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Harmonic mitigation and power quality improvement in utility grid with solar energy penetration using distribution static compensator

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Abstract

Distribution static compensator is based on power electronic devices technology which is utilized to supply rapid changes in active power as well as reactive power of utility grids. This is useful to achieve corrections in power factor, balancing of load, compensation of current and filtering of harmonics. Therefore, proposed work investigates the improvement of the power quality by utilizing the distribution static compensator, which is equipped by battery energy storage system and interfaced to distribution network with solar photo voltaic (PV) energy integration. In the present study, distribution static compensator is controlled using a control strategy based on the synchronous reference frame theory. Customised IEEE-13 nodes test system incorporating solar PV generation and distribution static compensator, is utilized to perform the harmonic mitigation and power quality analysis. Disturbances of power quality and harmonics have been investigated due to abrupt changes in the insolation of solar radiation, outage of PV plant from grid and synchronization of PV plant to grid. MATLAB/Simulink environment is utilized to perform the study. Effectiveness of a developed approach is validated by comparing results of simulation with results extracted in real time using real time digital simulator. Results indicate that the developed method is more effective for harmonic mitigation and improving power quality of electrical power in distribution network integrated with solar PV generation. Performance of the approach is compared with the performance of methods reported in the literature to establish the suitability of the method for harmonics mitigation and power quality improvement in grid with solar energy.

1 | INTRODUCTION

In recent years, renewable energy (RE) sources have captured global interests among academic institutions, industries, and governments due to their numerous advantages for improving energy reliability, efficiency, and minimizing carbon emission [1, 2]. RE resources like wind energy and solar photovoltaic (PV) are extensively used for generation of power at the grid level due to their capability of minimum impact on the environment, sustainability, zero fuel cost, minimum operation cost of the plant, and pollution-free electricity generation [3, 4]. The solar

PV energy has merits over the wind energy, such as its quiet operation and capability to be harvested easily in the residential areas. It has main disadvantages of non-availability during night hours and variable output with the time of day [5]. Grid integration of RE sources into the utility grid leads to issues of technical and economic nature in PQ field, reliability, harmonics, voltage stability, control, and protection. Large scale integration of RE sources to the utility grid also affects frequency control and allocation of reserves [6]. Integration of PV into the grid causes problems related to operation due to intermittent behaviour of these sources. It affects the frequency/load

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control, unbalancing of voltage levels, unbalancing of current levels and load following in the utility network. It further leads to the PQ problems like poor power factor, voltage disturbance, flicker and harmonic distortions [7].

Different signal processing techniques including wavelet transform (WT), Stockwell transform (S-transform), Fourier transform (FT), Hilbert Huang transform (HHT) and short time Fourier transform (STFT) have been utilized for recognizing PQ disturbances related to the grid interfaced PV systems. Various method utilized to detect PQ disturbances are presented in [8]. To detect islanding and recognize PQ disturbances in RE integrated hybrid system because of load rejection using WT and S-transform has been reported in [9]. Recognition of PQ disturbances related to grid interfaced 100 kW PV plant using discrete WT has been presented in [10]. Urbanetz *et al.* [11], has presented PQ analysis for grid integrated solar PV systems in Brazil utility network. Sinvula *et al.* [12], presented a study for harmonic analysis in grid with solar PV system integration where total harmonic distortion of voltage (THD_v) and current (THD_i) as high as 5.5% and 29.6% respectively have been observed. A method to assess the PQ events associated with grid interfaced RE sources is reported in [13]. This is focussed to assess PQ issues with a low computational burden during high RE penetration issues in distribution system. A study for assessment of PQ issues associated with the grid integrated wind power plants is detailed in [14].

The active and passive filters are used for improving PQ with RE sources integrated into the utility grid. A detailed description of various PQ improvement techniques has been reported in [15]. Study of the PQ improvement in 3-phase grid tied PV system using BESS has been introduced in [16]. Energy storage technologies for maximizing PV penetration into the grid addressing PQ have been investigated in [17].

Nowadays, custom power electronic technology based devices like dynamic voltage restorer (DVR), DSTATCOM, and unified power quality conditioner (UPQC) are widely utilized for improving PQ in RE sources based hybrid grid [18]. DSTATCOM is capable of controlling the voltage at the point of common coupling (PCC) with grid in flexible manner, which helps in PQ improvement. If a BESS is designed to be incorporated in parallel to DC bus capacitor, then DSTATCOM gains the capability of exchanging both active and reactive powers with grid. Above discussed power variations are mitigated in [19] by variation of amplitude and phase angle of converter voltage relative to the terminal voltage of the line. This helps for improving the dynamic performance of systems by voltage regulation and frequency control. BESS also enhances the capacity of DSTATCOM which achieve load balancing, compensation of reactive power, and elimination of harmonic currents. In [20], authors proposed a design of hybrid grid incorporating wind energy, solar energy, loads, BESS and conventional generator for minimizing the effects of grid disturbances. Minimization of power generation variability due to the variable nature of RE sources is achieved using DSTATCOM.

