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Investigation and Reduction of Harmonic in Grid Connected PV Fed DSTATCOM System

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ABSTRACT- The utilization of a photovoltaic-based distribution static compensator (PV-DSTATCOM) stands out as a prominent solution for addressing energy demand deficits and power quality challenges within contemporary power systems. This article focuses on enhancing the performance of PV-DSTATCOM to facilitate grid integration and elevate power quality standards. In the envisioned system, the power from the photovoltaic array is harnessed through the utilization of the sliding mode control, ensuring the extraction of maximum power. The performance of the PV-DSTATCOM is analyzed by using a Packed U cell 5 inverter. The control signals for the voltage-source inverter are generated using PQ control scheme. The efficacy of the proposed system is substantiated through MATLAB simulation results. The outcomes presented in this article highlight the accomplished improvement in the performance of PV-DSTATCOM, ensuring concurrent advancements in current THD.

General Terms: Packed U Cell 5 inverter, PQ Reference Theory.

Keywords: Photovoltaic Distribution Static Compensator (PV-DSTATCOM), Quality of Power (QoP), Reference DC-link Voltage, Voltage Regulation.

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1. INTRODUCTION

The significant proliferation of nonlinear loads, such as power supplies for electronic devices, variable speed drives, light dimmers, uninterrupted power supply, and rectifiers, imposes a strain on the power system equipment in the contemporary world. This strain results in suboptimal performance of power system equipment, collectively contributing to the challenges faced by the power grid. The power systems supporting these nonlinear loads diminish operating efficiency, necessitating remedial measures to mitigate the consequential impact on the power system [1]. Numerous techniques have been explored and documented in the literature [2]– [3]. Moreover, technologies like the Distributed Static Compensator (DSTATCOM), Dynamic Voltage Restorer, and Unified Power Quality (PQ) Conditioner play a crucial role, with DSTATCOM emerging as a notable solution that effectively addresses prevailing PQ issues [4].

Additionally, the gap between energy demand and supply can be addressed by integrating renewable energy resources into the existing power system. In response to the current global warming concerns, nations such as the U.K., Sweden, Denmark, and Japan have reevaluated their strategies to reduce carbon dioxide (CO2) emissions by 2050 [5]. To achieve their net-zero ambitions, a substantial deployment of available green energy technologies, including solar, wind, and fuel cells, is essential.

Leading the charge for green energy investment, solar photovoltaic (SPV)-integrated DSTATCOM topologies have gained prominence in recent times, contrasting with self-supporting DSTATCOM topologies [4] [6]– [15]. The latter, documented in the literature, involves withdrawing active power from the grid to maintain the dc-link capacitor voltage. In contrast, SPV-integrated DSTATCOM topologies utilize solar energy not only to sustain the dc-link voltage but also for grid integration. This concerted effort contributes to preserving power quality (PQ) and facilitating grid integration.

Continuing this trajectory, a comprehensive literature review has been conducted on the current state-of-the-art techniques for SPV-integrated DSTATCOM. In [6], a photovoltaic DSTATCOM (PV-DSTATCOM) system is presented, extracting maximum power from PV for supplying the functional load and directing excess power to the grid. The control of the voltage-source converter (VSC) in this approach is achieved by generating load current fundamental components, synchronizing, and enhancing PQ using the same algorithm. However, the system response reveals some fluctuations in the dc-link voltage during load imbalances. In [7], a solar energy conversion system is introduced, incorporating PQ enhancement through a modified least mean square (LMS)-based technique.

In [8], an adaptive-linear-neuron-based solution is explored for VSC control in a PV-integrated grid-tied system. While it involves sensing grid voltages and load currents, it necessitates online training to extract the fundamental load component, thereby increasing control complexity. In [9], a variable step-size adaptive neuron technique is introduced to mitigate steady-state and dynamic errors observed in previous methods in the literature. Moreover, in these methods [6]– [9], the PV array is connected to the boost converter before being linked to the VSC's dc-link. This configuration contributes to increased control complexity and overall cost [10].

