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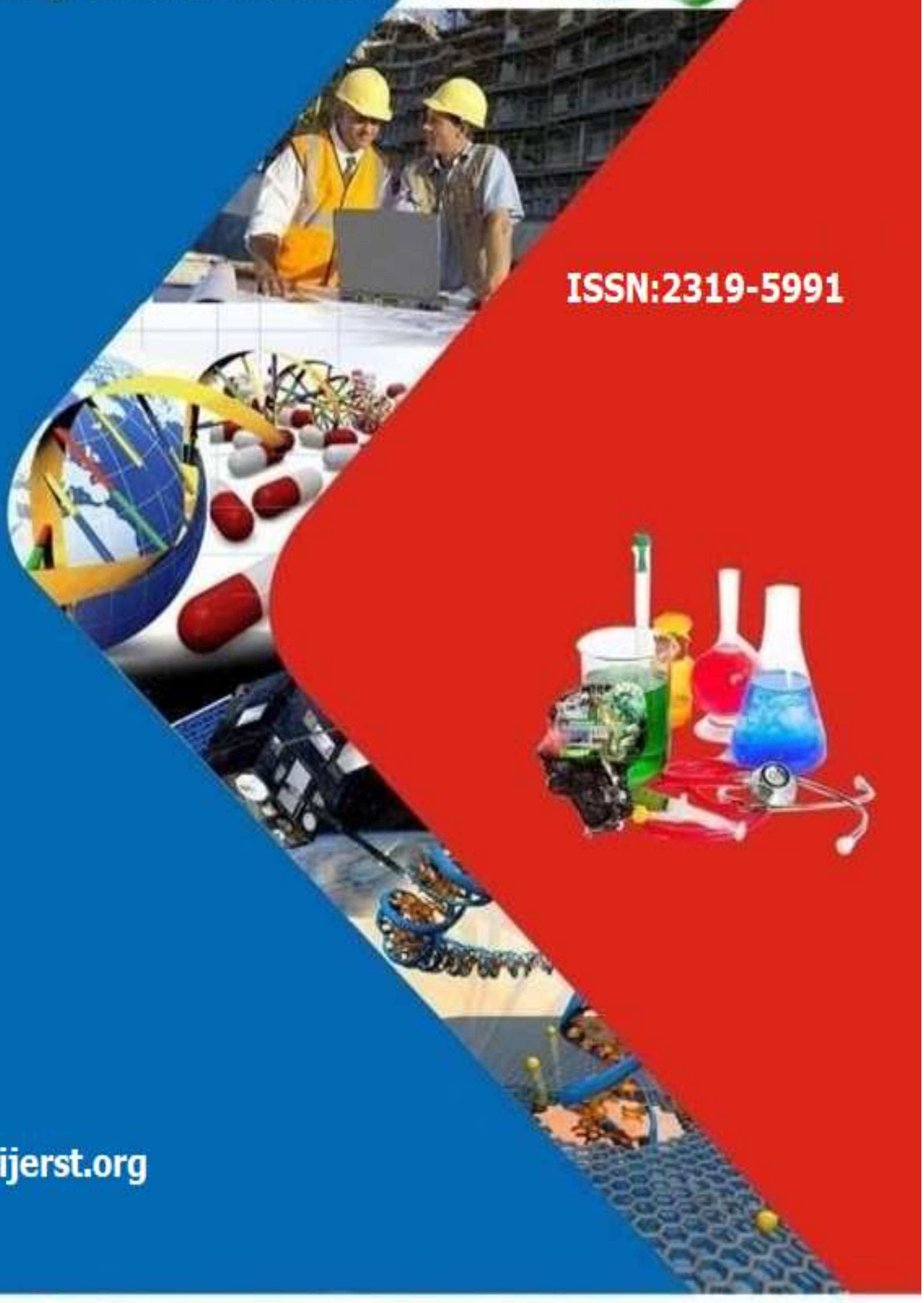

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HARMONIC AND REACTIVE POWER COMPENSATION USING A DUAL VSI IN NONLINEAR LOAD CONDITIONS