Implementation of DSTATCOM for improving PQ for individual applications like solar PV generation, wind generation, water pumping system, load compensation, and residential low

voltage network, has been reported in the literature. However, few studies are available focussed on the use of DSTATCOM for addressing improvement of PQ for grid integrated PV plant. Implementation of DSTATCOM controlled by adaptive neural network supported control method for suppression of harmonics, balancing of load, and regulation of voltage in isolated distributed generation system has been presented in [21]. Shahnia *et al.* [22], has described the use of DSTATCOM for the circulation of excess power in the medium and low voltage DN interfaced with the 1-phase renewable power generation system. Mahela *et al.* [23], presented a method for improving the quality of power using DSTATCOM incorporated with BESS in hybrid utility grid RE penetration using simulation studies. The aforementioned literature review clearly indicates the research gap that needs to be properly addressed for future smart grids with the high level of penetration of solar PV plants.

After critically reviewed the above discussed research, it is observed that different techniques are reported for the recognition of PQ events in the utility grid, interfaced with the RE sources. Further, existing research also focussed on the study of PQ disturbances associated with the constraints of converter design used in grid interfacing of solar PV panels. Improvement of the PQ in the presence of RE sources is studied in case of the isolated operation of solar PV plants. PQ improvement during the operational events in the presence of solar PV plant integrated with a utility grid is considered in this paper, which is the extension of the previously published research work [23]. The main contributions of this paper are as follows:

1. Propose the utilization of the DSTATCOM equipped with BESS, in 3-phase distribution network integrated with solar PV plant to mitigate the power quality issues occurred due to grid synchronization of the solar PV plant, outage of solar PV plants from grid and variation in insolation of solar radiation.
2. Apply SRF theory supported controlling technique to control the DSTATCOM. Results shows that it is easily implemented at the grid level in the availability of solar PV plants for reducing the THD level below 5% as specified in IEEE-519 standard. Harmonic mitigation up to 90% has been achieved against the 60% achieved in [23].
3. Simulation Results are validated in real time by RTDS. It is established that real time results are comparable to simulated results with an error in the range of 1% to 2%.
4. Performance of the proposed approach is further validated by comparing the results with that reported in literature.

2 | TEST SYSTEM

The customized IEEE-13 node network is used for implementing the developed method. In original, test system is rated at 5 MVA, 60 Hz and a radial feeder of distribution network operating on 4.16 kV and 0.48 kV voltage levels and supplying power to loads of balanced as well as unbalanced nature [24, 25]. This test feeder has been modified to incorporate a 500kW solar PV plant and a DSTATCOM with BESS as described in Figure 1.