In response to these challenges, researchers have displayed significant interest in the single-stage Solar Photovoltaic (SPV)-integrated Distribution Static Compensator (DSTATCOM) [10]– [15]. In [10], a flexible control approach is introduced, extracting the reference grid current through a reweighted zero-attracting control technique. This system can function as a grid-connected system, incorporating DSTATCOM functions when PV generates power. Conversely, in the absence of PV array power, it operates as a classical shunt active filter. In [11], switching pulses for the Voltage Source Inverter (VSI) are generated using a second order Volterra filter, enhancing the dynamic behavior of the PV-grid integrated system during unbalanced load conditions and ensuring stable operation. It's noteworthy that the grid power transitions slightly slowly to its steady state during varying irradiance.

Additionally, in the previously disseminated literature, the voltage across the dc-link is typically regulated and constructed based on the peak voltage of the PV system, as determined by the Maximum Power Point Tracking (MPPT) algorithm, to extract maximum power from the solar PV array. However, when PV array power is unavailable, the voltage across the dc-link is often kept constant, irrespective of the functional load at the Point of Common Coupling (PCC), leading to increased switching losses [16], [17]. To address this issue, researchers have mathematically derived an expression for the minimum dc-link voltage corresponding to the connected reactive load for a hybrid active power filter [16]. In [18], the voltage across the dc-link is adaptively regulated based on the reference filter current. Nevertheless, the current Total Harmonic Distortion (THD) exhibits a slight difference compared to the conventional method discussed in this article, and the voltage across the dc-link shows some ripples. In [19], a multilevel converter is employed to redistribute the voltage across the dc-link, requiring operation in different modes.

This investigation introduces a PV-DSTATCOM in which the reference dc-link voltage is set as the peak voltage for the PV, estimated by the MPPT algorithm. However, in the absence of PV array power, the dc-link voltage is regulated based on the connected load at the PCC. The PQ technique is implemented for VSI control. The PQ reference scheme efficiently determines the reactive power demanded by the connected load compared to previously discussed control schemes, making the proposed approach well-suited to achieving its objectives. Finally, the proposed system addresses the concurrent effects of nonlinear loads on the power system and maintains THD within the IEEE standard 519-2014 [20].

The key findings of this article can be summarized as follows:

The Photovoltaic Distribution Static Compensator (PV-DSTATCOM) is realized using the PUC5 inverter.
PQ control theory is employed to generate the pulses to the voltage source inverter.

Notably, the current Total Harmonic Distortions (THDs) demonstrate improvement. *Figure 1* depicts the schematic representation of the overall proposed system,

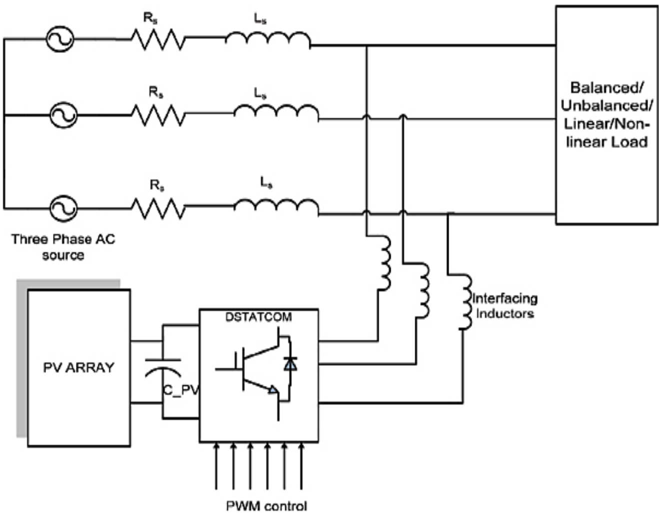

Figure 1. Schematic diagram of the proposed system

2. DESCRIPTION OF THE PROPOSED SYSTEM

The overall proposed system, as illustrated in *fig. 1*, incorporates a Distribution Static Compensator (DSTATCOM) connected to the Point of Common Coupling (PCC) of the AC grid, a Voltage Source Inverter (VSI) control technique, and a Photovoltaic-Integrated DSTATCOM (PV-DSTATCOM). The PV-DSTATCOM is interfaced with the AC network using an interfacing inductance (Lf), and to mitigate switching-induced ripples, RC ripple filters (r_{rf} and c_{rf}) are employed.