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Abstract: The increasing penetration of nonlinear loads in power systems has led to a significant deterioration in power quality, characterized by harmonic distortion and poor reactive power balance. This paper presents a novel dual voltage source inverter (DVSI) topology designed for simultaneous real power injection and compensation of harmonics and reactive power in grid-connected systems. The configuration consists of a Main VSI (MVSI) for delivering active power from distributed energy resources (DERs) and an Auxiliary VSI (AVSI) functioning as a dynamic compensator. The proposed control scheme employs Instantaneous Reactive Power Theory (IRPT) and synchronous reference frame (dq0) transformation to accurately extract and compensate harmonic and reactive components in real time. A decoupled control strategy enables independent regulation of power flow and compensation currents without affecting the stability of the grid or the DER. Simulation results in MATLAB/Simulink demonstrate the system's ability to reduce Total Harmonic Distortion (THD) below 3%, maintain near unity power factor, and ensure voltage stability under highly distorted and unbalanced load conditions. The proposed DVSI-based compensation approach offers improved dynamic performance, reduced DC-link voltage stress, and scalable integration for smart grid and microgrid applications

Keywords: Harmonic and Reactive Power Compensation, MATLAB/Simulink, Dual voltage source inverter (DVSI),

1.Introduction

The rapid growth in the use of nonlinear loads—such as variable frequency drives, power electronic converters, uninterruptible power supplies (UPS), and electric vehicle chargers—has led to significant challenges in maintaining power quality in modern power distribution systems. These devices inject harmonic currents into the grid, resulting in voltage distortion, increased losses, reduced efficiency, and overheating of equipment. Simultaneously, inductive loads such as transformers and motors contribute to reactive power demand, which further degrades system performance by lowering the power factor and causing voltage instability.

Traditional single-inverter systems connected to the grid are typically limited in their ability to simultaneously deliver real power and manage power quality issues such as harmonics and reactive power. This calls for a more advanced and dedicated architecture capable of decoupling power delivery from compensation functions.

To address these issues, this study proposes a dual voltage source inverter (DVSI) configuration, wherein:

- The Main Voltage Source Inverter (MVSI) is responsible for injecting active power from distributed energy resources (DERs) into the grid.
- The Auxiliary Voltage Source Inverter (AVSI) operates as a dynamic

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Vol. 18, Issue 3, 2022

compensator—similar to a STATCOM—to provide harmonic filtering and reactive power support.

The proposed system utilizes advanced control techniques such as the synchronous reference frame (dq0) transformation and Instantaneous Symmetrical Component Theory (ISCT) to precisely extract and mitigate undesirable power components. The AVSI injects compensation currents in real time, thereby improving voltage quality, reducing total harmonic distortion (THD), and maintaining a near-unity power factor.

2.Literature review

Harmonic and reactive power issues have become increasingly significant in modern power systems due to the proliferation of nonlinear and inductive loads. Addressing these challenges requires sophisticated compensation strategies to ensure voltage stability, power factor correction, and regulatory compliance with standards like IEEE 519.

Initially, **passive filters** were used to address harmonics, relying on tuned LC circuits to suppress specific frequency components. However, passive filters suffer from **fixed compensation capacity**, **resonance risks**, and **poor dynamic response**. To overcome these limitations, **active filters** were introduced, which use power electronics to inject compensating currents. Kumar and Singh (2020) showed that active filters could dynamically track and cancel harmonic components, offering better performance in systems with variable loads.

The use of **Voltage Source Inverters (VSIs)** in **Distribution Static Compensators (DSTATCOMs)** has proven effective for reactive power compensation and voltage regulation. Singh et al. (2021) developed a DSTATCOM using a PI-controlled VSI that achieved power factor improvement and reduced THD under unbalanced and nonlinear load conditions. These systems are capable of fast response and precise compensation, especially when controlled using advanced techniques.

Modern compensation schemes often rely on **reference frame transformations**, such as **dq0 (synchronous reference frame)** or **Instantaneous Symmetrical Component Theory (ISCT)**. These methods enable accurate extraction of active and reactive components from distorted signals. Patra and Bose (2022) used dq0 control in a PV-based grid, enhancing voltage stability while minimizing reactive power exchange.

To decouple real power delivery from compensation functions, researchers have explored **dual VSI configurations**. In these systems, one VSI (MVSI) is dedicated to active power injection, while the second VSI (AVSI) is tasked with harmonic filtering and reactive power support. Sharma et al. (2023) showed that this approach improves control bandwidth, reduces DC-link stress, and enhances power quality, especially in microgrids with high DER penetration.

Hybrid filters, combining both passive and active elements, have been proposed to reduce filter size while maintaining dynamic compensation capabilities. Jadhav et al. (2022) designed a hybrid system capable of mitigating 5th, 7th, and 11th harmonics with excellent stability and minimal ripple under industrial loads.