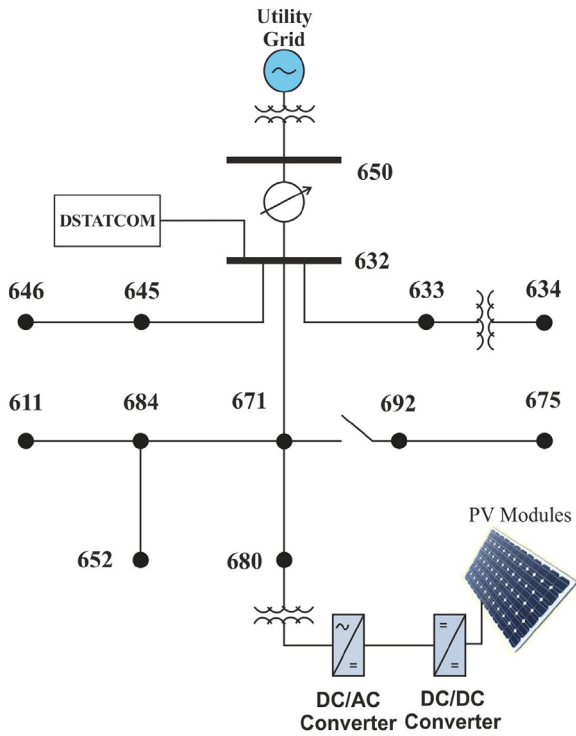


FIGURE 1 Test system

In Indian power system, the PV plants are installed in the remote areas due to the availability of low cost land and integrated to the grid by a localized network constructed for integration of RE sources to the grid. Therefore, in the proposed study, bus 680 is utilized for PV integration in the modified system through the transformer (XSPV). Further, bus 650 is used for connecting this localised network to grid through substation transformer. For providing compensation to the grid disturbances, DSTATCOM associated with BESS is utilized that rapidly supplied and absorbed the active and reactive powers. Therefore, DSTATCOM is installed in parallel with bus 632 where the system's disturbances are reduced at the integration point of the test system to grid. The underground cables among the buses 692 and 675 in addition to buses 684 and 652 uses configuration 606. All the overhead distribution lines designed according to 601 configuration. All feeders are three phase and all loads considered in this network are three phase and balanced. Table 1 describes the status of the loading of the modified test system. Transformer separating the buses 633 and 634 is designated as XFM-1. Transformer data is presented in Table 2. The modified system omitted the voltage regulator integrated amid nodes 650 and 632 of the original feeder. The switch amid nodes 671 and 692 is realized with the help of three poles circuit breaker (CB). Feeder lengths are considered the same as used in the standard system.

The positive and zero sequence capacitances of simulated overhead line are respectively 1.57199 nF/km and 1.3398 nF/km. These capacitances pertaining to the configuration 606 are the same and equal to 15.96979 μ F/km. As per type of feeder's conductor and topology, matrices of series impedance

TABLE 1 Load-data of the system under consideration

Nodes	Type of Load Model	Load		Capacitor (kVAr)
		kW	kVAr	
634	PQ/Y	400	290	
645	PQ/Y	170	125	
646	PQ/Y	230	132	
652	PQ/Y	128	86	
671	PQ/Y	1155	660	
675	PQ/Y	843	462	600
692	PQ/Y	170	151	
611	PQ/Y	170	80	100
632-671	PQ/Y	200	116	

of feeders of test network (Ω /km) with configurations 601 (Z_{601}) and 606 (Z_{606}) are presented by the following relations [21, 26]:

$$Z_{601} = \begin{bmatrix} .2149 + .6319i & .0970 + .3120i & .0979 + .2629i \\ .0970 + .3121i & .2098 + .6509i & .0949 + .2389i \\ .0979 + .2629i & .0949 + .2389i & .2119 + .6429i \end{bmatrix} \quad (1)$$

$$Z_{606} = \begin{bmatrix} .4959 + .2768i & .1984 + .0210i & .1769 + .0090i \\ .1977 + .0202i & .4910 + .2509i & .1979 + .0203i \\ .1768 + .0090i & .1979 + .0202i & .4958 + .2780i \end{bmatrix} \quad (2)$$

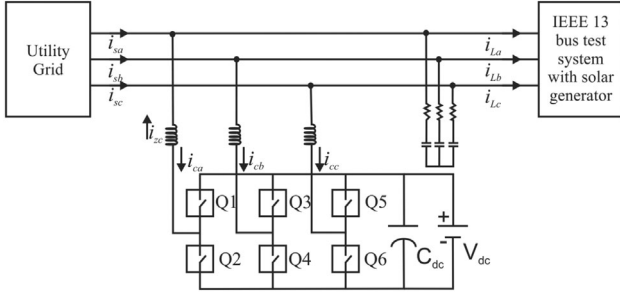
The PV system comprised of 5 units, with the rating of 100 kW for each one, and connected in parallel. The generated DC voltage from each PV unit is 273.50 V. The power generated is supplied to boost converter (DC-DC) that enhanced the voltage to 500 V. Power from boost converter is supplied to an inverter that converted the DC nature power into AC nature power, at 260 V voltage level. To mitigate the harmonic components from the inverter's output, a filter is utilized that comprising of a resistance of 0.5 $m\Omega$ and inductance of 50 μ H connected in series and a capacitance of capacity 50 $kVAr$, connected in parallel. XSPV is utilised to integrate the inverter's output to the system.

3 | MODELLING OF DSTATCOM AND PQ IMPROVEMENT STRATEGY

DSTATCOM is a shunt type device using voltage source inverter (VSI) based technology and supported by a DC link capacitor used to store short term energy. It is utilized to compensate distortions and load unbalancing such that balanced sinusoidal currents flows through the feeder at which it is connected [27]. Further, it is effective to improve the PQ of RE

TABLE 2 Transformers-data of the studied System

Trans.	MVA	High-kV	Low-kV	HV Winding		LV Winding	
				R(Ω)	X(Ω)	R(Ω)	X(Ω)
Substation	10	115	4.160	29.0950	211.599	.1139	.8306
XFM-1	5	4.16	.480	.3810	2.7677	.0509	.0042
XSPV	1	4.16	.260	.1729	195.700	.0008	.7645

**FIGURE 2** Proposed distribution static compensator supported by BESS

integrated grid supply and helps to increase RE integration into the grid [28]. Authors in [29] presented a study of various topologies and controlling techniques of DSTATCOM. The proposed DSTATCOM topology and controlling methods are described in the following subsections.

