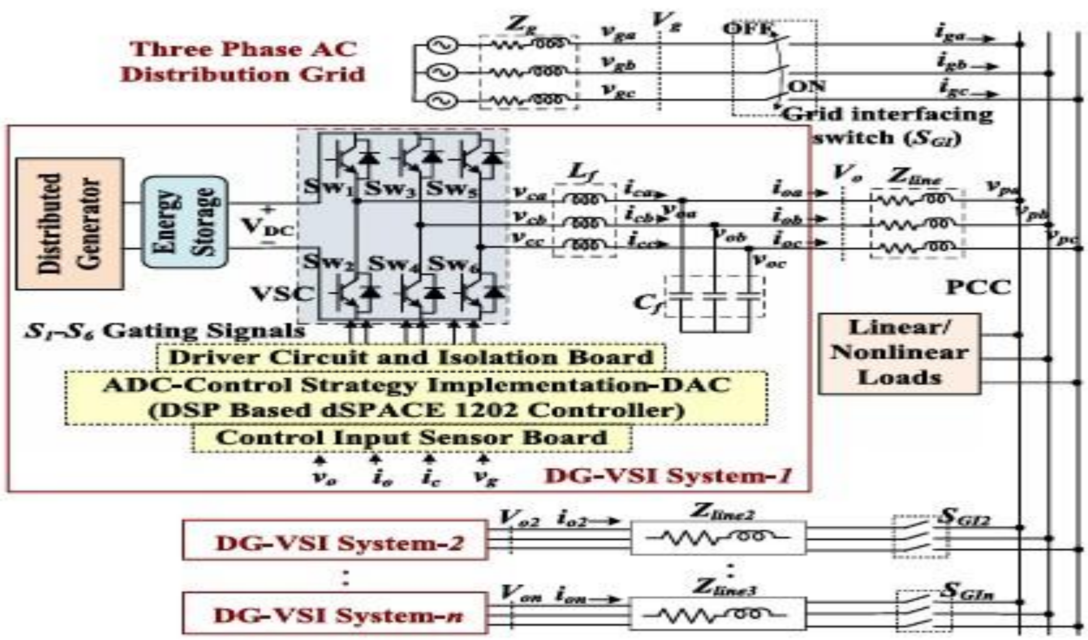

Fig 3.1 System Configuration

• DG unit: Provides the primary power source.

• Voltage-source inverter (VSI): Regulates voltage output and harmonic compensation.

• LC filter: Mitigates high-frequency harmonics before injecting power into the grid

• Nonlinear loads: Represent industrial and residential loads that cause harmonic distortions.

• Grid interface: Ensures compliance with grid standards and regulates harmonic compensation.

3.3 Optimal Switching Vector (OSV) Control Approach

3.3.1 Control Logic and Voltage Tracking:

By forecasting and choosing the best switching vector for the VSI, the OSV controller maximizes harmonic voltage management. The following are part of the control logic:

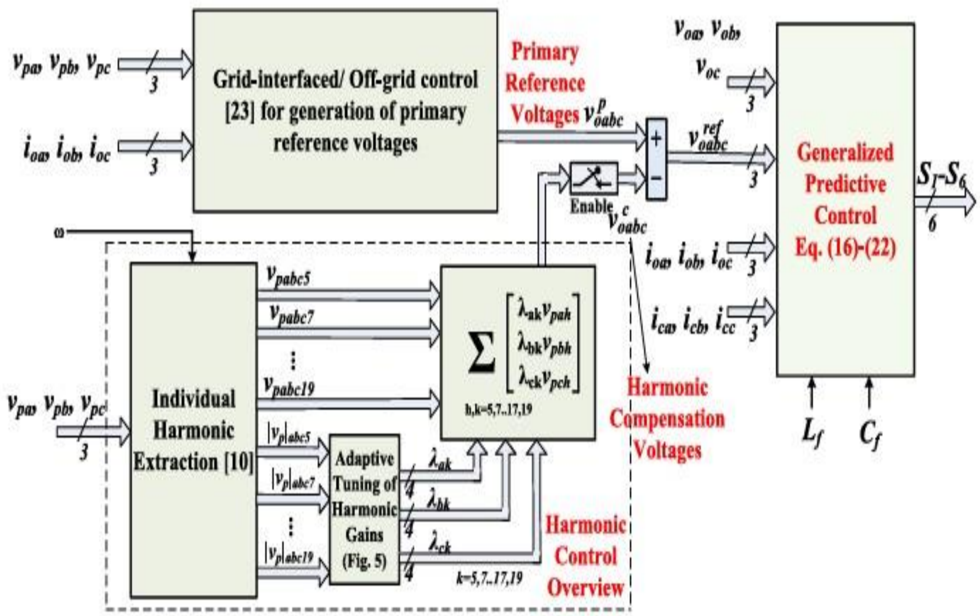

Fig 3.2 Controller Schematic of OSV

1.State-Space Modeling: The system dynamics are represented in a discrete -time state space model, allowing for real-time computation of future system states.

2. Harmonic Voltage Estimation : An adaptive observer is used to extract specific harmonic components from the point of common coupling (PCC) voltage.

3. Prediction and Cost Function Minimization : The OSV controller predicts future control actions based on a quadratic cost function minimization, ensuring accurate voltage tracking and harmonic suppression.

4. Real-Time Switching Vector Selection: The optimal voltage vector is selected dynamically based on minimizing voltage error and harmonic distortion.

3.4 Harmonic Voltage Injection Strategy :

To decrease harmonic impedance and lessen current harmonics, the OSV controller implements adaptive harmonic voltage injection. The dominant harmonics are extracted from the PCC voltage as part of the harmonic injection process.

•Modifying the DG output voltage to offset the harmonics that have been detected.

• Preserving system stability while guaranteeing suppression of harmonic current.

3.5 Advantages of the Proposed Method

The OSV-based control strategy provides the following advantages over conventional harmonic compensation techniques:

• Elimination of PI/PR controllers, which lowers tuning complexity and stability difficulties.

• Adaptability in real time, enabling dynamic regulation of harmonic impedance.

• Computational efficiency, which makes embedded control systems feasible to use.

• Support for both off-grid and grid-connected modes of operation.

SUMMARY:

A reliable and effective technique for controlling harmonic voltage in DG inverters is presented by the suggested Optimal Switching Vector (OSV) control scheme. The approach guarantees exceptional power quality and adherence to industry standards by utilizing adaptive tuning, predictive control, and real-time voltage tracking. The following stage entails using simulation and experimental testing to confirm the suggested method's efficacy.