The control signals for the shunt connected VSI are generated through a comparison between the grid current (i_{gabc}) and the reference grid current (i^*_{gabc}), utilizing the PQ control technique. Notably, when Photovoltaic (PV) array power (P_{pv}) is available, an essential consideration for efficient PV-DSTATCOM operation is to extract the maximum power from the PV system (P_{pv_m}) regardless of irradiance. To achieve this, the Sliding Mode Control algorithm [21], [22] is employed.

2.1 Voltage Source Inverter and Control Technique

Figure 1 illustrates the holistic control scheme for the proposed system, employing the PQ Reference Frame control method to generate switching pulses for the Voltage Source Inverter (VSI). The comprehensive control scheme encompasses both dc voltage regulation and ac voltage regulation.

In this paper the Packed U-cell (PUC5) inverter topology is used, exploring into such as design criteria, switching techniques, voltage balancing of DC capacitors, and the ratings of switch voltages which is shown in *figure 2*.

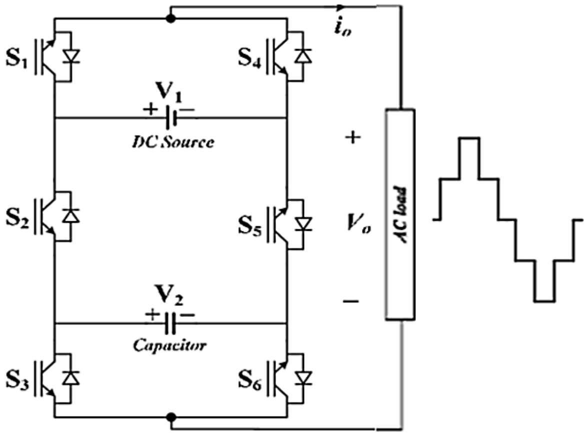

Figure 2. Packed U Cell 5 Inverter

A comparative analysis [23] is conducted between the newly introduced Packed U-cell (PUC5) inverter topology and other well-established multilevel inverter configurations, including the flying capacitor, 5-level cascaded H-bridge (CHB) and neutral point clamped (NPC). This comparison encompasses factors such as component count, voltage balancing complexity, size number of DC sources and cost and is shown in *table 1*.

Table 1. Comparison of PUC 5 with classical Multi Level Inverters

Type of Inverter **Component Count**	**Neutral point Clamped**	**Flying Capacitor**	**Cascaded H Bridge**	**PUC 5**
Capacitors	4	10	0	1
Clamping Diodes	6	0	0	0
Switches	8	8	8	6
DC Source	1	1	2	1
Size	Complex	Complex	Moderate	Small
Cost	More	More	More	Less

Assuming $V_1 = 2V_2$, it is necessary to regulate the capacitor voltage at half level, resulting in $V_2 = \frac{1}{2} V_1$. This configuration yields 5 voltage levels at the output while utilizing a single DC source.

The corresponding switching states are enumerated in *table 2.*

Table 2. Switching states of Packed U Cell 5 Inverter

State	S1	S2	S3	S4	S5	S6	Output Voltage	Va
State 1	1	0	0	0	1	1	V_1	Vdc
State 2	1	0	1	0	1	0	V_1-V_2	Vdc/2
State 3	1	1	0	0	0	1	V2	Vdc/2
State 4	1	1	1	0	0	0	0	0
State 5	0	0	0	1	1	1	0	0
State 6	0	0	1	1	1	0	0	-Vdc/2
State 7	0	1	0	1	0	1	V_2-V_1	-Vdc/2
State 8	0	1	1	1	0	0	0	-Vdc

Examining *table 2* reveals that switching states 2, 3, and 6, 7 produce the same voltage level at the output but through different paths. These redundant switching states could be incorporated into the modulation technique to achieve capacitor voltage balance at the desired level.

