Sparse quaternion-valued minimization based technique with pre-predictive PV control loop of distributed PV power generation system

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Abstract
This paper presents a sparse quaternion-valued minimization (SQVM) based control technique of a two-stage grid supportive photovoltaic (PV) power system with power conditioning capabilities. The grid side converter (GSC) is controlled by utilizing an SQVM control technique. The proposed algorithm enables the GSC to mitigate the load harmonics current and provides reactive power compensation at the point of common coupling (PCC). The proposed control is tuned to mitigate the DC offset error, harmonics current and to improve the frequency response of the proposed system. A DC link pre-predictive is incorporated to improve the dynamic response by reducing the burden on the outer Proportional-Integral (PI) voltage controller loop. Further, it is used to extract the fundamental component of load currents for generating the reference currents. An adjustable DC link voltage loop is incorporated in the proposed control technique to adapt the PCC voltage variation, which helps in minimizing the losses of the PV system. For real-time execution of the adjustable DC link voltage concept, the DC link voltage is adapted with a variation in the PCC voltage. The operation and control of the system topology are validated experimentally under various scenarios.

1 | INTRODUCTION

The complexity of the electrical grid is increasing day by day due to massive load demand and the integration of renewable energy resources (RESs) [1]. Moreover, solar energy is among the fastest-growing renewable energy sources. In addition, the solar PV systems have a great potential to assist grid power quality, especially at night when the photovoltaic (PV) array is off [2]. The generated power from the PV power system can be utilized by the consumer load and the remaining excess power can be delivered to the grid or can be stored in the energy storage systems. The power converters play a critical role in system operation as it controls the injected power to the utility grid [3–5]. The solar PV-based systems are basically divided into standalone and grid-connected PV systems [6–8]. In an islanded controlled PV inverter, energy storage (battery) is used to store the PV-generated power. Moreover, the energy management is a key task in a standalone system. However, grid integrated PV inverters are very popular compared to off-grid PV inverters because of the size and the cost of energy storage, where the grid is accessible. The power electronic converter is used to harvest the peak power from PV panel by tracking the optimum array voltage corresponding to the irradiance [7, 8]. To achieve this function, the perturb and observe (P&O) maximum power point tracking (MPPT) algorithm continuously perturbs the PV panel variables such as voltage and power and measures the differences between perturb variables ahead and subsequent to the perturbation to track the maximum power.

The power quality of the distribution grid largely depends on the characteristic and the type of load connected at the point of common coupling (PCC). Significant nonlinear loads such as electronic ballast, switch-mode power supplies (SMPS),
flourescent lamps and compact fluorescent lamps (CFLs) are utilized in household applications, and they draw the distorted current from the utility grid. The proportional-integral (PI) control [9], proportional-resonant (PR) control [10] and hysteresis control [11], are commonly used for tackling the control over harmonics due to efficient nonlinear load. The PR control is a representation of the PI control in the rotating reference frame, and it is selected because it is able to control sinusoidal references unlike the PI control, which is able to control only constant set points. Hysteresis current is a basic control that turns the output on or off based on a set point, and it is chosen because of its fast-current control response, inherent peak current limiting capability and simplicity of implementation. In [12], a comprehensive review is carried out to recognize the sources of harmonics and to come up with some cost-effective retrofit solutions for improving the power quality. In [13–15], there are a large number of control algorithms which have been reported for power quality improvement in distributed PV power systems. Here, the two-stage grid supportive PV system provides ancillary services such as compensation of non-active power, load balancing and reduction in harmonics under low generation or outage of solar power (particularly in night time, overcast and rainy weather) it functions as a compensator unit. Thus, it can provide sufficient reactive power compensation and filtering capability for harmonics mitigation. Therefore, the DC–AC power converter is utilized more effectively, and the cost of the converter is recovered in less time. In addition, the IEEE-519 specifies the guideline for the setting limits on the harmonic distortion of voltage and current [16]. The motivation of the paper is to develop and test a sparse quaternion-valued minimization (SQVM) controlled [17–19] PV power system in order to supply nonlinear loads with multifunctional at various operating conditions. Here, the beauty of this controlled approach is that it has fewer parameters as convergence width and sparsity constraints, which have a wide range of choices to generate a good response [20–22]. Therefore, it is not necessary to select exact internal parameters, which are the main demerits of existing controlled approaches. This type of distribution network interfaced PV system based on tuning of learning rates is much effective where controller inputs are varying rapidly, and the customer wants a very fast response at any instant of time. Additionally, in such situations, the SQVM approach is very effective, because this scheme is less sensitive to the variation of internal signals and also has fewer constraints [23–25]. In PV-utility interfaced power system, the harvested solar power is injected to the grid and supplied to loads by utilizing the DC link pre-predictive loop for the solar power. In addition, the grid side converter (GSC) adaptively injects the required reactive and harmonics powers at the PCC to make the grid current harmonics free and sinusoidal. Moreover, at the outage of PV generation, the distributed PV power system functions as a power conditioning unit and upgrades the utilization factor of GSC. The factors of SQVM control are modelled precisely so that the evaluated fundamental components are harmonics free while keeping a low computational burden for hardware implementation. Therefore, these coefficients play a crucial part for enhancing the steady-state, dynamic and transient responses of the grid-tied PV power system. In addition, the ripple content in the grid current is limited within IEEE-519 Std. at nonlinear load. The contribution and advantages of using the proposed system and controls are given as follows.