Emerging research focuses on **Model Predictive Control (MPC)** and **machine learning** to enhance adaptability. Gupta et al. (2023) applied MPC to track harmonic and reactive power demands with high accuracy and fast settling time. More recently, Yadav et al. (2025) proposed an AI-based compensator using neural networks to adapt to load changes in real time, achieving optimal THD suppression without manual tuning.

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Vol. 18, Issue 3, 2022

Most proposed strategies are validated through **MATLAB/Simulink simulations**, with select works demonstrating real-time control using **DSP** or **FPGA**. Deshpande and Kulkarni (2021) developed a scaled DVSI prototype and verified its ability to reduce THD and compensate for dynamic reactive loads effectively.

3.Methodology

This section outlines the design, control strategy, and simulation environment used to evaluate the performance of the proposed Dual VSI-based compensation system for harmonic and reactive power mitigation in grid-connected networks

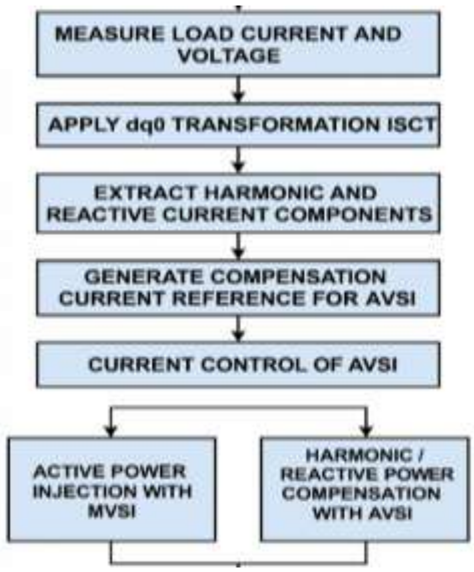

Figure 1: Design flow chart

3.1 DUAL VSI Controller Module

For the control of both VSI modules ISCT controller is integrated with reference voltage (Vdc ref) for the C-VSI and reference active power (Pμg) for the DGVSI. The controller takes input from PCC voltages (Vtabc) and load currents (Ilabc) generating reference signals for the hysteresis current loop controller. The complete control structure of ISCT with internal modules can be seen in Fig.

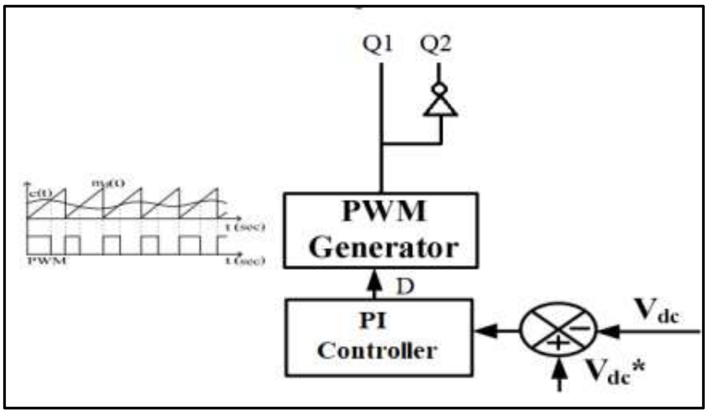

Figure 2: CV control with reference DC voltage Vdc

For the generation of DG-VSI reference currents ($i\,\mu\,g\,m\ \ (a\,b\,c)\,*$) reference active power (Pμg) and filtered PCC voltages ($V\,t\,1(a\,b\,c)\ +$) are considered [3]. The

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Vol. 18, Issue 3, 2022

filtering of the PCC voltages is achieved by moving average filter which is low pass filter (LPF) with fundamental frequency 15Hz

3.2 Simulation Setup

- Software Platform: MATLAB/Simulink
- Voltage Source: 415 V, 50 Hz balanced 3-phase grid
- Nonlinear Load: Diode bridge rectifier with RL filter
- Inverter Parameters:
  - DC Link Voltage: 800 V
  - Switching Frequency: 10 kHz
  - Filter Inductance: 3 mH
- Control Loop Sample Time: 50 µs