4. **Harmonic Voltage Controls Results :**

4.1 DG OSV WITHOUT HARMONIC CONTROLLER :

The modeling and simulation of the system are executed in MATLAB/Simulink using Simscape toolbox. A threelegged insulated gate bipolar transistor (IGBT)-based VSI is considered herein. A three-phase 208-V, 50-Hz distribution grid is considered for interfacing purpose. The system is depicted in Fig10.2, with R = 1 for a single DGVSI-based system and R = 2 for a double DG-VSI based system. The system specification and the parameters of the controller used for simulation purpose are stated in Appendix.

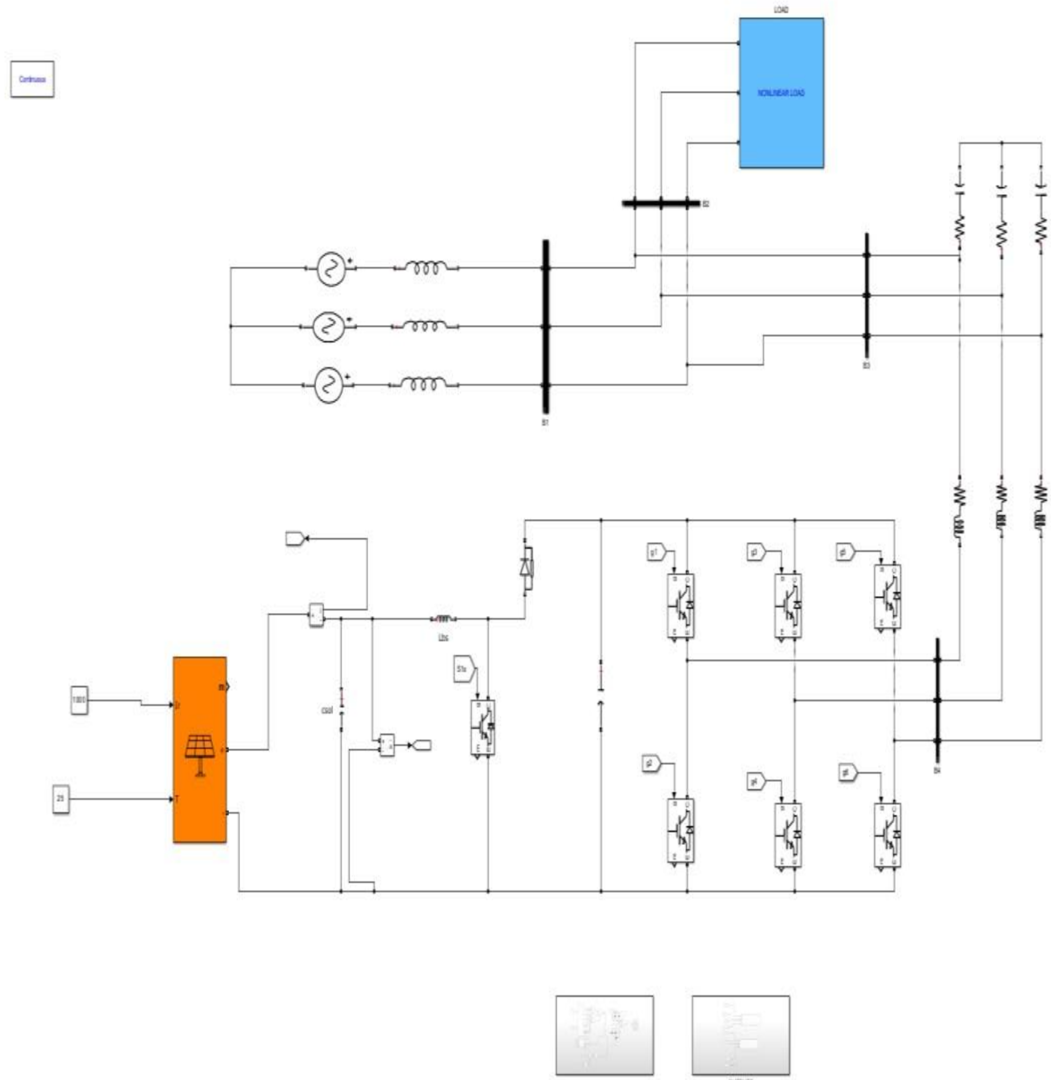

Fig 4.1 MATLAB/SIMULINK circuit diagram of DG-VSI system in GI mode.