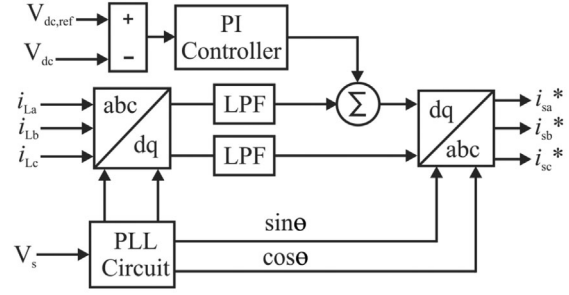
3.1 | DSTATCOM

A 3-phase 3-wire DSTATCOM having 3-leg topology and supported by BESS interfaced in shunt with DC-link capacitor is proposed to improve the PQ in DN, which is integrated with the PV system as shown in Figure 2. Each leg of the DSTATCOM consists of two power switches connected in series. Each switch is designed by the series combination of four insulated gate bipolar transistors (IGBTs), interfaced with anti-parallel diodes to achieve the desired DC bus voltage level of 7000 V. On-state resistance of the switch is considered equal to $1m\Omega$. This is integrated to node 680 of modified test system. It consists of elements including DC link capacitor, ripple filter, VSI, inductor (AC type) and BESS. It is working on the concept that by varying voltage magnitude of inverter output and phase angle difference amid node voltage and output voltage of inverter, reactive and active powers can be varied [30]. This power exchange can be expressed by the following relations:

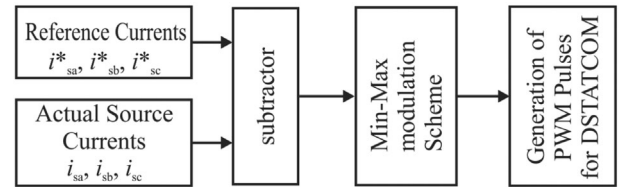
$$P = \frac{V_{pcc} V_c \sin\alpha}{X} \quad (3)$$

$$Q = \frac{V_{pcc}(V_{pcc} - V_c \cos\alpha)}{X} \quad (4)$$

where V_c is the inverter voltage; P indicates active power exchange; Q represents reactive power exchange; V_{pcc} is the volt-



(a)



(b)

FIGURE 3 Synchronous reference theory based control technique. (a) Block scheme representation of SRF for control of DSTATCOM (b) PWM signal generation block scheme

age at PCC; α is the angle of V_{pcc} relative to V_c ; X is reactance of both transformer and branch collectively.

This paper considered the design value of the DC link capacitor of value $10,000 \mu F$ which is calculated using the relations reported in [31]. The design value of AC inductor is selected as $40 mH$ using the relations reported in [32]. The resistance and inductance of the ripple filter are taken as 0.1Ω and $10 \mu F$ respectively, which are based on the constraints reported in [33]. Voltage of the battery energy storage system is kept at $7000 V$ and calculated using the relations reported in [34]. Design relations and parameters of DC link capacitor, AC inductor, DC link voltage, ripple filter resistance and inductance are included in the Appendix section.

3.2 | Method for Controlling of DSTATCOM

It is controlled by using SRF theory supported control method. Block schemes of SRF control method and pulse width modulation (PWM) signal generation for gating of DSTATCOM used in the proposed study are detailed respectively in Figure 3(a) and (b) [35, 36]. SRF based control method is selected due to reasons

TABLE 3 Performance of SRF Control Techniques

S.No.	Attributes	Performance of SRF control method
1	Compensation of reactive power	Good
2	Mitigation of harmonics	Good
3	Balancing of load	Average
4	Elimination of source neutral current	Good
5	Computational complexity	Average
6	Cost involved	Low
7	Implementation procedure	Easy and simple

mentioned in Table 3 [29]. SRF control technique is effective in harmonic mitigation and PQ improvement. It can be easily implemented with low cost.

SRF theory is implemented by transformation of currents in $d-q$ frame rotating synchronously. Clarks transformation is utilized for converting 3-phase recorded currents into 2-phase currents (i_α, i_β) in a frame which is stationary in nature. For converting these currents from stationary frame to $d-q$ frame components (i_d, i_q) , Parks transformation is utilized, which is shown in following relations [37]:

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (5)$$

where θ represents transformation angle.

