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Adaptive In-Phase Quadrature LMS (IPQ-LMS)-Based Reference Current Generator for Grid-Connected DSTATCOM

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Abstract: This paper proposes an In-Phase and Quadrature Least Mean Square (IPQ-LMS)-based control strategy for grid-connected DSTATCOM under three-phase nonlinear load and unbalanced load conditions. The controller adaptively extracts the fundamental component of the load current using orthogonal reference signals derived from the phase angle of the grid voltage. A proportional-integral (PI) regulator is employed to maintain the DC-link voltage at 700 V, ensuring effective active power injection. To improve current symmetry under load imbalance, an averaged adaptive weight vector is used across all three phases. The reference current thus generated ensures balanced grid injection and reduced harmonic content. The proposed control strategy is implemented in MATLAB/Simulink, and performance is validated under various dynamic load switching scenarios. Simulation results demonstrate that the proposed method achieves effective harmonic mitigation, voltage regulation, and current balancing, thereby improving overall power quality in compliance with IEEE-519 and IEEE-1547 standards.
Keywords: DSTATCOM, Least Mean Square, Unbalance Load, DC link Voltage, Total Harmonics Distortion

I. INTRODUCTION

Power quality degradation in distribution systems has become a significant concern, largely due to the increasing use of nonlinear and unbalanced loads. These include common industrial and commercial equipment such as rectifiers, adjustable speed drives, and computing systems, all of which inject harmonic currents and reactive power into the grid [1]-[3]. Such disturbances can lead to voltage distortion, unbalanced source currents, and poor power factor, ultimately affecting the stability and efficiency of the power network.

To address these issues, the Distribution Static Compensator (DSTATCOM) has been widely adopted as an effective shunt-connected compensator. By injecting suitable compensating currents through a voltage source inverter (VSI), the DSTATCOM is capable of reducing harmonic distortion, supplying or absorbing reactive power, and balancing load currents at the point of common coupling (PCC). Its fast response and flexibility make it particularly suitable for dynamic load conditions in low- and medium-voltage distribution systems [4],[5].

A critical component of DSTATCOM performance lies in its control strategy. Classical control methods such as the synchronous reference frame (SRF) theory [6], instantaneous reactive power theory (IRPT) [7], and power balancing approaches have been extensively reported in the literature. While effective under steady-state conditions, these methods typically rely on phase-locked loops (PLLs) and low-pass filters (LPFs), both of which introduce delays and are sensitive to frequency deviations and noise. As a result, their performance under dynamic and unbalanced load scenarios becomes limited.

To overcome these drawbacks, adaptive signal processing techniques—particularly those based on the Least Mean Square (LMS) algorithm—have gained attention. The LMS algorithm is known for its simplicity, low computational burden, and ability to operate without PLLs or LPFs. Variants such as ADALINE-based LMS and normalized LMS (NLMS) [8],[9] have shown improvements in speed and robustness. However, most conventional LMS applications consider each phase separately, which may result in poor performance under load unbalance [10]-[12].

This study proposes an enhanced In-Phase and Quadrature LMS (IPQ-LMS) control algorithm for DSTATCOM systems operating under nonlinear and unbalanced load conditions. The algorithm utilizes orthogonal reference signals (i.e., sine and cosine components of the grid voltage angle) to estimate the fundamental components of load currents. By adaptively updating weights for each phase and averaging them, the proposed method generates balanced and sinusoidal reference currents, even during asymmetrical load switching. In addition, a PI controller is integrated to maintain the DC-link voltage at a regulated value, ensuring proper inverter operation.

The configuration considered in this work involves only the DSTATCOM and grid-connected nonlinear and unbalanced loads. The absence of renewable energy components simplifies the control objectives and focuses solely on power quality improvement. The proposed system is validated in MATLAB/Simulink under a variety of operating conditions, including dynamic loading, harmonic disturbances, and unbalance. The results confirm the effectiveness of the proposed approach in achieving current balancing, harmonic suppression, and DC voltage stability.

This article provides a in phase and quadrature LMS based control algorithm for conditioning of the grid current. The contributions of this work are as follows.

- A LMS based control algorithm is introduced for operation of DSTATCOM.
- The proposed control algorithm is implemented for PQ improvement in case of nonlinear loading and unbalanced loading condition.

This article is organized into five sections. Section II gives a detailed analysis of the system configuration. Section III presents the proposed control topology. Section IV discusses the simulation results in detail, and Section V concludes the article with key findings.