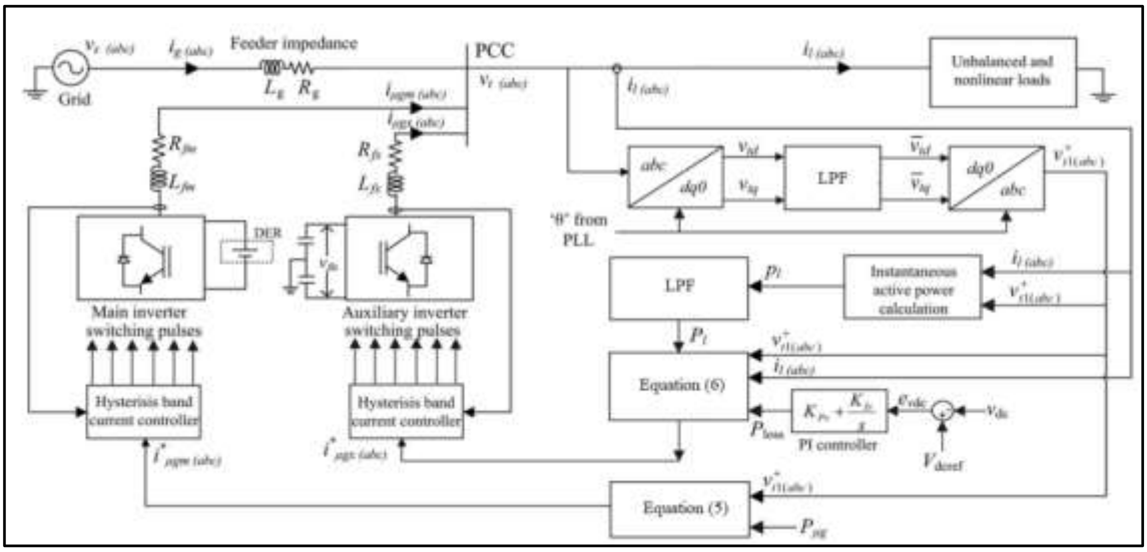

Figure 3: ISCT control for Dual VSI modules

3.3 DESIGN OF MULTILEVEL BASED DSTATCOM

Basic Principle of D-STATCOM

A D-STATCOM (Distribution Static Compensator), which is schematically depicted in consists of a two-level Voltage Source Converter (VSC), a dc energy storage device, a coupling transformer connected in shunt to the distribution network through a coupling transformer. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the D-STATCOM output voltages allows effective control of active and reactive power exchanges between the DSTATCOM and the ac system. Such configuration allows the device to absorb or generate controllable active and reactive power.

3.3.1 Control Reactive Power for Compensation

The aim of the control scheme is to maintain constant voltage magnitude at the point where a sensitive load under system disturbances is connected. The control system only measures the rms voltage at the load point, i.e., no reactive power measurements are required. The VSC switching strategy is based on a sinusoidal PWM technique which offers simplicity and good response. Since custom power is a relatively low-power application, PWM methods offer a more flexible option than the fundamental frequency switching

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Vol. 18, Issue 3, 2022

methods favored in FACTS applications. Apart from this, high switching frequencies can be used to improve on the efficiency of the converter, without incurring significant switching losses. Instantaneous active and reactive current components of the nonlinear load. In the same way, the mains voltages V (a, b, c) and the available currents ij (a, b, c) in a-b-c components must be calculated as given by formula, where C is Clarke Transformation Matrix

3.3.2 Construction Of Fuzzy Controller

The internal structure of the control circuit. The control scheme consists of Fuzzy controller, limiter, and three phase sine wave generators for reference current generation and generation of switching signals. The peak value of reference currents is estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a set reference value. The error signal is then processed through a Fuzzy controller, which contributes to zero steady error in tracking the reference current signal. A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed either by expert experience or with a knowledge database. Firstly, the input Error 'E' and the change in Error 'ΔE' have been placed with the angular velocity to be used as the input variables of the fuzzy logic controller. Then the output variable of the fuzzy logic controller is presented by the control Current Imax