For extraction of DC components from each of the i_d and i_q current components, a low pass (LP) filter is utilized. These current components provide the controlling of active and reactive powers [38]. The inverse Parks transformation is used to transform back the generated reference DC currents i_{ddc} and i_{qdc} into $\alpha-\beta$ frame by utilizing the following relations [39]:

$$\begin{bmatrix} I_{\alpha dc} \\ I_{\beta dc} \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} I_{ddc} \\ I_{qdc} \end{bmatrix}. \quad (6)$$

These currents are used for obtaining the 3-phase reference source currents into $a-b-c$ coordinated by utilizing the following relation [40]:

$$\begin{bmatrix} I_{sa}^* \\ I_{sb}^* \\ I_{sc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_{\alpha dc} \\ I_{\beta dc} \end{bmatrix}. \quad (7)$$

For generating the pulse width modulation (PWM) pulses, currents of reference source are compared to source cur-

rents recorded in controller (hysteresis). Hysteresis controller is employed due to its simplicity and robust nature. But the drawback of this controller is its variable switching frequency, which results in the generation of variable ripple frequency that is mitigated by the use of a ripple filter. Generated pulses are effectively used to provide switching of DSTATCOM. The detailed depiction of the control algorithm is available in [36].

3.3 | Power quality improvement strategy

A DSTATCOM with BESS is integrated to the modified IEEE-13 nodes test network at bus 632. A PV system of capacity 500 kW is integrated at the bus 680 of modified test feeder using a CB. Voltage measured at node 632 and currents injected into a utility network test system are monitored continuously using a controller based on SRF theory for the generation of the error signal. The generated error signal depends on variations in the actual values of the current and voltage signals. This error signal is used for gating of the IGBTs of the voltage source converter (VSC) by generating PWM signals. This helps to achieve the controlling of power exchange among the DSTATCOM and PCC. Therefore, the DSTATCOM with BESS using SRF theory controlling can efficiently be employed for improving the quality of electrical power.

4 | RESULTS RELATED TO PQ ENHANCEMENT AND THEIR DISCUSSION

The results related to the PQ enhancement in the DN with PV integration by utilizing DSTATCOM which is associated with BESS are presented in this section. Power supplied by utility into the test network and utilized by load is taken as positive.

DSTATCOM supported by BESS behaves as an active and reactive power generating source when power flows out of it whereas the same behaviour as load when power is absorbed by it. Following relation expresses the active power supplied by DSTATCOM (P_d).

$$P_d = P_l - P_s \quad (8)$$

where, (P_s) represents the grid power and (P_l) represents the load.

Positive sign is assigned to P_d when power is flowing from DSTATCOM towards load. However, the negative sign is considered for power flow in reverse direction. In similar fashion, the following relation is used to express the reactive power (Q_d) supplied by DSTATCOM. Here, (Q_s) and (Q_l) respectively represent reactive power supplied by utility and consumed by load.

$$Q_d = Q_l - Q_s. \quad (9)$$

Positive sign is assigned to Q_d when reactive power flows from DSTATCOM towards grid. However, the negative sign

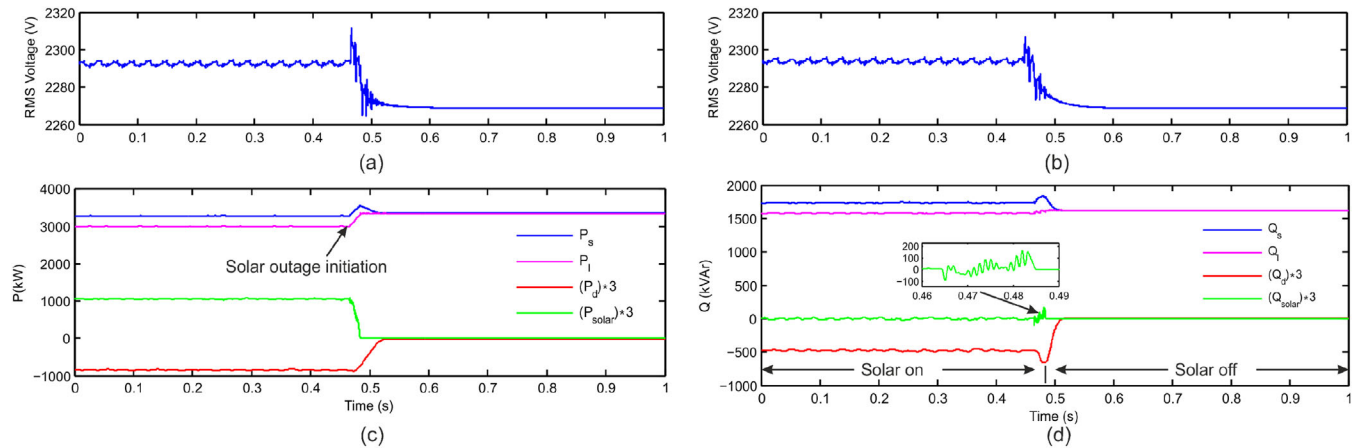


FIGURE 4 Outage of PV plant (a) voltage with the unavailability of DSTATCOM (b) voltage signal with the availability of DSTATCOM (c) flow of real power with the availability of DSTATCOM (d) flow of reactive power with the availability of DSTATCOM