II. SYSTEM CONFIGURATION

Figure 1 illustrates the proposed system configuration, which consists of a three-phase grid, a voltage source inverter (VSI), an interfacing inductor, a passive RC filter, and a nonlinear load connected at the point of common coupling (PCC). The VSI operates as a DSTATCOM to compensate for power quality issues such as current harmonics, reactive power imbalance, and load unbalancing. The topology adopts a single-stage configuration where the DSTATCOM is directly interfaced with the grid via the PCC. To ensure proper control and monitoring, the system utilizes several sensors: three AC sensors are used to measure grid currents, three are used for load currents, and one DC sensor is used to monitor the DC-link voltage. These sensed signals are processed by the control block to generate reference current signals, which are then used to determine the appropriate switching pulses for the inverter.

The DSTATCOM injects compensating currents into the grid to maintain sinusoidal and balanced source currents even under nonlinear and unbalanced load conditions. During operation, the DC-link voltage is regulated using a PI controller to ensure continuous and stable performance. The control strategy is designed to supply the required reactive power and mitigate harmonics, thereby improving the overall power quality at the PCC.

TABLE I

SYSTEM PARAMETER

Parameter	Value
Supply voltage (Line to Line) (V_S)	415 V
Source impedance (Z_S)	0.7 Ω
DC link capacitance (C_{dc})	13000 µF
DC link voltage (V_{dc})	700 V
Interfacing Inductor (L_f)	5mH
Filter capacitance (C_f)	10 µF
Unbalanced load (L_1)	50 kVA,0.8pf
Nonlinear load (L_2)	16 kW
Short circuit ratio	2.46

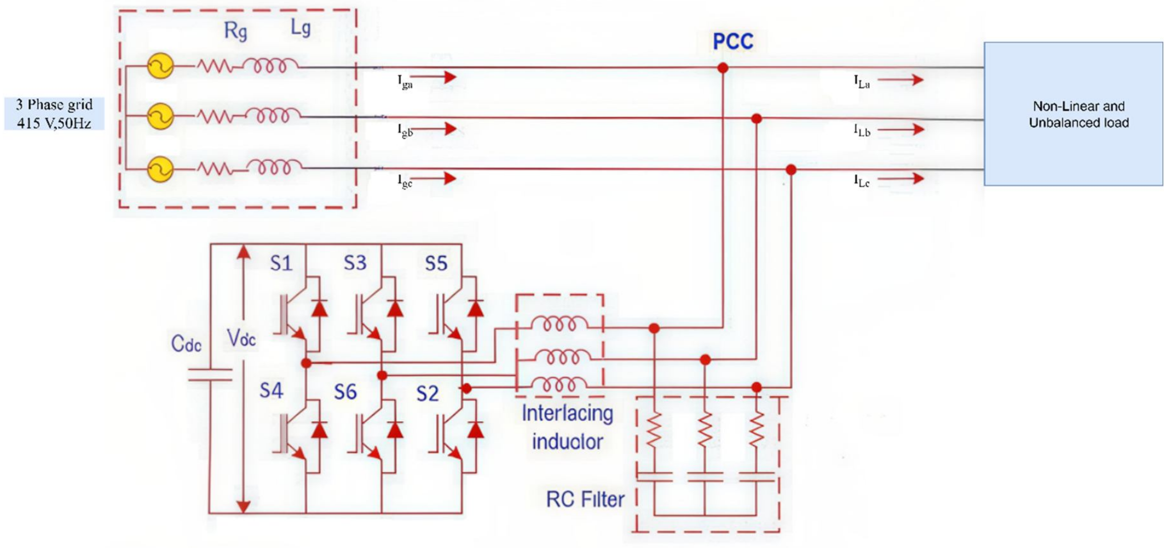

Fig.1: System Configuration

III.CONTROL TOPOLOGY

This section presents a control strategy based on the Adaptive In-Phase Quadrature Least Mean Squares (IPQ-LMS) algorithm for a DSTATCOM. The main objective is to extract the fundamental reference source currents accurately, ensuring harmonic compensation and reactive power support under unbalanced and nonlinear load conditions. Unlike traditional transformation-based methods, the IPQ-LMS algorithm works directly in the time-domain abc frame and relies on dynamic adjustment of filter weights using sinusoidal reference templates derived from the grid voltage angle.