- In this work, a two-stage distributed PV power system is investigated. In conventional single-stage systems, at a decrease in the irradiance from 1000 W/m$^2$ to 200 W/m$^2$, there is a noticeable undershoot in DC bus voltage and oscillations in the utility currents which results in poor performance of the PV systems [26, 27].

- A pre-predictive control loop is utilized for enhancing the transient analysis and reducing the burden on PI regulator. Under abrupt change in PV insolations, the grid currents oscillate and take significant settling time in settle steady state. However, here, the pre-predictive control loop gives the information about the extracted PV power to the grid in a pre-defined way, which is developed with the help of PV power and amplitude of grid voltages.

- An adaptive DC link voltage concept is implemented, which gives flexible control over the DC link voltage dependency on the grid voltages. This concept reduces the unnecessary tripping of the grid-tied converter under a sudden change in grid voltages. It also helps in reducing the stress and switching losses across the devices.

- A fast method of convergence of fundamental weights is reported in this paper. This method has a good dynamic response as compared to the reported controllers in [13, 14]. Moreover, in the Results and Discussion section, it is shown that there are no oscillations and no amplitude overshoot in fundamental weights with dynamic loading scenarios. Therefore, it is concluded from the results that the SQVM control has improved response in weight convergence, harmonics error reduction and is effective in harmonics mitigation. The SQVM algorithm has the superior performance as compared to conventional synchronous reference theory (SRFT) and least mean square (LMS) techniques.

The paper is organized as follows. Section 2 provides the system configuration, Section 3 describes the control algorithms used for GSC and adaptive DC bus voltage concept along with the loss model of using the fixed and adaptive DC link voltages. Section 4 explains the simulation results and comparative analysis. Sections 5 provide experimental results of the distributed PV power generation system. This section also discusses the results along with providing comparative analysis of the existing algorithms. Section 6 concludes the paper.

## 2 | SYSTEM CONFIGURATION

Figure 1a shows the system topology of distributed PV power system, which is implemented in the laboratory. The GSC is fed by the PV simulator via boost converter in which the $I–V$ curve is programmed. A DC-DC boost converter is chosen for the purpose of MPPT. For DC-AC conversion, an SQVM based controlled GSC with interfacing inductor is chosen. Nonlinear
loads and for the elimination of higher-order frequency components from the utility voltage, an R-C filter, are connected at the PCC. In addition, this system offers the following advantages:

- Flexibility in control and reliability for PV power injection at grid and load ends.
- DC link voltage fluctuations are minimized under grid side voltage unbalance.
- The control scheme has reliability and flexibility while designing two-stage topology due to its having independent MPPT and grid current control strategies.

- The size, weight, and cost of the DC link capacitance are reduced as ripple is reduced.