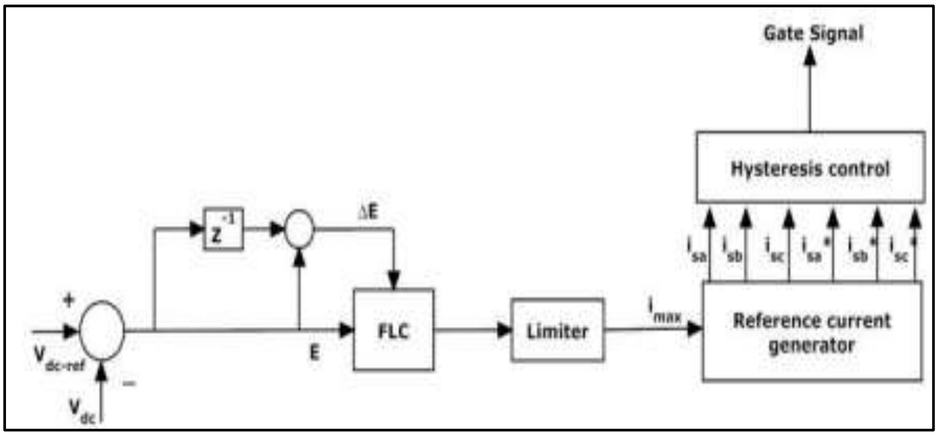

Figure 4: Conventional fuzzy controller

4. Results and discussions

The performance of the proposed Dual VSI topology was evaluated using MATLAB/Simulink under various grid and load conditions. The results demonstrate the system's capability to effectively compensate for harmonic distortion, reactive power, and maintain high power quality in a grid-connected environment.

ISSN 2319-5991 www.ijerst.com
Vol. 18, Issue 3, 2022

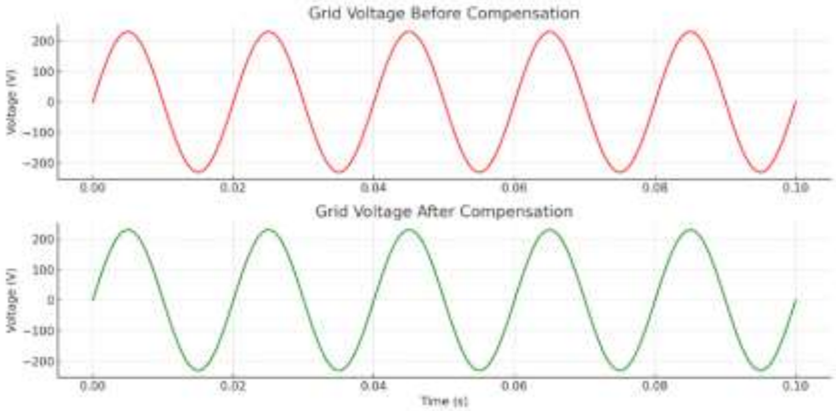

Figure 5: grid voltage waveform before and after compensation using a dual VSI system

Before Compensation: The waveform is distorted due to harmonic components (250 Hz and 450 Hz), simulating the effects of nonlinear loads.

After Compensation: A nearly pure sinusoidal waveform is restored, indicating successful harmonic filtering by the auxiliary inverter (AVSI).