is considered for reactive power flow in reverse direction. In absence of PV system, there is no power exchange by the DSTATCOM. During the events of grid synchronization, PV system outage and abrupt variation in insolation of solar radiation, power exchanges will be made by DSTATCOM. This work investigated the PQ during the above mentioned events. Further, compensation of active power, compensation of reactive power and compensation for harmonics have also been investigated under all above mentioned events. For the proposed study, voltage of bus 632 is measured.

4.1 | Outage of solar PV plant

Outage of PV system from the test network is carried out by opening the CB used to integrate PV system on the bus 680 at 0.47 s. RMS value of the voltage at bus 632 in absence and presence of DSTATCOM is illustrated correspondingly in Figure 4(a) and (b). Active and reactive powers flow in the test system incorporated with DSTATCOM are depicted correspondingly in Figure 4(c) and (d). This is seen that voltage at the time of solar PV outage rises to 2312 V from 2295 V and then decreases to a minimum voltage of 2265 V without DSTATCOM and finally it settles at 2270 V during the time solar PV is switched off as illustrated in Figure 4(a). Presence of DSTATCOM with solar PV outage raises the voltage at the time of solar PV outage to 2305 V from 2295 V and then it reduces to 2270 V during the time solar PV is turned off as depicted in Figure 4(b). Hence, improvement in voltage peak by 41% is achieved using DSTATCOM. Transient in the voltage during solar PV outage is also reduced significantly by using DSTATCOM as detailed in Figure 4(a) and (b). From Figure 4(c), it is evaluated that surplus active power available with PV generation stores energy in BESS and capacitor of DC-link charging. Though, active power provided by the PV system and power drawn by DSTATCOM decreased to zero at time of PV outage. Variations of low frequency are also available in active power at the moment of PV system outage. From Figure 4(d), it is pointed out that surplus

reactive power available has been absorbed by the DSTATCOM to charge the capacitor whereas reactive power is not delivered by the PV because it generated the DC power. After the PV outage, the reactive power is not absorbed by the DSTATCOM. However, a transient event in the reactive power is observed due to the outage of the PV system. This is due to the reactive compensation provided to the PV by the use of a capacitor.

The harmonic analysis of voltage waveform measured at the node 632 is evaluated using a fast Fourier transform (FFT). Total harmonic distortions in voltage (THD_v) without DSTATCOM is calculated as 5.50%, whereas availability of DSTATCOM reduced THD_v to 3.73%. Hence, a reduction of 37.63% in values of (THD_v) is obtained by the application of DSTATCOM with BESS.

4.2 | Synchronization of PV system to Test Network

Event of PV plant grid synchronization is simulated by connecting the CB, which is used for integrating PV system at 0.52 s. Figure 5(a) and (b) respectively illustrated voltages at node 632 without and with DSTATCOM. Furthermore, the flow of active and reactive powers in presence of DSTATCOM are correspondingly represented by Figure 5(c) and (d). From these figures, this is concluded that maximum voltage deviation at instant of grid synchronization of PV plant without DSTATCOM is 10 V (0.4402%), whereas with DSTATCOM, the voltage deviation is reduced to 7 V (0.3083%). Therefore, the improvement of 29.96% in the voltage deviation is obtained by the implementation of DSTATCOM with BESS. Active as well as reactive powers supplied to test network by substation transformer are decreased due to the availability of PV power generation at load end. Thus, DSTATCOM absorbed surplus power flows at this time duration. Transient powers have appeared with the flow of active power as well as reactive power for a time period of 1s as detailed correspondingly in Figure 5(c) and (d).