3 | CONTROL ALGORITHMS

In this section, SQVM based control technique is used to extract the fundamental component based on the concept of sparse system recognition. In which, the input signal has various small and large harmonic coefficients along with the fundamental component. Therefore, the quaternion-valued algorithm is derived by...
estimating the norms of the adaptive weight vector. Moreover, the sparsity of the control algorithm improves the convergence speed rate without deteriorating the computational time. The proposed control establishes a norm vector in its cost function compared to the conventional control to improve the response of evaluated fundamental weights of nonlinear load with a zero-attractor loop.

3.1 Estimation of synchronizing signal using unit templates based technique

The PCC sensed line voltages \(v_{lab}, v_{lhc}\) are transformed in the phase voltage as follows:

\[
v_{la} = \frac{2v_{lab} + v_{lhc}}{3}, v_{lb} = \frac{-v_{lab} + v_{lhc}}{3}, v_{lc} = \frac{-v_{lab} - v_{lhc}}{3} \tag{1}
\]

The peak of PCC voltages \(v_{la}, v_{lb}, v_{lc}\) is calculated as

\[
V_i = \sqrt{\frac{2}{3}(v_{la}^2 + v_{lb}^2 + v_{lc}^2)} \tag{2}
\]

The in-phase unit templates \((S_{pa}, S_{pb}, S_{pc})\) are calculated using grid voltages as expressed in (3).

\[
S_{pa} = \frac{v_{la}}{V_i}, S_{pb} = \frac{v_{lb}}{V_i}, S_{pc} = \frac{v_{lc}}{V_i} \tag{3}
\]

3.2 Estimation of load current component using SQVM method

The concept of the adaptive filter with the desired output \(Y_{L,a}[n]\) and error signal \(e[n]\) is shown in Figure 1b. Moreover, for evaluation of the active weights \((Y_{L,a}, Y_{L,b}, Y_{L,c})\) of the input signal, the SQVM technique is used in all three phases, which are derived with the help of load currents \((i_{La}, i_{Lb}, i_{Lc})\) and estimated in-phase synchronizing signal \((S_{pa}, S_{pb}, S_{pc})\) as shown in Figure 1c,d. These are shown as,

\[
Y_{L,a}(n + 1) = f_{SQVM}[i_{La}(n), S_{pa}(n)] \tag{4}
\]

\[
Y_{L,b}(n + 1) = f_{SQVM}[i_{Lb}(n), S_{pb}(n)] \tag{5}
\]

\[
Y_{L,c}(n + 1) = f_{SQVM}[i_{Lc}(n), S_{pc}(n)] \tag{6}
\]

Extracted active weight of phase ‘a’ from distorted load current is expressed as follows:

\[
Y_{L,a}(n + 1) = Y_{L,a}(n) + \frac{1}{2}(\mu_a - 4\sigma_a)[e_a(n), S_{pa}(n)] + \mu_a \sim N_a f_0(n) - \frac{1}{4} \mu_a \delta_a \operatorname{sign}(Y_{L,a}(n)) \tag{7}
\]

where \(e_a\) is the error between active weight and input load current, \(\mu_a\) is the quaternion error factor, \(\delta_a\) is the weight factor and \(\sigma_a\) is the sparsity control parameters. The \(f_0\) is the cost function and \(N_a\) is matrices of quaternions.

Similarly, active weights of phases ‘b’ and ‘c’ are extracted as:

\[
Y_{L,b}(n + 1) = Y_{L,b}(n) + \frac{1}{2}(\mu_b - 4\sigma_b)[e_b(n), S_{pb}(n)] + \mu_b \sim N_b f_0(n) - \frac{1}{4} \mu_b \delta_b \operatorname{sign}(Y_{L,b}(n)) \tag{8}
\]

\[
Y_{L,c}(n + 1) = Y_{L,c}(n) + \frac{1}{2}(\mu_c - 4\sigma_c)[e_c(n), S_{pc}(n)] + \mu_c \sim N_c f_0(n) - \frac{1}{4} \mu_c \delta_c \operatorname{sign}(Y_{L,c}(n)) \tag{9}
\]

where the cost function \(f_0\) for minimizing the mean square error of active weights is given as

\[
f_0(n) = [(1 - \delta_a) \times e_a(n)] e_a^*(n) + \delta_a \| Y_{L,a}(n + 1) \| \tag{10}
\]