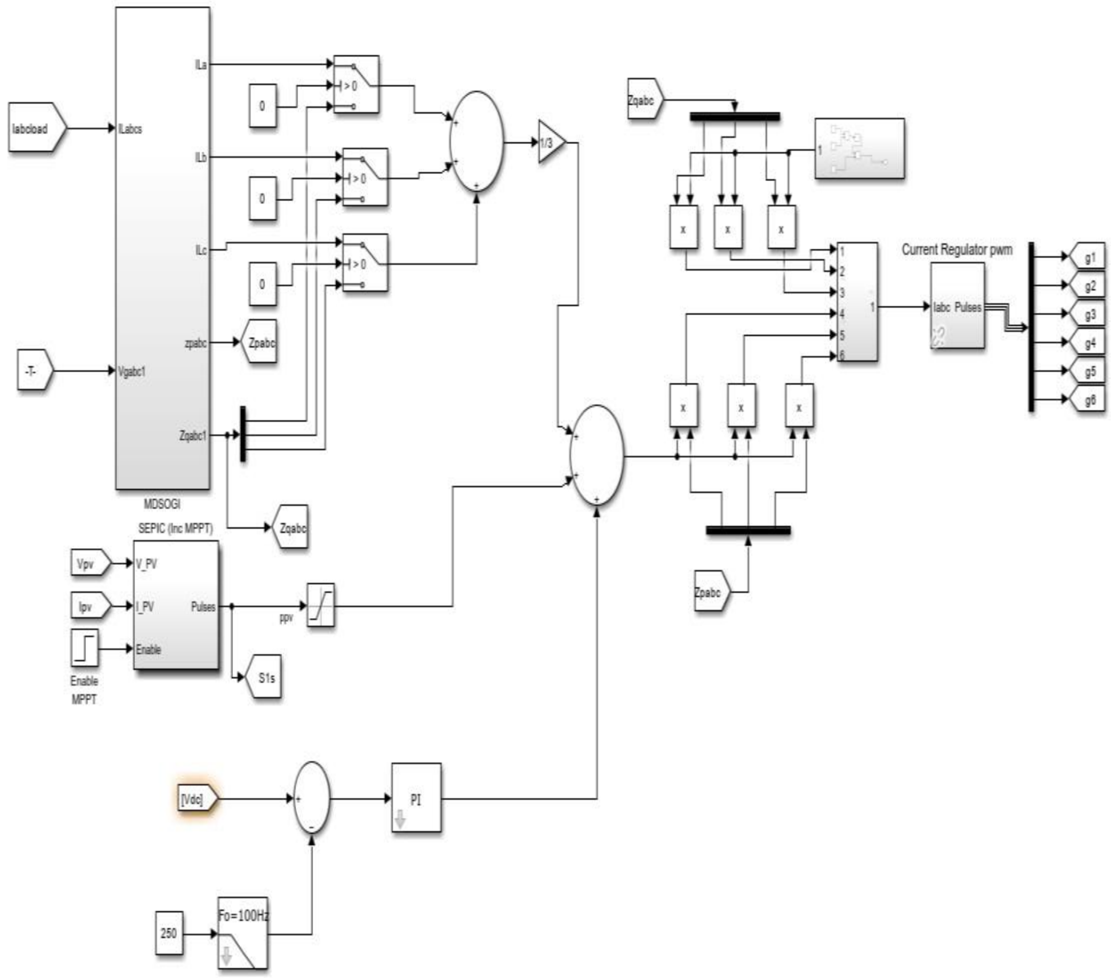

Fig 4.2 Control schematic of without harmonic controller

The succeeding stage following evaluation of the future samples is the predictive control, which generates optimal switching sequences resulting in the minimum error between predicted voltages and the voltage references

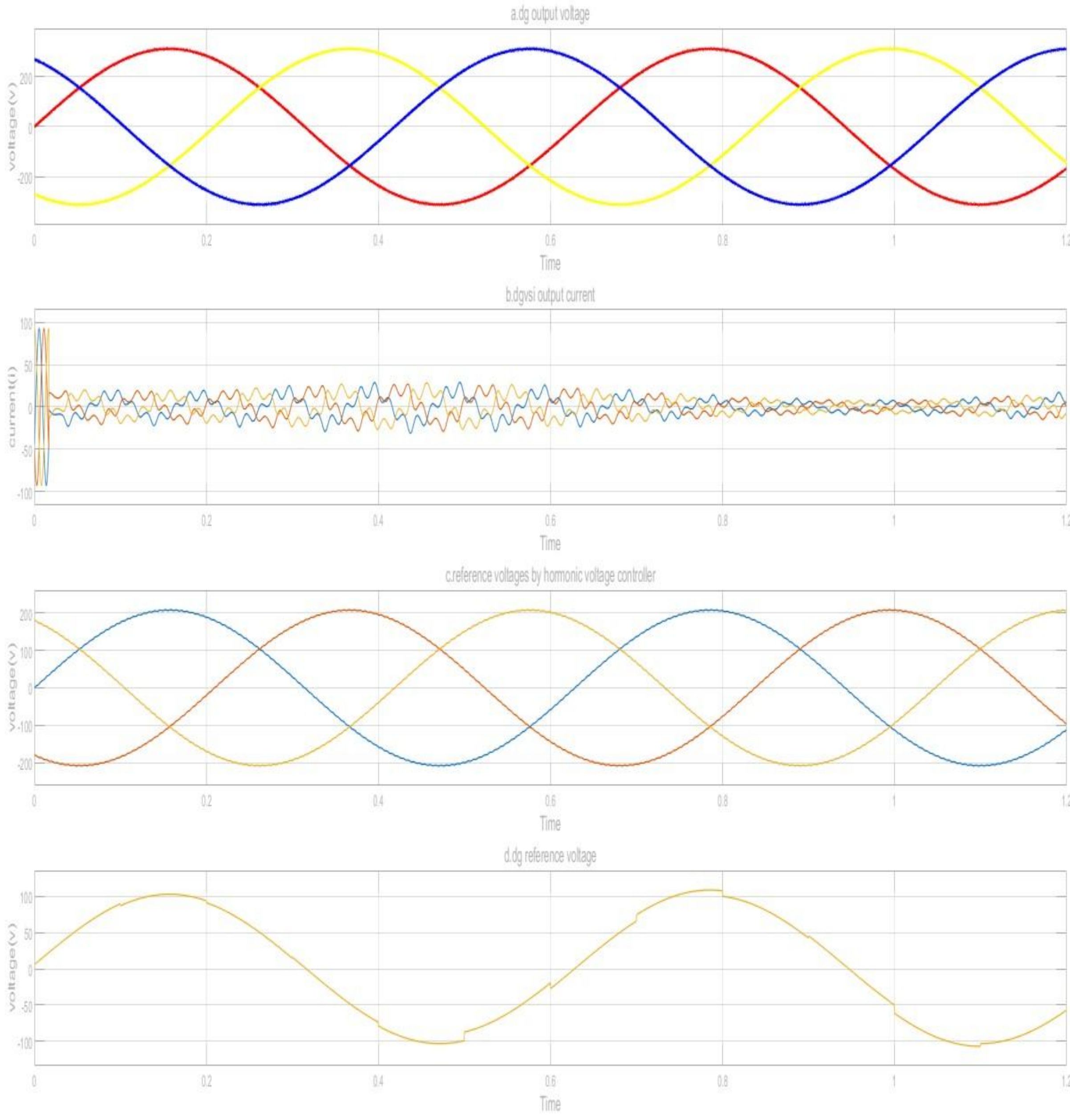

FIG 4.3 SHOWS:PERFORMANCE OF DG VSI MODE WITHOUT CONTROLLER OF VO,VP,HARMONIC REFERENCE VOLTAGE ,DV REFERENCE VOLTAGES

a). DG Output Voltage: It shows the distribution generation of output voltage without optimal vector switching controller. It refers to the voltage level at the point of connection where a distributed generation unit supplies power to the grid or a local load.

b). DG VSI Output Current: Its shows distribution generation voltage source inverter output current without optimal switching controller and output current contains harmonics. The output current of the DG VSI is a crucial factor that determines power quality and system stability.

c). Reference voltages by harmonic voltage controller: In harmonic voltage control for Distributed Generation (DG) systems, the reference voltage is dynamically adjusted to reduce harmonic distortion and improve power quality. The controller generates a re ference voltage waveform that the Voltage Source Inverter (VSI) must track to minimize harmonic content.

d). DG Reference Voltage: The reference voltage in a Distributed Generation (DG) system is the desired voltage level that the Voltage Source Inverter (VSI) aims to maintain at its output. This reference voltage is crucial for stable operation and effective integration with the grid or local loads.

The harmonic voltage control, the grid current is contaminated with significant harmonics. However, these harmonics are eliminated with the harmonic control, since the DG output harmonic voltages are automatically adjusted as observed.