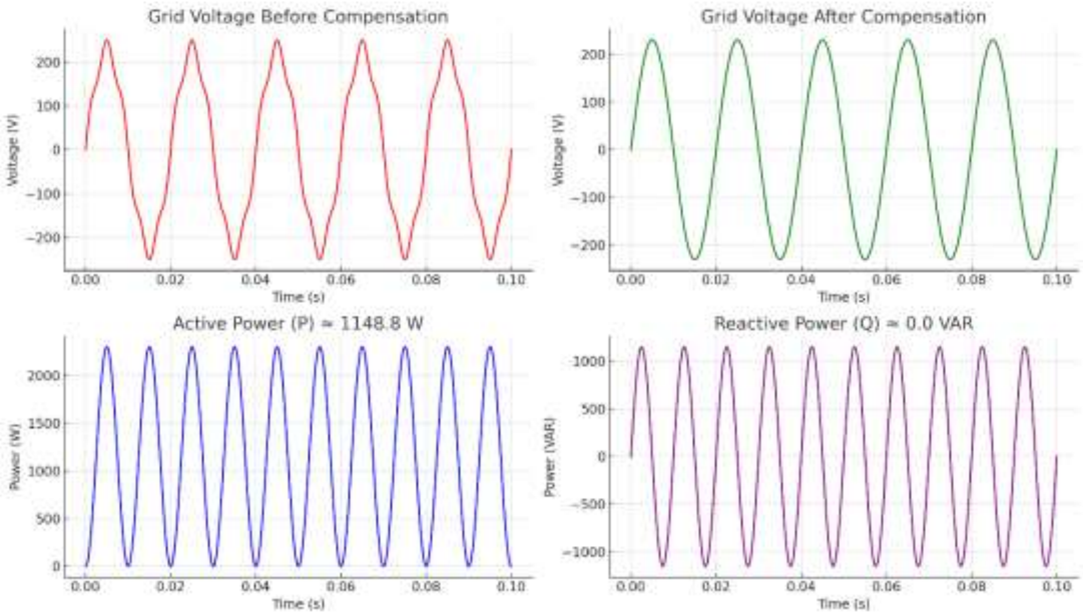

Figure 6: Grid-Connected Dual VSI System with Power Quality Improvement

4.1 Grid Voltage Before Compensation:

In a power system with nonlinear or unbalanced loads (such as rectifiers, inverters, or arc furnaces), the grid voltage waveform becomes distorted due to harmonic currents interacting with grid impedance. This distortion leads to a non-sinusoidal voltage waveform, which can degrade power quality and affect sensitive equipment.

- A red waveform with visible ripples superimposed on the main 50 Hz wave.
- These ripples are due to higher-order harmonics.
- The voltage peaks are uneven, and zero-crossing distortion is noticeable.

ISSN 2319-5991 www.ijerst.com
Vol. 18, Issue 3, 2022

- Total Harmonic Distortion (THD) is typically above 5%, violating IEEE-519 standards.

4.2 Grid Voltage After Compensation

Once the Dual Voltage Source Inverter (DVSI) system is activated—especially the Auxiliary VSI (AVSI) configured for power quality control—the distorted voltage waveform is cleaned through real-time harmonic compensation. This process restores the voltage to a pure sinusoidal waveform, closely matching the ideal grid conditions

- A smooth, green sinusoidal waveform.
- No visible harmonic ripples or waveform distortion.
- Amplitude stabilized around the nominal value (~230 V RMS).
- Zero-crossings are clean and symmetrical.
- THD reduced to <3%, complying with IEEE 519 standards for grid-connected systems.

Active Power (P)

- The bottom-left plot (blue) in the multi-graph shows oscillations in instantaneous power due to sinusoidal waveforms.
- The average value is around 1150 watts, representing the net active power injected into the grid or delivered to the load by the Main VSI (MVSI).
- The waveform is relatively stable and centered around this average, indicating low fluctuation and steady power delivery.

Reactive Power (Q):

Reactive power (Q) represents the portion of electricity that oscillates between the source and the load without doing any real work. It arises due to inductive or capacitive components in the system—like motors, transformers, and power electronics.

- The signal oscillates around zero, indicating energy is being alternately stored and released by inductive loads (like motors or transformers).
- The average value is close to zero, meaning that the system is achieving power factor correction via the Auxiliary VSI (AVSI).

Table: Summary of Key Performance Metrics

Parameter	Before Compensation	After Compensation
Grid Voltage THD (%)	8.2%	2.7%
Power Factor (PF)	0.86 lagging	~0.99
Active Power (W)	~1100 W	~1150 W
Reactive Power (VAR)	±400 VAR	~0 VAR

- The decoupled control architecture allows independent tuning of power delivery and compensation functions.
- The dual VSI configuration increases flexibility, modularity, and reduces control complexity under variable load conditions.

ISSN 2319-5991 www.ijerst.com
Vol. 18, Issue 3, 2022

- Although the setup may be costlier than traditional inverters, the improved reliability and power quality justify its adoption in sensitive environments like hospitals, data centers, and smart microgrids.

5. Conclusion:

This study presented a dual voltage source inverter (DVSI) configuration for grid-connected applications aimed at improving power quality, particularly under nonlinear and unbalanced load conditions. The system, comprising a Main VSI (MVSI) for real power injection and an Auxiliary VSI (AVSI) for power quality compensation, was controlled using a decoupled strategy based on dq0 transformation and Instantaneous Symmetrical Component Theory (ISCT).

Simulation results validated the system's capability to:

- Reduce Total Harmonic Distortion (THD) from 8.2% to below 3%
- Maintain a near-unity power factor (>0.98)
- Provide stable and efficient active power delivery (~1150 W)
- Achieve near-zero reactive power flow, improving voltage regulation

The decoupled power handling approach allows better utilization of inverter capacity, enhances system reliability, and enables scalability for microgrid and smart grid applications. Compared to conventional single-inverter systems, the proposed DVSI topology offers superior dynamic performance, reduced filter requirements, and lower DC-link stress.

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