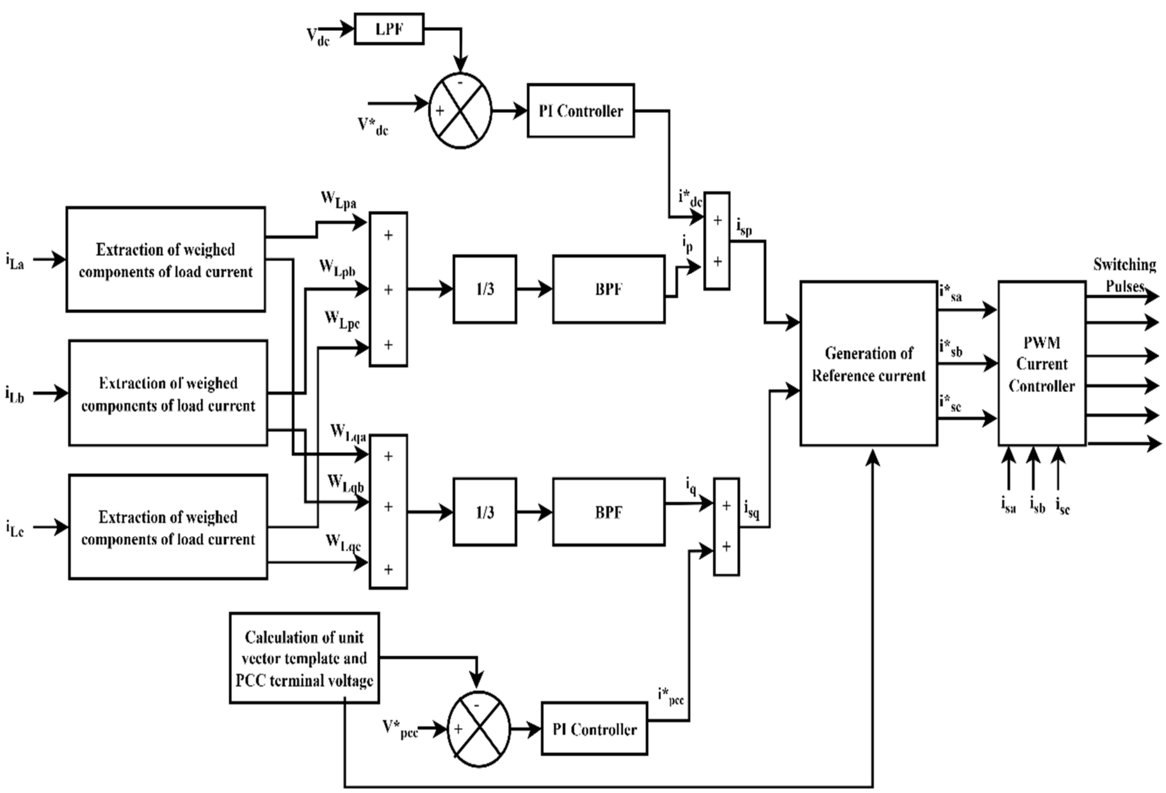

Fig.2: IPQ-LMS base control Algorithm

A. Reference Template Generation•

The algorithm begins by generating in-phase and quadrature unit vectors for each phase based on the instantaneous grid angle δ(k). These templates serve as reference signals for projecting the load current components:

$$x_a(k) = [sin(\delta(k)), cos(\delta(k))]^T \tag{1}$$

$$x_b(k) = [sin(\delta(k) - 120), cos(\delta(k) - 120)]^T \tag{2}$$

$$x_c(k) = [sin(\delta(k) + 120), cos(\delta(k) + 120)]^T \tag{3}$$

B. Reference Template Generation

Using the reference vectors, the fundamental components of the load current are estimated through inner products with adaptive weight vectors:

$$\hat{\imath}_a(k) = W_{La}^T(k) \cdot x_a(k) \tag{4}$$

$$\hat{\imath}_b(k) = W_{Lb}^T(k) \cdot x_b(k) \tag{5}$$

$$\hat{\imath}_c(k) = W_{Lc}^T(k) \cdot x_c(k) \tag{6}$$

C. Error Computation and Adaptation

The difference between the actual nonlinear load current and the estimated fundamental component constitutes the estimation error. These errors are calculated for each phase as:

$$e_a(k) = i_{La}(k) - \hat{\imath}_a(k) \tag{7}$$

$$e_b(k) = i_{Lb}(k) - \hat{\imath}_b(k) \tag{8}$$

$$e_c(k) = i_{Lc}(k) - \hat{\imath}_c(k) \tag{9}$$

To minimize these errors, the weight vectors are adjusted using a gradient descent rule commonly referred to as the Widrow-Hoff update method:

$$W_{Lap}(k+1) = w_{Lap}(k) + \mu \cdot e_a(k) \cdot i_{Lap}(k) \tag{10}$$

$$W_{Lbp}(k+1) = w_{Lbp}(k) + \mu \cdot e_b(k) \cdot i_{Lap}(k) \tag{11}$$

$$W_{Lcp}(k+1) = w_{Lcp}(k) + \mu \cdot e_c(k) \cdot i_{Lap}(k) \tag{12}$$

Extraction of weighed value of fundamental component of loads current $(W_{aq}, w_{bq}, w_{cq})$are:

$$W_{Laq}(k+1) = w_{Laq}(k) + \mu \cdot e_a(k) \cdot i_{Laq}(k) \tag{13}$$

$$W_{Lbq}(k+1) = w_{Lbq}(k) + \mu \cdot e_b(k) \cdot i_{Laq}(k) \tag{14}$$

$$W_{Lcq}(k+1) = w_{Lcq}(k) + \mu \cdot e_c(k) \cdot i_{Laq}(k) \tag{15}$$

The parameter μ is the learning rate, for this system it is 0.01, $i_{Lap}, i_{Lbp}, i_{Lcp}$ are in phase component of load current and i_{Laq}, i_{Lbq}, i_{Lcq} are quadrature phase component of load current.

The mean value (W_P) of the weighting values of the three- phase active component is calculated as follows:

$$w_p = \frac{W_{Lap}+W_{Lbp}+W_{Lcp}}{3} \tag{16}$$

Similarly average reactive weighted component

$$w_q = \frac{W_{Laq}+W_{Lbq}+W_{cq}}{3} \quad (17)$$

The average weighted values of both active and reactive power components are processed through a Band Pass Filter (BPF) with a pass band frequency of 40Hz-60 Hz to extract the active (i_P) and reactive (i_q) parts of the reference source current

D. DC-Link Voltage Control

Maintaining the DC-link voltage at a stable level is crucial for continuous DSTATCOM operation. A feedback control loop is employed using a Proportional-Integral (PI) controller:

$$e_{dc} = V_{dc_{ref}} - V_{dc}(k) \quad (18)$$

The output of PI controller

$$i^*_{dc} = K_p.e_{dc}(k) + K_i.\sum e_{dc}(k) \quad (19)$$

The magnitude of total active load current component is achieved by adding DC pi controller's output and filtered active weighted load current component

$$i_{sp} = i^*_{dc} + i_p \quad (20)$$

E. PCC Voltage Control

To maintain the PCC voltage, the voltage at the PCC is sensed and compared with the reference voltage. The resulting error is then processed through a PI controller.

$$V_t = V_{pcc_{ref}} - V_{pcc} \quad (21)$$

$$i^*_{pcc} = K_p.v_t(k) + K_i.\sum v_t(k) \quad (22)$$

Total load current reactive component is sum of filtered reactive weighted load current component and output of AC pi controller

$$i_{sq} = i^*_{pcc} - i_q \quad (23)$$

F. Generation of Reference Current

Three phase source active and reactive component is achieved by the multiplication of voltage unit vector template with active and reactive load current component

$$i_{ga_a} = i_{sp} * u_{pa}, i_{ga_b} = i_{sp} * u_{pb}, \quad i_{ga_c} = i_{sp} * u_{pc} \quad (24)$$

$$i_{gr_a} = i_{sq} * u_{qa}, i_{gr_b} = i_{sq} * u_{qb}, \quad i_{gr_c} = i_{sq} * u_{qc} \quad (25)$$

The desired three-phase reference source currents *(* $i^*_{sa}, i^*_{sb}, i^*_{sc}$*)* are obtained by summing the corresponding active and reactive components of the reference source current, and can be expressed as follows:

$$i^*_{sa} = i_{ga_a} + i_{gr_a} \quad (26)$$

$$i^*_{gb} = i_{ga_b} + i_{gr_b} \quad (27)$$

$$i^*_{gc} = i_{ga_{cc}} + i_{gr_c} \quad (28)$$

These reference source current signal and grid current is use to getting triggering pulses for suitable operation of DSTATCOM.