2.1.1 VSI Control Technique

- The current control signals for the multilevel inverter are generated based on the PQ reference [24] frame control scheme.
- MLI is realized by using a reduced switch 5 level inverter.
- The control current signals are used to generate PWM, pulses to inverter switches which is shown in *figure 3*.

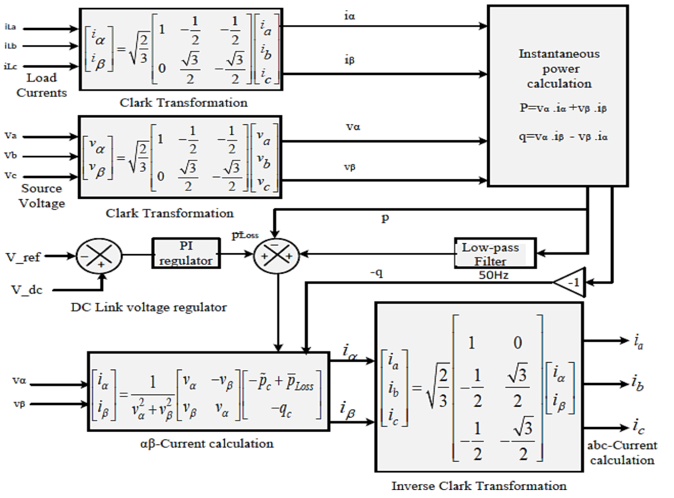

Figure 3: PWM Technique to Generate Current control signals using PQ theory.

2.1.2 PQ Theory using Clark Transformation

The Clark transformation uses three-phase currents ia, ib and ic to calculate currents in the two-phase orthogonal axis iα and iβ and three-phase voltages va, vb and vc to calculate voltages in the two-phase orthogonal axis vα and vβ

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} v\alpha \\ v\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} va \\ vb \\ vc \end{bmatrix} \qquad (2)$$

The equations for voltages and currents in two-phase orthogonal axis α and β are given below.

$$i\alpha = \sqrt{2/3}\left[ia - \frac{ib}{2} - \frac{ic}{2}\right] \qquad (3)$$

$$i\beta = \sqrt{2/3}\left[\frac{\sqrt{3}ib}{2} - \frac{\sqrt{3}ic}{2}\right] \qquad (4)$$

$$v\alpha = \sqrt{2/3}\left[via - \frac{vb}{2} - \frac{vc}{2}\right] \qquad (5)$$

$$v\beta = \sqrt{2/3}\left[\frac{\sqrt{3}vb}{2} - \frac{\sqrt{3}vc}{2}\right] \qquad (6)$$

Instantaneous Active Power

$$\text{p}= pdc + pac = v\alpha i\alpha + v\beta i\beta \qquad (7)$$

Where pdc - average value or fundamental value of instantaneous Active power

pac – Harmonic value of instantaneous Active power

Instantaneous Reactive Power

$$\text{q} = qdc + qac = -\, v\beta i\alpha + v\alpha i\beta \qquad (8)$$

Where qdc- average value or fundamental value of instantaneous reactive power

qac – Harmonic content of instantaneous reactive power

Active power and reactive power in matrix form can be represented below.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v\alpha & v\beta \\ -v\beta & v\alpha \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \qquad (9)$$

Reference currents in (α β 0) reference frame, i_α* and i_β* currents are calculated from *equation (10)*

$$\begin{bmatrix} i\alpha * \\ i\beta * \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v\alpha & -v\beta \\ v\beta & v\alpha \end{bmatrix} \begin{bmatrix} -p_c + P_{Loss} \\ -Qc \end{bmatrix} \qquad (10)$$

i_a^*, i_b^* and i_c^* calculations from i_α^* and i_β^*

$$\begin{bmatrix} i_{a*} \\ i_{b*} \\ i_c * \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha * \\ i_\beta * \end{bmatrix} \qquad (11)$$

i_a^*, i_b^* and i_c^* are compared with measured values of currents and the PWM pulses are generated to the inverter (DSTATCOM).