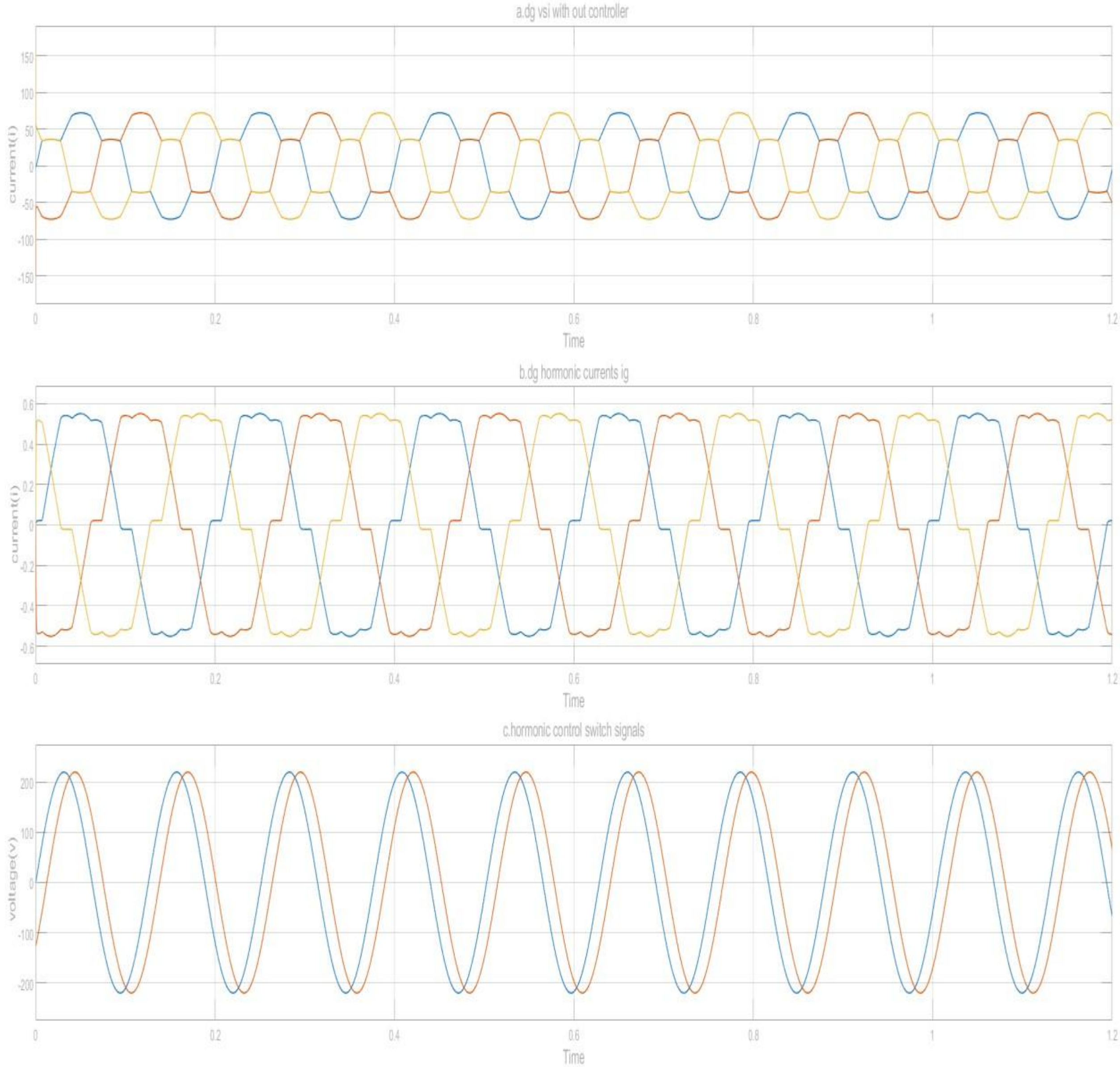

FIG 4.4 SHOWS:PERFORMANCE OF DG VSI WIITHOUT OSV CONTROLLER FOR IO,IG,HORMINIC CONTROL SWITCH,DG OUTPUT VOLTAGE

a). DG VSI Current Without Controller: It is a three-phase current waveform from a DG VSI without a controller. The plot has three sinusoidal waveforms (likely corresponding to three-phase currents: Ia, Ib, and Ic). The waveforms are distorted, meaning harmonics are present. The amplitude of the waveforms fluctuates, indicating voltage or load variations.

b). DG Harmonic Currents ig: It shows the harmonic components of the gate current in a three-phase VSI. The waveform has a stepped and distorted shape, indicating higher-order harmonics present in the gate current. The repetitive pattern suggests that switching harmonics are dominant due to PWM operation. The waveform exhibit sharp transitions, which are typical of harmonics generated by the rapid switching of power semiconductor devices.

c). Harmonic control switch signal: The graph displays the switching signals used for harmonic control in a threephase VSI (Voltage Source Inverter).It represents the voltage waveforms of the switching control signals without using the Optimal Switching Vector (OSV) strategy. The signals exhibit a sinusoidal waveform with high frequency, indicating modulated control signals. The red and blue waveforms are closely aligned, representing phase-shifted signals corresponding to different switching devices. The amplitude and frequency remain consistent, suggesting a uniform switching strategy. Since this control signal is without OSV, the switching strategy may not be optimal for harmonic suppression. The presence of harmonics in the VSI output voltage and current could be higher, leading to increased THD (Total Harmonic Distortion)