The sign function of \(Y_{L,a}(n)\) is defined as expressed in (11),

\[
\text{sign}(Y_{L,a}(n)) = \begin{cases} \frac{Y_{L,a}(n)}{|Y_{L,a}(n)|}, & Y_{L,a}(n) \neq 0 \\ 0, & Y_{L,a}(n) = 0 \end{cases} \tag{11}
\]

where \(\delta_a\) is a weight factor, which controls the steady state and dynamics of the estimated weight. Similarly, the cost function is defined for the other two phases of load current. The error \(e_a(n) = i_{La}(n) - [Y_{L,a}(n) \times S_{pa}(n)]\) and the conjugate form of the error between load current and fundamental weights are estimated as

\[
e_a^*(n) = i_{La}^*(n) - [Y_{L,a}(n) \times S_{pa}^*(n)] \tag{12}
\]

Moreover, the fundamental weights are a combination of the unit templates and sine wave. The net active weights of load currents are updated by reducing the instantaneous square error [19],

\[
f_0(n) = [e(n) e^*(n)] \tag{13}
\]

3.3 Estimation of PV pre-predictive loop

The pre-predictive DC link control loop is utilized in the SQVM technique to reduce the oscillations in the grid currents in response to the change of the PV power generation. It also reduces the burden on the PI controller. Therefore, the injection of generated PV power to the grid with the help of PCC voltage is mathematically computed as

\[
Y_{vpp} = 2P_{pv}/(3 \times V_i) \tag{14}
\]
The voltage PI regulator is utilized to sustain the DC bus voltage \( V_{dc} \); the mathematical computation is given as

\[
I_{\text{loss}}(n) = I_{\text{loss}}(n-1) + k_p \{ V_{dc}(n) - V_{dc}(n-1) \} + k_i V_{dc}(n)
\]

where \( I_{\text{loss}} \) is the active signal required to regulate the DC bus voltage and \( V_{dc} \) is the DC voltage error.

3.4 Extraction of utility reference currents

For the estimation of reference currents \( (i_{sa}^*, i_{sb}^*, i_{sc}^*) \) for a PV system, the net amplitude of the active signal is multiplied by the synchronizing signals. The net amplitude of the active signal is computed as

\[
Y_{p,\text{net}} = Y_{p,\text{avg}} + Y_{\text{loss}} - Y_{p,\text{vp}}
\]

The reference utility currents are calculated as

\[
i_{sa}^* = Y_{p,\text{net}} \ast u_{pa}, \quad i_{sb}^* = Y_{p,\text{net}} \ast u_{pb}, \quad i_{sc}^* = Y_{p,\text{net}} \ast u_{pc}
\]

3.5 Estimation of PWM pulses for GSC

To estimate PWM signals for GSC, current errors are extracted from the difference between reference utility currents \( (i_{sa}^*, i_{sb}^*, i_{sc}^*) \) and sensed grid currents \( (i_{sa}, i_{sb}, i_{sc}) \). The extracted signals are supplied to hysteresis current controller to turn on the GSC.

3.6 Adaptive DC bus voltage concept

An adaptive DC bus voltage loop is suggested instead of a fixed DC-link structure, which helps for minimization of GSC switching losses and unnecessary tripping caused by low voltage of the distribution network. It also supports in minimization of ohmic losses by minimizing the ripple content across the interfacing inductor. The stress across IGBT switches is reduced by adjusting DC link voltage as per PCC voltage \( (V) \). Here, 10% overshoot and undershoot in the grid voltage is considered. Therefore, the formulation development of DC-link
voltage structure is given as

$$V_{dc}^* = \sigma \sqrt{3} V_t$$  \hspace{1cm} (18)

where $\sigma$ is an adaptive factor and its value is between 1.1 and 1.2. Therefore, this factor accommodates the ohmic losses, GSC tripping and switching losses of GSC.