3. RESULTS AND DISCUSSION

The necessary switching pulses for the Voltage Source Inverter (VSI) are generated using a hysteresis band current controller, based on the reference grid current [26]. The compensation objective is to restrict the percentage of the Total Harmonic Distortion (THD) of the grid currents to within 5%.

To assess the effectiveness of the PV-DSTATCOM method proposed for the system illustrated in *fig. 1*, thorough simulations were conducted on the MATLAB platform. Detailed parameters are shown in *table 3*.

Table 3. Specifications of grid connected system with PV inverter

	Parameter	**Value**
Source voltage	Vph -Vph	400V(RMS)
	Frequency	50Hz
Line Impedance	Line Impedance	Rs=1Ω, Ls=0.1mH
Non-Linear Load	Three Phase Diode Bridge Rectifier	R=1mΩ
Filter Capacitance	Filter Capacitance	0.01µ F
Load R, L	Resistance, Inductance	8Ω,0.4mH
Solar PV	Temperature	25^0 C
	Irradiance	1000W/m^2
	Open Circuit Voltage	22.2 Volts
	Short Circuit Current	5A
DC-DC Boost Chopper	Inductance	1µ H
	Capacitance	2m F
PI Controller	Kp, Ki	0.006, 0.08

The performance of the system is analyzed and simulated considering three cases of PV-DSTATCOM

Case I: The system is analyzed for total harmonic in current on the grid side without involving any PV-STATCOM and THD is 25.91%

Case II: The PV DSTATCOM is considered and is released with a 3 leg Voltage Source Inverter and the total Harmonic Distortion on PV side and Grid side is analyzed and is 14.06%.

Case III: The PV DSTATCOM is considered and is released with a 5 level PUC Voltage Source Inverter and the total Harmonic Distortion on PV side and Grid side is analyzed and is 4.9%.

The FFT analysis of grid system in all the three cases is depicted in *figure 4* and the harmonic distortion in all the three cases is tabulated in *table 4*.

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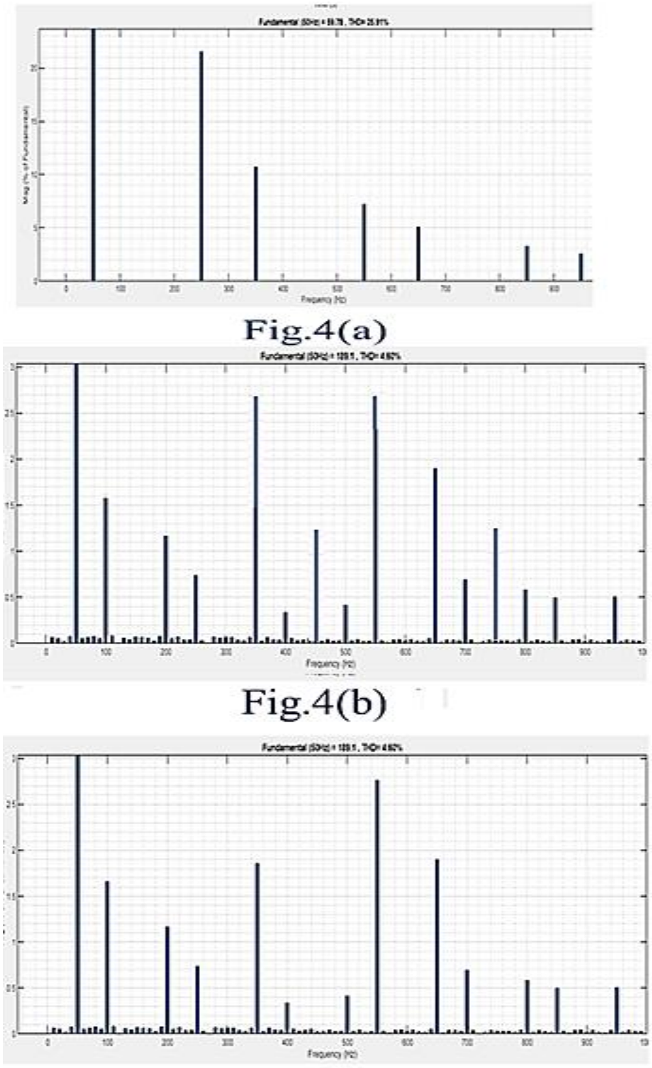