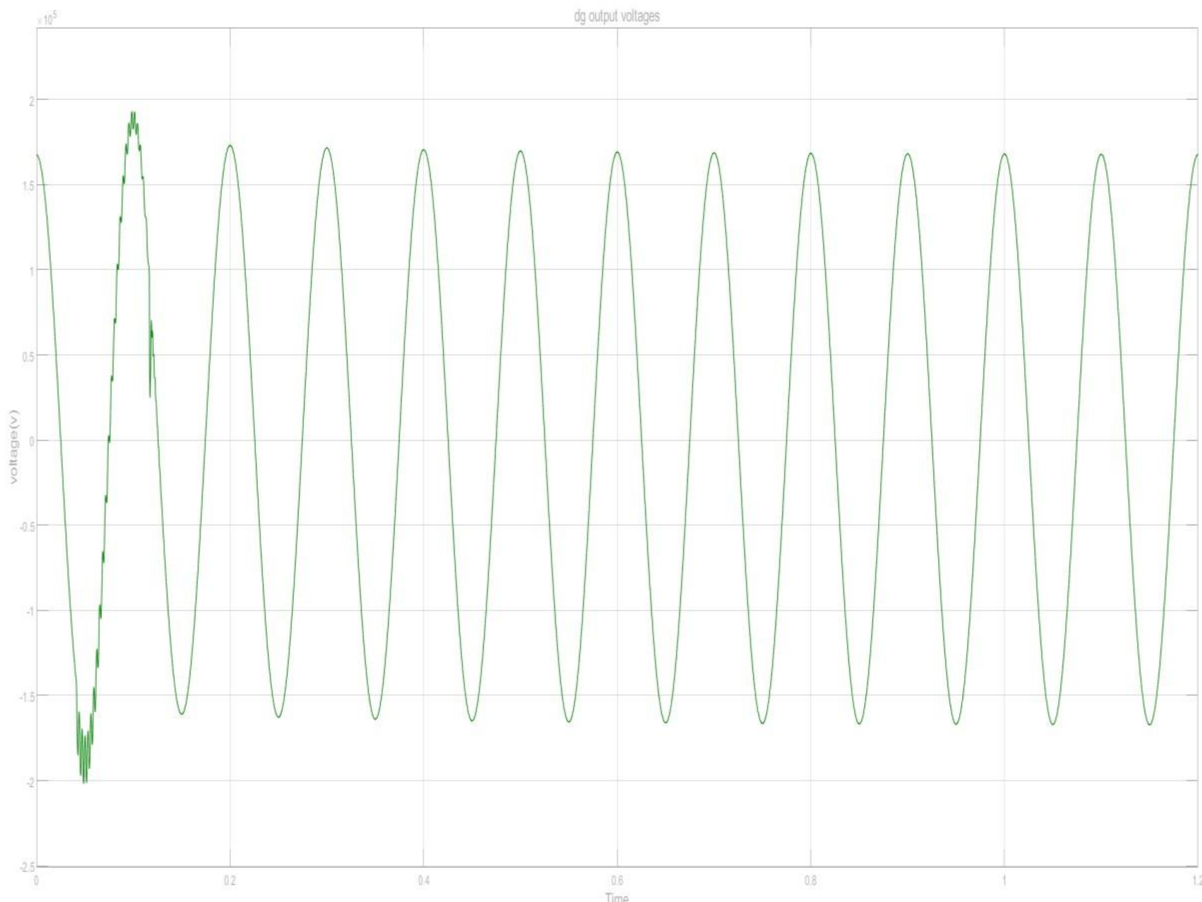

FIG 4.5 SHOWS DG OUTPUT VOLTAGE

DG Output Voltage: It represents the DG output voltage over time. Initially, there is a transient response with high amplitude, indicating system startup or a sudden change in operating conditions. As time progresses, the waveform stabilizes into a nearly sinusoidal shape, suggesting that the system reaches a steady-state condition. The frequency and amplitude remain consistent after stabilization, which is typical of an inverter-controlled distributed generation (DG) system. The presence of initial disturbances may indicate switching effects or load variations before the system achieves a balanced output

4.2 DG VSI WITH OSV CONTROLLER

The controller performance under change in the reference active power of the DG is also recorded, where the DG reference active power is gradually reduced by 50% and then restored back. It shows the system performance under decrease in the DG reference power, while depicts the performance under increase in the DG reference power. Accordingly, the current injected into the grid is decreased and increased, as pointed out respectively. The dynamic operation is observed smooth, and the grid currents are maintained sinusoidal throughout the operation, despite the nonlinear load current .Thus, the harmonic control strategy properly adapts to the dynamic perturbations in the DG-distortion

VSI system. A Distributed Generation (DG) Voltage Source Inverter (VSI) with an Optimal Switching Vector (OSV) Controller is designed to enhance power quality in distribution systems by effectively controlling the harmonic voltage

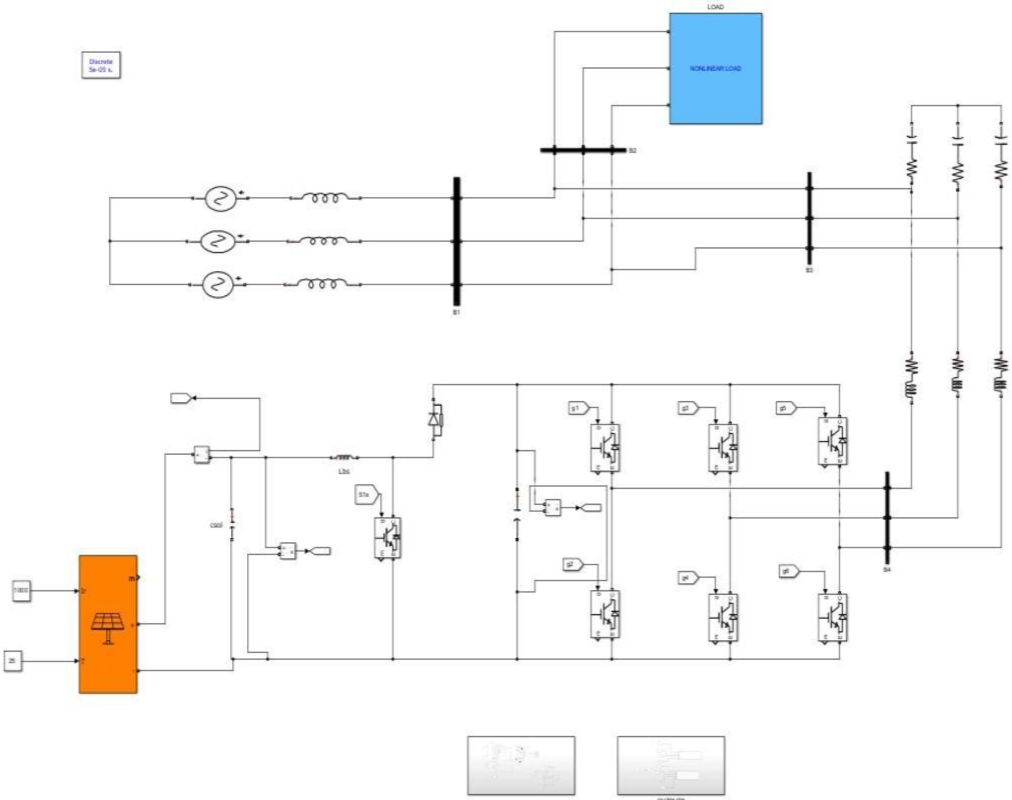

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Fig 4.6 MATLAB/SIMULINK circuit diagram of DG-VSI system in GI mode