Figure 2a presents the DC link voltage model for conventional SRF control. Here, it is observed that the extracted PV array energy and loss component is carried by the PI controller. However, load component ($I_{ld}$) is estimated using the conventional SRF technique. In Figure 2b, the load feed-forward component ($Y_{pavg}$) is estimated using the SQVM technique and extracted PV power is handled by the PV pre-predictive loop unlike the conventional algorithm. Therefore, the loss component and PV power are separated, reducing the burden on the PI regulator. The pre-predictive loop predicts the injection of solar energy in the grid. There is an active power balance between the extracted PV power and the injected grid power on considering the lossless GSC. Hence, the pre-predictive loop is derived as

$$P_{pp} = P_{grid}$$  \hspace{1cm} (19)

The power balanced in term of voltage and current is as

$$V_{pp} I_{pp} = 3 V_p I_p = \frac{3 V_{rms} I_{rms}}{2}$$  \hspace{1cm} (20)

$$I_{pp} = \frac{2 P_{pp}}{3 V_t}$$  \hspace{1cm} (21)

where $I_{pp}$ is the predictive current injected to the grid.

The DC link control for power stored in the capacitor is given as

$$C_{dc} \frac{d V_{dc}}{dt} = (I_{pv} - I_{rms})$$  \hspace{1cm} (22)

$$[V_{dc}^* (n + 1) - V_{dc} (n + 1)] = \frac{T_f}{C_{dc}} [I_{pv} (n + 1) - I_{rms} (n + 1)]$$  \hspace{1cm} (23)

$$I_{rms} (n + 1) = [I_{pv} (n + 1) - \frac{C_{dc}}{T_f} [V_{dc}^* (n + 1) - V_{dc} (n + 1)]]$$  \hspace{1cm} (24)

As the net extracted energy is equal to the power injected to the grid. Therefore, from Equation (21), the net predictive estimation is illustrated as

$$I_{pp} = \frac{2 V_{dc} (n + 1)}{3 V_t (n + 1)}$$

$$\times \left[ I_{pv} (n + 1) - \frac{C_{dc}}{T_f} \left[ V_{dc}^* (n + 1) - V_{dc} (n + 1) \right] \right]$$  \hspace{1cm} (25)
FIGURE 4  (a,b) Response under sudden change grid voltage. (c,d) Response at change in operating modes (a) PV to DSTATCOM (b) DSTATCOM to PV system
TABLE 2  Grid and load measurements

| Components     | Utility grid measurement | Load measurement |
|----------------|--------------------------|-------------------|
| Voltage        | 93.9 V                   | 5.51 A            |
| Current        | 85.7 V                   | 1.92 A            |
| Active power   | −892 W (power injected   | 275 W (power       |
|                |    to the grid)          | consumed by the   |
|                |                          | load)             |
| THD            | Grid voltage = 0.8%,     | Load current = 22.6% |
|                | Grid current = 4.8%      |                   |
| Power factor   | −0.994                   | 0.967             |

Therefore, the grid expects the power injection in predetermined levels for the next sampling period. Moreover, DC link voltage is also fixed between the allowable range during the step change in PV irradiance.

4  SIMULATION RESULTS

In this section, the simulation results of the proposed system are shown to validate the effectiveness of the control technique. The MATLAB software tool is used for simulating the behaviour of the SPV system under various working scenarios. Under this section, the effectiveness of PV pre-predictive loop, the concept of adaptive DC link voltage, the change of operational mode, and the usefulness of the SQVM technique compared with the conventional control technique are demonstrated. The steady-state and the dynamic performances of the proposed system are illustrated in response to the changes of the grid voltage, PV power, as well as load variation. The loss model under grid voltage variation for fixed and adaptive DC link is shown in Figure 2c. The fixed DC link voltage is selected as 750 V. However, adaptive DC link voltage is decided with the help of the amplitude of grid voltages. It is observed from the loss model that under fixed DC link voltage, the injected power to the grid is 9.5 kW under grid voltage dip. However, power injected to the utility with adaptive DC link voltage concept is 10 kW, which means a system with adaptive DC link voltage injects more power as compared to fixed DC link voltage. Moreover, a comparative analysis for various components is shown in Table 1. The system specifications are given in the Appendix.

4.1  Comparative analysis with and without PV pre-predictive control loop

Figure 3a shows the comparative analysis of the proposed algorithm with and without including PV pre-predictive control loop during the operation of utility interfaced PV supportive system.