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IV. SIMULATION RESULTS

The performance of proposed control algorithm is tested for nonlinear loading and unbalanced loading condition. The control algorithm is implemented on a sample system shown in Fig.1, the simulation is performed at MATLAB/SIMULINK .at both load switching the grid voltage, grid current, PCC voltage, load current, dc-link voltage, and load power waveform is observed

A. System Performance at non-linear Load Condition

The rectifier-based RL load of 16 Kw is considered as a nonlinear load which is connected at t=1 sec. to t=1.8 sec. during this period the load current is pure nonlinear but the effect of this nonlinearity at grid current is successfully mitigated by DSTATCOM and the THD of source current is under the permissible limit of IEEE 519 and the DC link voltage is maintained at 700 volt.

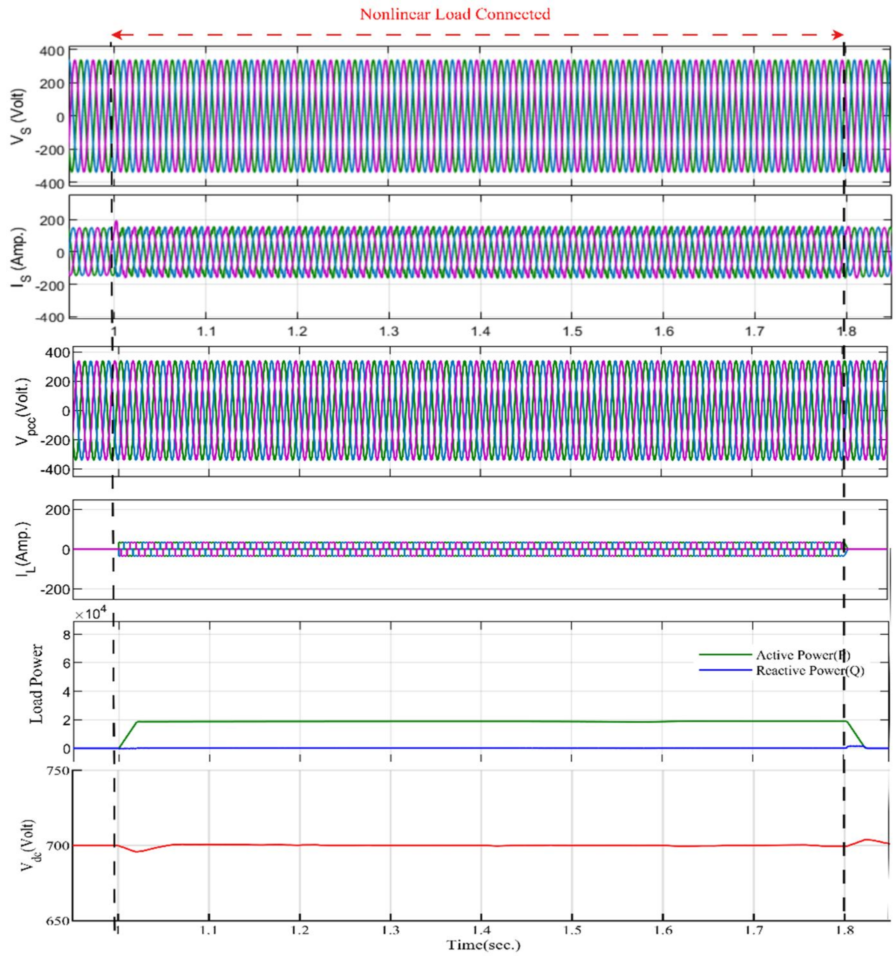

Fig.3: System performance at non-linear load condition

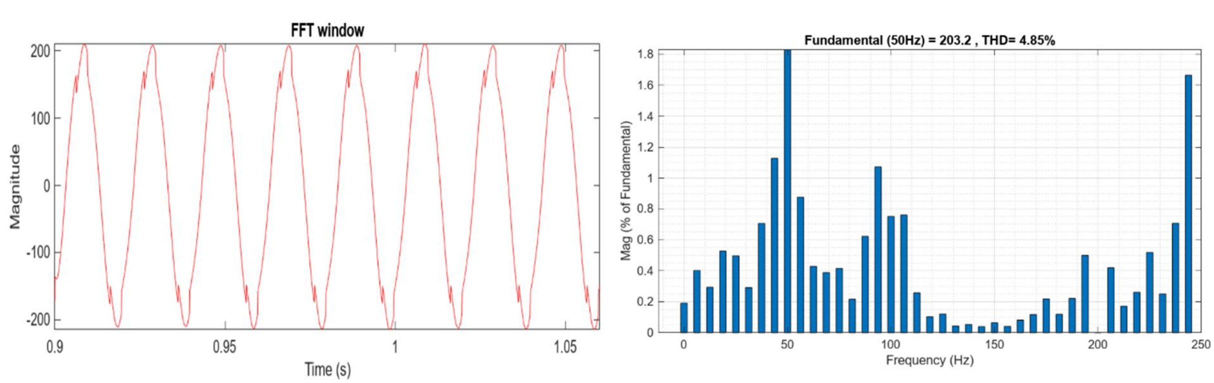

Fig.4: THD Analysis of Source current

B. System performance at Unbalanced load condition:

A three-phase 50kVA, 0.8pf, load is connected at t=2.1 sec. to 2.9 sec. to make load unbalanced one phase is removed from three phase load. The magnitude and phase of grid current and grid voltage is balance during unbalanced load condition.

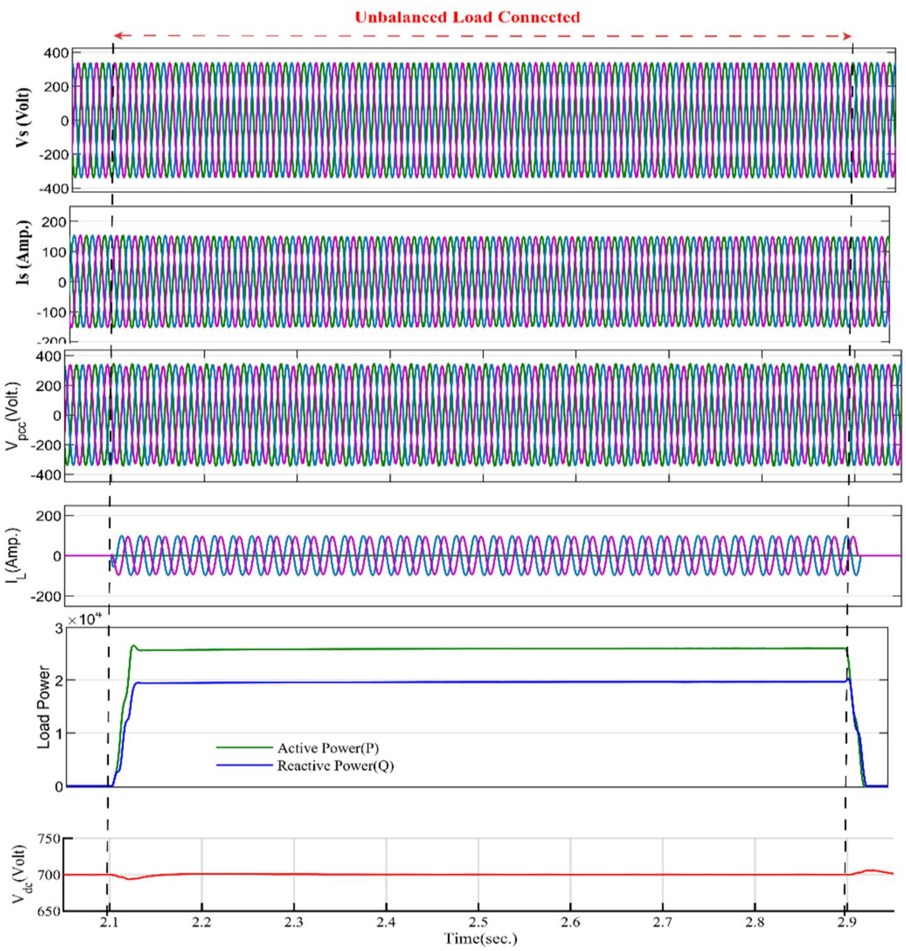

Fig.5: System performance at unbalanced loading condition

V. CONCLUSION

The proposed In-Phase Quadrature Least Mean Square (IPQ-LMS) control algorithm has been effectively implemented in a DSTATCOM system to enhance power quality under two critical load conditions: nonlinear and unbalanced loading. Under nonlinear load conditions, the algorithm significantly mitigates current distortion by accurately extracting and compensating the harmonic components of the load current. This leads to a substantial reduction in THD of the source current, achieving a value of 4.85%, which complies with the IEEE-519 standard (limit < 5%). In the case of unbalanced loading, the IPQ-LMS algorithm dynamically adjusts the reference source currents to maintain balance across all three phases, thereby achieving nearly symmetrical grid current profiles despite the unbalanced nature of the load. This results in improved the profile of voltage and current waveform PCC.