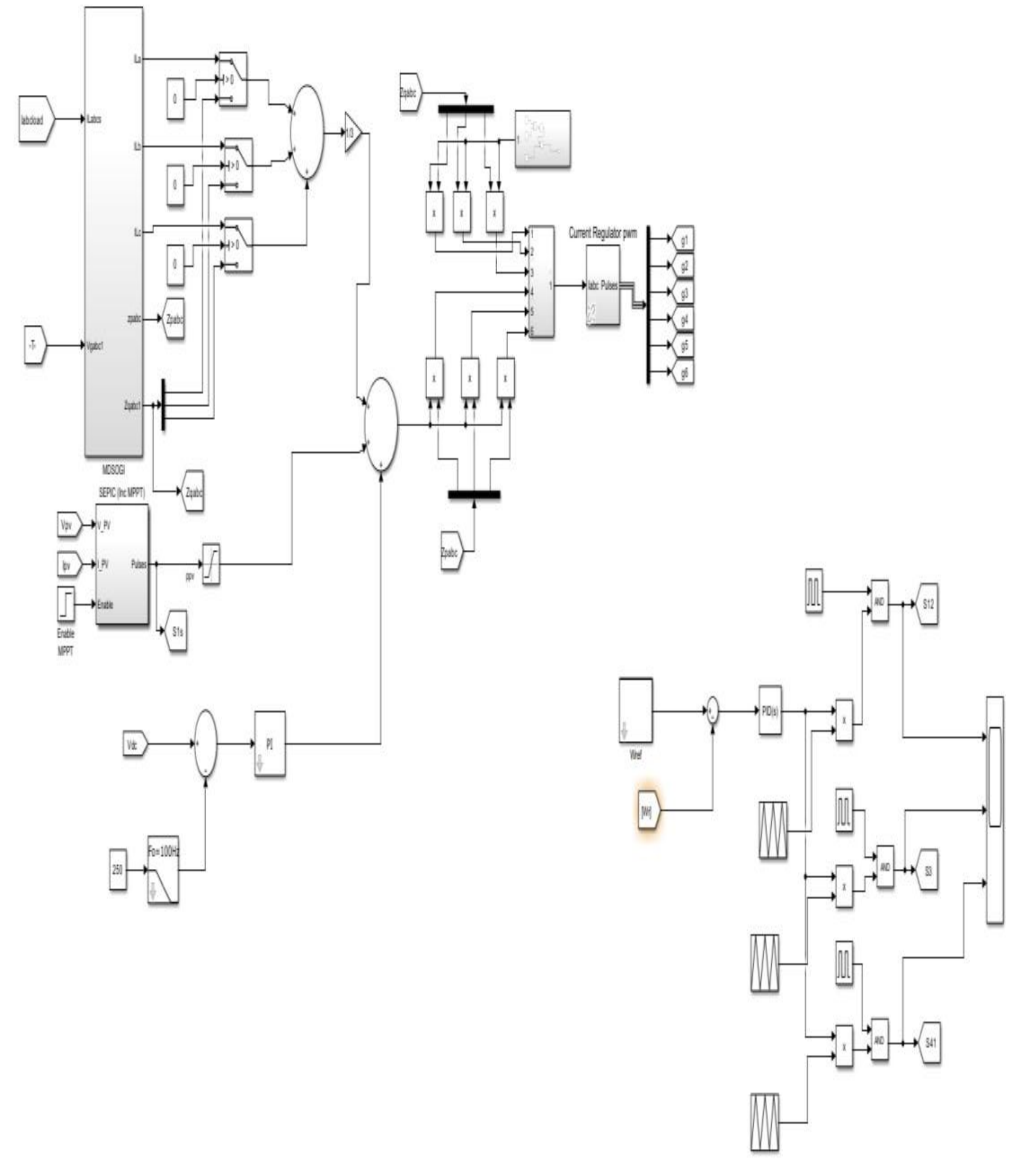

Fig 4.7 Control schematic with harmonic voltage controller

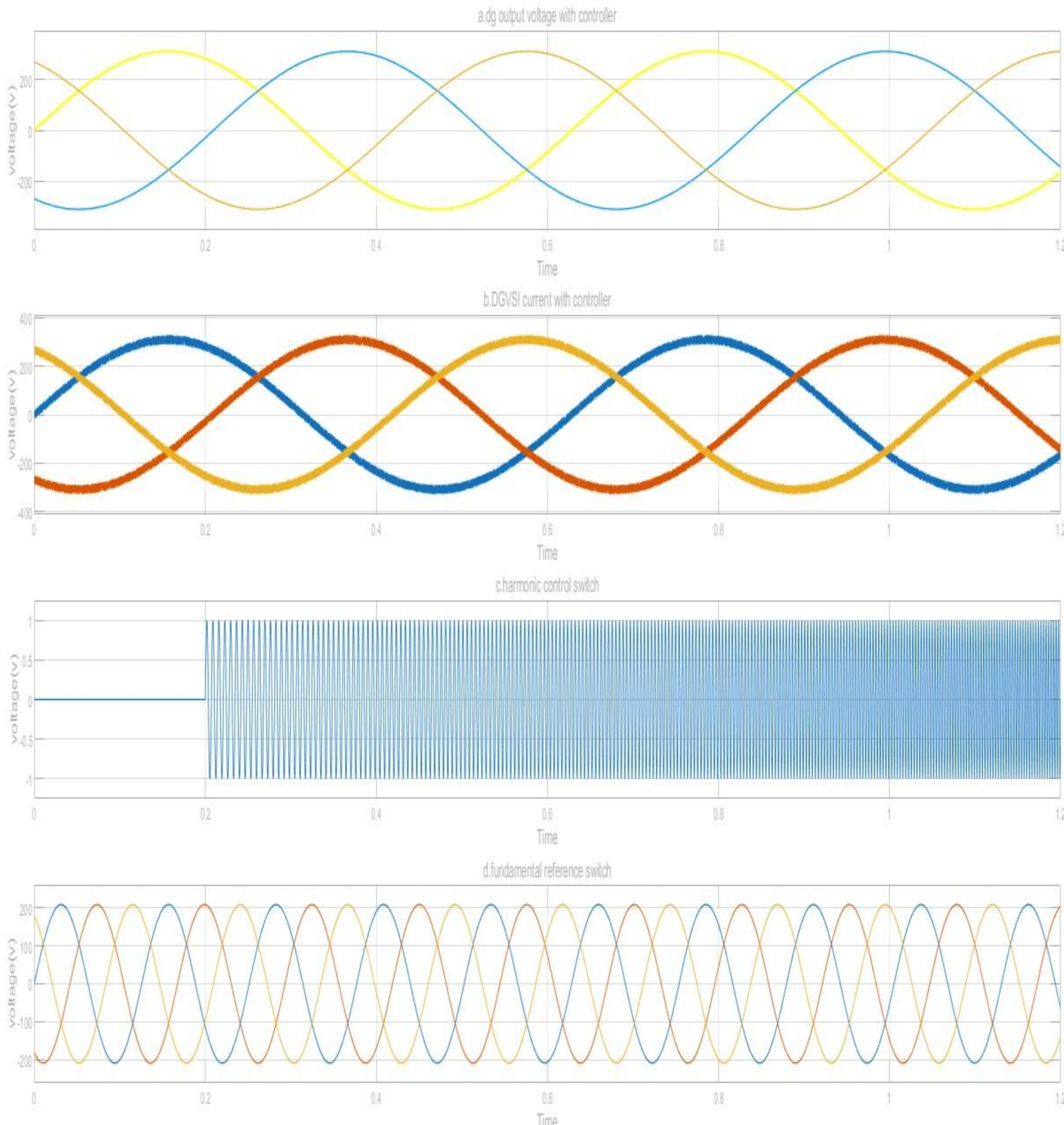

FIG 4.8 SHOWS:PERFORMANCE OF DG VSI MODE CONTROLLER OF VO,VP,HARMONIC REFERENCE VOLTAGE ,DG HORMONIC REFERENCE VOLTAGES.