Performance is analyzed as grid voltage (\(V_g\)), grid current (\(i_g\)), DC link voltage (\(V_{dc}\)), and output of DC. Here, the control loop is used to mitigate the oscillations in the grid currents and overshoot/undershoot due to the occurrence of dynamic changes such as variation in PV isolations. Figure 3a presents the operation of the system without pre-predictive control loop under the occurrence of fast PV radiation changes from 500 to 1000 W/m² at 0.3 s. Here, the dynamic response is slow and grid currents have taken 2–3 cycles to reach the steady-state conditions. Moreover, the DC link voltage is also not regulated and under sudden variations, there is an increase in the voltage around 50 V. The stress on the PI controller is also shown here. Without the pre-predictive loop, net harvested power from the PV array is passed through the PI controller. Moreover, under a change in
insolations, there is a change in the output of the PI controller, which deteriorates the dynamic response of the PV system.

Figure 3b illustrates simulation results with a pre-predictive loop. Here, it is observed that when the system works with the pre-predictive loop, there is no change in the DC link voltage and the power carried by the PI controller is almost zero, which indicates less burden on the PI controller and the pre-predictive loop is responsible for the injection of active power to the grid along with the improved dynamic response.

### 4.2 Adaptive DC link voltage concept under variations in grid voltages

The behaviour of the PV-based distributed system is examined at unanticipated variations in the amplitude of utility voltage as shown in Figure 4a. Generally, in grid-connected converters the DC link is kept constant, corresponding to the amplitude of utility voltages. However, here the adaptive DC bus voltage phenomenon is utilized at overvoltage and undervoltage to avoid unnecessary tripping of GSC and to reduce the switching losses of GSC. Moreover, the amount of ripple in the grid currents is also reduced by regulating the DC bus voltage. Therefore, at a change in PCC voltages, the utility currents are enlarged to inject constant power at sag condition. Nevertheless, the adjustable DC link voltage is decreased as the amplitude of utility voltage is reduced, which shows the adaptive nature of DC bus voltage. In these operating scenarios, the extracted PV energy is sustained to its respective value. Moreover, at an increase in PCC voltage, a vice versa effect is observed in Figure 4b.

### 4.3 Change of mode of operation

Figure 4c,d shows the change of operating modes of the PV system from PV to DSTATCOM and DSTATCOM to PV. The operating modes are changed without any interruption of load power. In Figure 4c, till 0.5 s, the PV array has supplied the power to the grid as well to the loads.

Therefore, the grid currents are out of phase with grid voltages, which confirms that the power is being fed to the distribution system. However, in the night-time or when insolation is not available then without any disturbance, the proposed system has worked as DSTATCOM.
Under such condition, the load starts drawing power from the grid and grid currents are in phase with the grid voltages, which confirms the unity power factor operation of the PV system. Figure 4d presents the change of operation from DSTACOM to PV generated mode. Till 0.5 s, grid currents are in phase with the grid voltages as the load is consuming power from the grid. However, after 0.5 s, the PV array starts supplying power to the grid as well to the loads. Therefore, the grid currents are out of phase with the grid voltages.

4.4 Comparative investigations of traditional and SQVM control techniques

Figure 5a presents the investigation of traditional and SQVM controller under sudden variation in nonlinear load. The performance of SQVM-based technique is presented as grid voltages ($v_g$), load current of phase ‘a’ ($i_{La}$), error in frequency ($\omega_{er}$), estimated frequency ($\omega_0$) and extracted fundamental component ($i_{fLa}$). The variations in the evaluated frequency using conventional techniques are more under steady-state and load perturbation. Hence, accuracy is significantly enhanced by using the proposed technique. The evaluation of active power signal ($Y_{PLa}$) using the proposed SQVM-based control, SRF and LMS controls are also presented in Figure 5b. It is noticed that $Y_{PLa}$ attains zero and a steady-state shape is attained within a cycle, under the load thrown from 0.4s to 0.7s. However, the evaluated $Y_{PLa}$ with the traditional technique takes 3 to 4 cycles to settle zero and in steady state. Therefore, it is observed that steady-state and dynamic responses of SQVM based techniques are good, as well as quick as compared to traditional techniques.