Fig.4(a)

Fig.4(b)

Fig.4(c)

Figure 4. Harmonic spectrum of Grid System (a) without Inverter (b)with 3 leg VSI as PV-DSTATCOM (c)with PUC5 as PV-DSTATCOM

Table 4. THD of Grid connected System

THD in current	Grid side source current	Inverter side current
Without PV DSTATCOM	25.91%	-
With PV DSTATCOM (3 leg inverter)	14.06%	8.70%
With PV DSTATCOM (PUC 5)	4.90%	8.02%

The performances PV-DSTATCOM depicting grid voltages (v_{gabc}), grid currents (i_{gabc}), load currents (i_{Labc}), and PVD currents (i_{PVDabc}) is simulated without and with inverter and are shown in *figure 5* and *figure 6*.

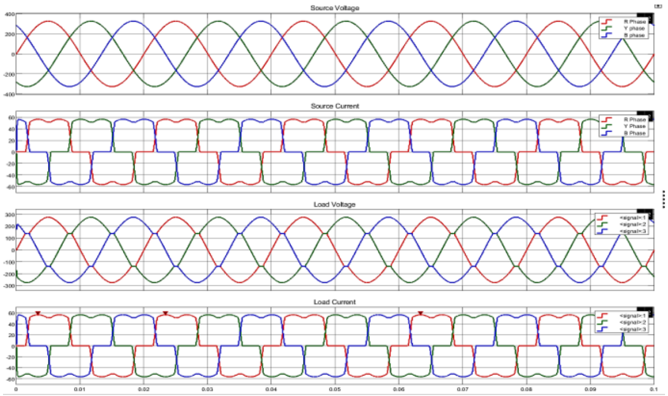

Figure 5. Source voltage, load voltage, Load voltage and load current waveforms without inverter.

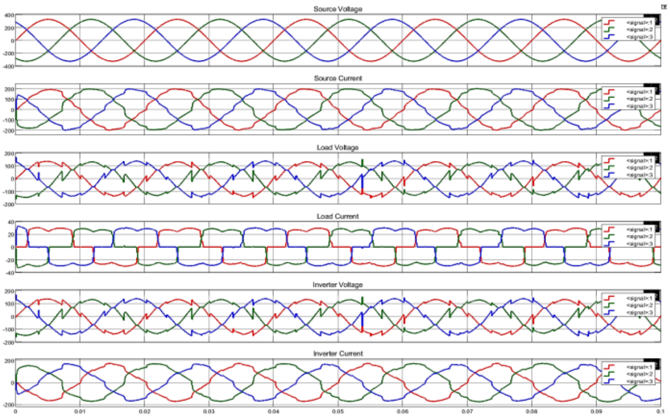

Figure 6. Source voltage, load voltage, Load voltage, load current, inverter voltage and current waveforms with inverter

The total harmonic distortion of Grid connected PV System with and without PV system is analyzed.

- The THD of the system without PV DSTATCOM is 25.91%
- The THD in grid side source current of PV inverter with 3 leg inverter is14.06% and that with PUC 5 inverter is 4.9%
- The THD in inverter side current of PV inverter with 3 leg inverter is 8.7% and that with PUC 5 inverter is 8.021%.

4. CONCLUSION

This article presents an enhanced operational framework for the unified PVDSTATCOM, meticulously detailing its functioning in the context of Power Quality (PQ) improvement and seamless grid integration.

The validity of the proposed system is confirmed by simulation results. The article thoroughly examines the system's performance highlighting a notable enhancement in current Total Harmonic Distortion (THD) by achieving a value of 4.9 %. In comparison, the PV DSTATCOM with 3 leg VSI produces a higher current THD of 14.06%.

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