a). DG Output Voltage with Controller: It represents a three-phase voltage waveform generated by a DG VSI with a controller. The three waveforms (blue, yellow, and orange) correspond to the three-phase voltages. They are evenly spaced, indicating a balanced system. Each phase is shifted by 120°, which is typical for a three-phase AC system. This ensures smooth power delivery and minimal torque ripple in motor applications. The waveforms appear clean and undistorted, indicating effective harmonic suppression by the controller. This ensures high power quality and reduces stress on electrical equipment. It demonstrates a well-regulated three-phase output voltage from a DG VSI, where the controller effectively maintains a balanced, low-harmonic, and stable waveform.

b) DG VSI Current with Controller: The waveform shown in the second graph represents the three-phase output currents of a Distributed Generation (DG) Voltage Source Inverter (VSI) under a controlled strategy. The three waveforms (blue, red, and yellow) are 120° phase-shifted, representing a balanced three-phase system. The sinusoidal shape suggests that the controller is effectively regulating the inverter output to match the desired reference waveform. The smoothness of the waveforms implies that harmonic distortions are minimized. The controller ensures that the inverter does not introduce significant unwanted harmonics into the system.

c).Harmonic Control Switch: It represents the switching waveform of the harmonic control strategy applied to the VSI. It shows a high-frequency switching pattern with densely packed pulses, indicating active modulation to minimize harmonic distortions. The variation in pulse density suggests an optimized modulation technique, likely space vector modulation (SVM) or pulse-width modulation (PWM), ensuring effective harmonic suppression. The consistent switching pattern over time reflects stable inverter operation under the controller, maintaining power quality and reducing unwanted harmonics in the output.

d). Fundamental Reference Switch Voltage: It represents the fundamental reference switching voltage used in the DG VSI mode controller. It shows three-phase sinusoidal waveforms that serve as the reference for generating the switching signals in the inverter. These reference voltages are essential for maintaining synchronization and ensuring that the inverter produces an output waveform with minimal distortion. The smooth and consistent nature of the waveforms indicates that the controller effectively regulates the switching process, aligning with the desired voltage levels to reduce harmonics and improve power quality.

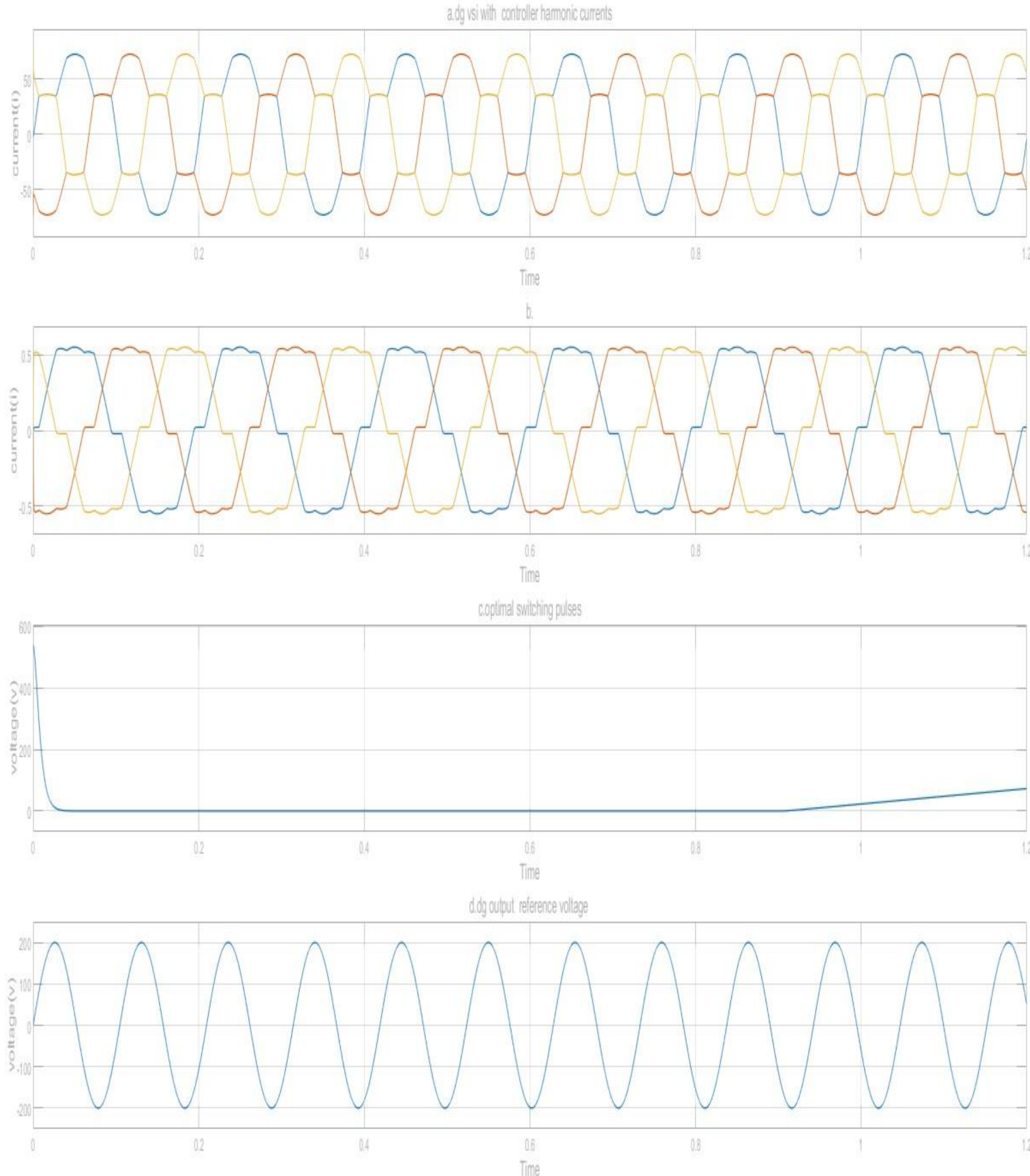

FIG 4.9 SHOWS:PERFORMANCE OF DG VSI WIIT OSV CONTROLLER FOR IO,IG,HORMINIC CONTROL SWITCH,SS1,SS2.