5 EXPERIMENTAL RESULTS

A prototype of distributed PV power generation system with solar array and DC-AC converter along with its control technique has been implemented using DSP (dSPACE-1103). The proposed system is modelled using MATLAB simulink and simpower system toolboxes. The sensed signals are fed to analog to digital (ADC) converter of DSP and digital I/O communications are utilized to acquire the switching pulses of GSC. The data used in the experimental prototype is presented in the Appendix. The developed prototype along with DSP (dSPACE-1103), the characteristics of PV array are obtained by utilizing the DC programmable power supply, which is depicted in Figure 6a.

5.1 Steady-state response with balanced non-linear load

Figure 6b–6d presents the constant power injection to the utility with addressing power quality issues. Figure 6b shows the
The THDs of utility current is less than 5% with 22.6% harmonics in load current, which illustrates harmonic-rejection features of SQVM algorithm. The test results show that load current is compensated by GSC to make the grid current sinusoidal.

5.2 Dynamic operation at load and insolation change

The behaviour of the distributed generating system at load connection and disconnection are shown in Figure 7b. The operation is proven by showing grid current ($i_{g}$), load current ($i_{L}$), GSC current ($i_{G}$), and change in DC link voltage ($V_{dc}$). Under sudden connection of nonlinear load, the extracted power from the renewable source is shared between the load and grid. Hence, the grid current is reduced. Moreover, before the load connection, the compensation of load is not required, therefore, the GSC current is sinusoidal. However, after the load connection, GSC carries both active as well as harmonics power needed by the load. The change in DC link voltage is not more than 10 V, which shows the good controllability of the proposed algorithm. The vice-versa effect is realized in Figure 7b.

Figure 7c presents the experimental results of the distributed generating system at the sudden change in PV power. Under the unavailability of the PV array, the grid voltage and grid current are in-phase, which means the nonlinear load is drawing power from the grid. However, as the PV power appears more than the load demand, the grid current becomes out of phase, which means power is injected into the utility grid, and at these dynamic solar insulations, the quality of energy is always sustained. Under the regeneration of solar power, GSC carries the harvested power from the solar array as well as harmonics components.

5.3 Estimated control signal of the proposed algorithm under dynamic conditions

Figure 8a,d shows test results of the SQVM technique at dynamic load conditions to analyse the transient behaviour of the algorithm. The intermediate signals are settled in a few cycles, which shows the good dynamic behaviour of SQVM
6 | CONCLUSIONS

In this paper, the experimental response of the proposed distributed PV power system has been demonstrated to enhance the power quality due to efficient nonlinear load. The improved SQVM controller has provided power quality improvement and solar power injection into the distribution network. Its accuracy and response speed under sudden load disturbances have been found satisfactory. The distributed PV system has also demonstrated the features of grid currents balancing, power factor correction, and harmonics reduction to meet the IEEE 519 standard, at various operating scenarios. This enabled the optimum operation of the distributed PV system as a DSTATCOM and vice-versa in low-irradiance periods, enhancing the system utilization. The adaptive DC link and pre-predictive control have shown good performance over the conventional algorithm. Hence, the essential objectives have been obtained, namely, error-free evaluation of fundamental weight signal, feeding of active power to the grid, adaptive DC link and mitigation of load harmonic current.

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**TABLE A1** PV system symbols and parameters

| Parameter                      | Value                        |
|--------------------------------|------------------------------|
| Rated PV Power $P_r$           | 1.5 kW                       |
| Boost inductance $L_b$         | 10 mH                        |
| Nominal AC voltage $V_s$       | 100 V, $f = 50$ Hz           |
| DC link capacitor ($C_{dc}$)   | 1052 $\mu$F                 |
| Ripple filter $R_f$ and $C_f$  | 4 $\Omega$, 8 $\mu$F        |
| Interfacing inductors          | 3 mH                         |
| Switching frequency            | 10 kHz                       |
| Nonlinear load parameters      | $R_L = 20$, $L_L = 100$ mH   |
| DC voltage PI controller       | $k_p = 0.7$, $k_i = 0.01$    |
| SQVM controller parameters     | $\sigma = 0.02$, $\mu = 0.8$ and $\delta = 0.05$ |
| Sampling time                  | $T_s = 10$ ms                |