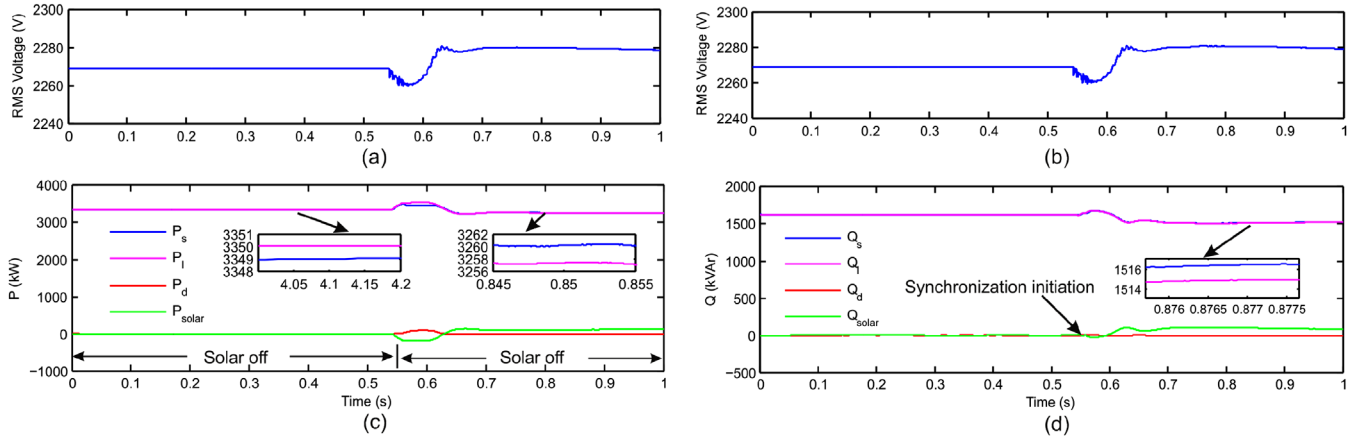


FIGURE 5 Grid integration of PV plant (a) voltage signal with the unavailability of DSTATCOM (b) voltage signal with the availability of DSTATCOM (c) flow of real power with the availability of DSTATCOM (d) flow of reactive power with the availability of DSTATCOM

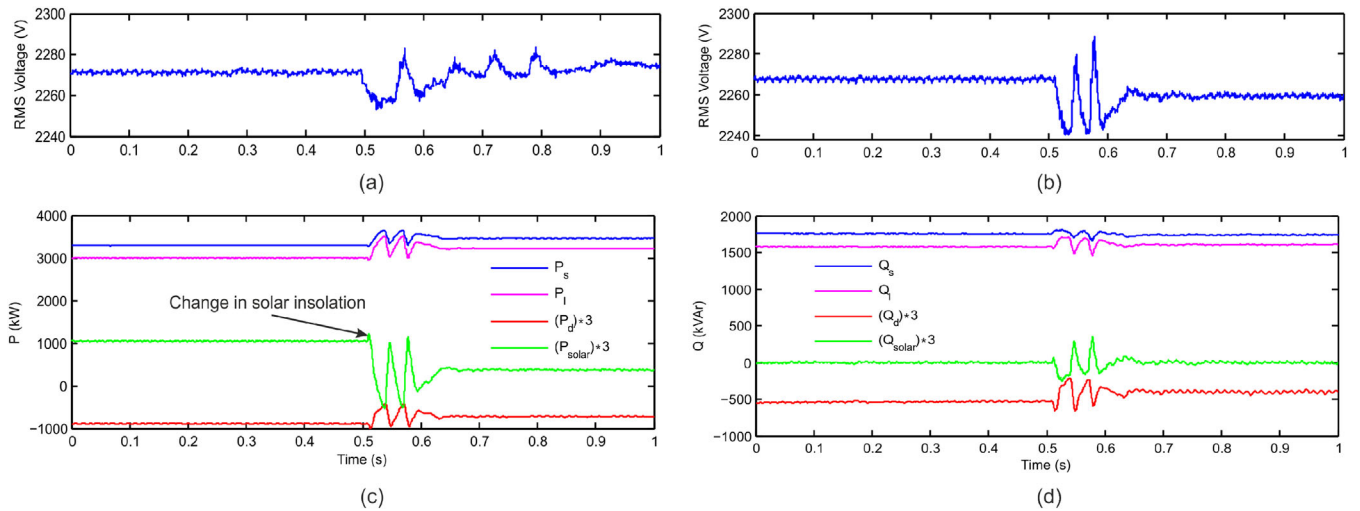


FIGURE 6 Abrupt change in the solar insolation (a) voltage signal with the unavailability of DSTATCOM (b) voltage signal with the availability of DSTATCOM (c) flow of real power with the availability of DSTATCOM (d) flow of reactive power with the availability of DSTATCOM

By harmonic analysis, the value of THD_v without DSTATCOM is computed as 2.59%. Utilization of the DSTATCOM minimized the value of THD_v to 0.20%. Therefore, an improvement in the value of THD_v has been achieved by 92.28%.