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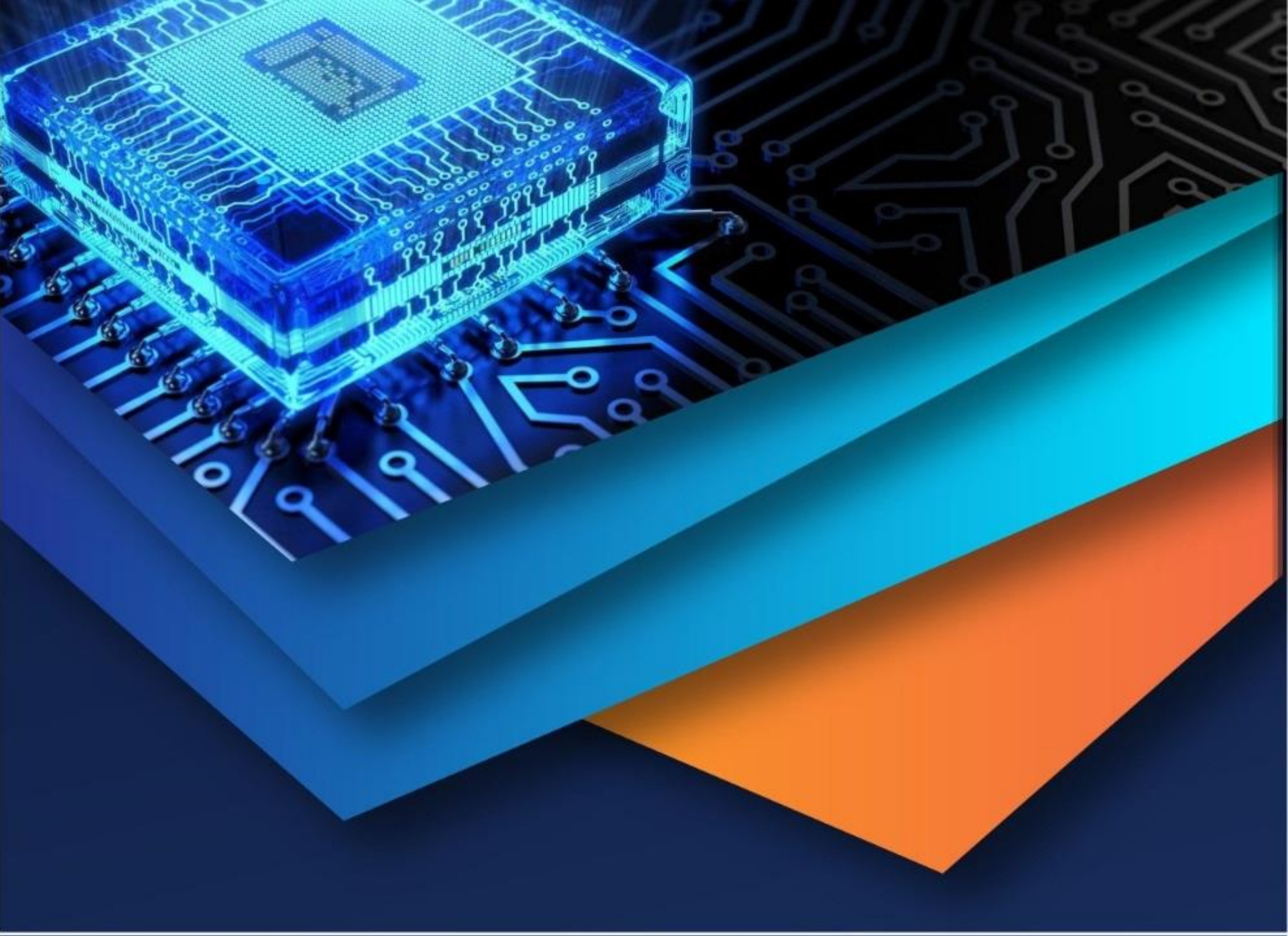

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