a).DG VSI with Controller Harmonics Current: It represents the output current waveform of the DG VSI controller, showing a balanced three-phase sinusoidal signal. The smooth nature of the waveform indicates that the controller effectively regulates the switching process to maintain a stable and low-distortion output. Any minor variations in the waveform may be due to transient effects or minimal harmonic components. The controller works to align the output current with the reference waveform, ensuring improved power quality and reduced total harmonic distortion (THD). This performance highlights the effectiveness of the controller in mitigating harmonics and maintaining a near-ideal sinusoidal current supply.

b).Harmonics Gate Current: It represents the harmonic gate current waveform controlled by the DG VSI controller. The waveform consists of a three-phase signal with noticeable distortions, indicating the presence of harmonics due to the switching operation of the inverter. The controller attempts to regulate these harmonics by adjusting the switching strategy, ensuring that the output current maintains a stable and predictable pattern. The periodic variations in the waveform suggest the influence of high-frequency switching pulses used to control harmonic components. This behavior highlights the controller's role in mitigating unwanted distortions and improving the overall current quality in the system.

c).Optimal Switching Pulses: It represents the optimal switching pulses controlled by the DG VSI (Distributed Generation Voltage Source Inverter) controller. The x-axis denotes time, while the y-axis represents voltage. The waveform initially exhibits a high voltage level, which rapidly decreases and stabilizes over time. This behavior indicates the controller's role in optimizing the switching pulses to regulate voltage fluctuations efficiently. The smooth transition in the waveform suggests that the controller effectively minimizes transient effects and ensures stable operation. The optimal switching strategy aims to reduce harmonics, enhance power quality, and improve the overall efficiency of the inverter system.

d).DG Output Reference Voltage: The DG output reference voltage controlled by the Optimal Switching Vector (OSV) controller. The sinusoidal waveform indicates that the controller effectively regulates the voltage output, minimizing distortions and ensuring stability. By dynamically adjusting the switching pulses of the voltage source inverter (VSI), the OSV controller ensures that the output voltage closely follows the reference waveform, reducing harmonic distortions. The smooth nature of the waveform confirms the controller's role in enhancing power quality and ensuring efficient distributed generation (DG) performance.

Before Harmonic control

• With out harmonic control

• Grid currents highly distorted due to nonlinear loads. Pcc voltage contains significant harmonics

. • Dg output voltage precisely tracks the reference voltages.

After enable hormonic control

• Dg output voltage waveform modified itself to include hormonic component.

• This ensures harmonic current suppress reducing thd in grid currents

5.CONCLUSION

A harmonic voltage control strategy using optimal switching vector controller has been explored for a threephase grid- connected and off-grid DG system. A minimization criterion is used in an OSV controller to achieve accurate output volt- age tracking performance and flexibly control the DG output harmonic voltage. In this way, the harmonic currents entering the grid are precisely regulated in the grid-connected mode of operation. In stand-alone mode of operation, the power quality is improved by elimination of PCC voltage harmonics caused by nonlinear load in the system. The controller eliminates the usage of multiple PR controllers, PI regulators, cascaded feedback loops, or phase locked loops in the system. Harmonic voltage control strategy using an Optimal Switching Vector (OSV) controller has been successfully explored for distributed generation (DG) systems operating in both grid-connected and stand-alone modes. The approach utilizes a minimization criterion within the OSV controller to achieve precise output voltage tracking and reduce harmonic distortion. This enables flexible and efficient control of the harmonic voltage at the DG output. In grid-connected mode, harmonic currents injected into the grid are effectively regulated, improving the overall power quality. In stand-alone mode, the system enhances voltage quality by eliminating harmonics at the point of common coupling (PCC) that typically arise due to nonlinear loads. The OSV method also reduces the complexity of the control system by removing the need for multiple PR controllers, PI regulators, or phaselocked loops. The strategy demonstrates strong potential for improving the performance of DG systems, offering a simplified yet effective solution for harmonic control. It lays a solid foundation for further research in optimizing switching control and applying it to advanced grid environments such as smart grids and microgrids.

CONFLICT OF INTEREST

	**Mr. B. Ramu** is currently pursuing a Bachelor of Technology (B. Tech) in Electrical and Electronics Engineering at Sir C R Reddy College of Engineering, Andhra Pradesh. His academic interests include power electronics, power systems, and renewable energy technologies. This paper is part of his research work on harmonic voltage control in distribution systems using optimal switching vector strategy. He aims to contribute to the development of efficient and sustainable electrical infrastructure**.** .

	**Ms. K. Krupa Jyothi** is currently pursuing a Bachelor of Technology (B. Tech) in Electrical and Electronics Engineering at Sir C R Reddy College of Engineering, Andhra Pradesh. Her academic interests revolve around smart grid technologies, energy storage systems, and sustainable energy management. With hands-on experience in simulation tools and system analysis, she has contributed to several technical initiatives in the department. She is passionate about finding practical solutions to real-world power quality challenges.

	**Ms. P. Ganga Bhavani** is currently pursuing a Bachelor of Technology (B. Tech) in Electrical and Electronics Engineering at Sir C R Reddy College of Engineering, Andhra Pradesh. She has a keen interest in control systems, electric drives, and automation. She has worked on mini-projects involving motor control and embedded systems, and she is committed to applying his technical skills to improve system efficiency and stability in power networks.
	**Mr. P. Nagendra** is currently pursuing a Bachelor of Technology (B. Tech) in Electrical and Electronics Engineering at Sir C R Reddy College of Engineering, Andhra Pradesh. His academic focus lies in harmonic mitigation, power system analysis, and the application of FACTS devices. Through this research paper, he has explored optimal switching techniques for enhancing voltage control and reducing harmonic distortion. He looks forward to contributing to the development of smart and sustainable power infrastructure
	**Mr. Nandigam Rama Narayana** is currently working as an Assistant Professor at Sir C R Reddy College of Engineering. He has over 15 years of field experience, specializing in Electrical Engineering, which strengthens his research in enhancing the efficiency of power systems. He is currently pursuing his Ph.D. in the Department of Electrical and Electronics Engineering at Annamalai University. His research interests include cybersecurity in MVDC distribution systems, High-Voltage Direct Current (HVDC) transmission systems, and high-voltage engineering. He has demonstrated a strong commitment to the advancement of power engineering through numerous international journal publications. To date, he has published over 18+ papers in international journals and conferences.

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