4.3 | Variation in Solar Insolation

In this case, the solar insolation is minimized suddenly from a value of 1000 W/m^2 to 600 W/m^2 at 0.5 s and observed the effect on PQ due to presence and absence of DSTATCOM. Fig 6(a) and (b) illustrated voltages at bus 632 in unavailability and availability of the DSTATCOM respectively. Power flows (reactive and active) in the availability of DSTATCOM are correspondingly depicted in Fig 6(c) and (d). This is concluded from figures that the voltage transients are observed for long duration in the unavailability of DSTATCOM whereas these transients are limited to 0.15 s in the availability of DSTATCOM associated

with the BESS as illustrated in Figure 6(a) and (b). Therefore, reduction in voltage transients is observed with the implementation of DSTATCOM. From Figure 6(c) and (d), it is concluded that deviations appeared in power flows (both active and reactive) for time period of 0.012 s following the sudden changes in the solar insolation. From Figure 6(c), this is concluded that power generated by PV plant is decreased due to the reduction in solar insolation and consequently the power taken by DSTATCOM is also reduced. Active power and reactive power taken by DSTATCOM for storage have been reduced with a reduction in the solar insolation. Therefore, this is observed that DSTATCOM in association of BESS is an effective solution for compensating active and reactive powers because of abrupt solar insolation changes.

Harmonic evaluation of voltage signal measured on node 632 at the time of sudden variation in solar insolation is carried out by using FFT. The value of THD_v in the unavailability of DSTATCOM is found as 6.62%. Use of the DSTATCOM

TABLE 4 Total Harmonic Distortion with PV generation

Case studies	THD_v (%) at bus 632		
	Without DSTATCOM	With DSTATCOM	Improvement in THD_v (%)
Outage of solar PV generator	5.50	3.43	37.63
Grid synchronization of solar PV plant	2.59	0.20	92.28
Change in solar insolation	6.62	3.73	43.65

interfaced with BESS has reduced value of THD_v to 3.73%. Therefore, an improvement in THD_v is obtained by the amount of 43.65%.

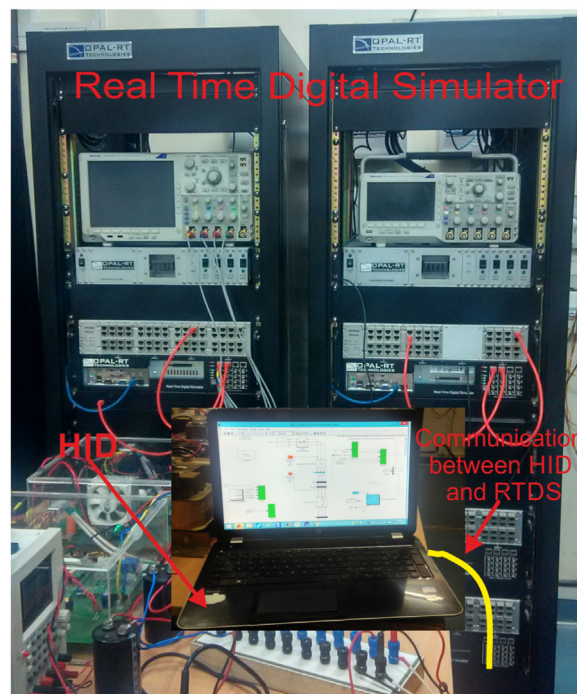
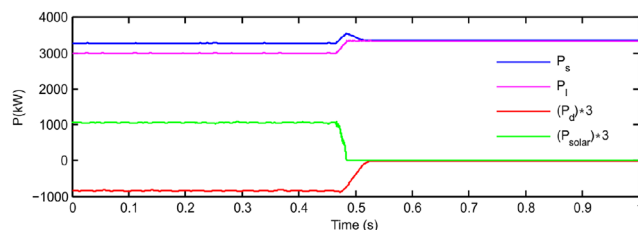
4.4 | Analysis of THD with and without DSTATCOM

Improvement in THD_v is achieved due to exchange of active and reactive power between DSTATCOM and PCC. During the event of high energy disturbances such as spikes, impulsive transient (IT) etc., energy is absorbed by the DSTATCOM and magnitude of such disturbances is reduced. This energy will be supplied to PCC to mitigate the effects of low energy disturbances such as voltage sag and momentary interruption (MI). The comparative study of THD_v with PV integration to the grid during different cases of study is tabulated in Table 4. This is inferred that DSTATCOM associated with BESS is very much efficient to reduce the harmonics developed because of PV integration with Distribution grid. Maximum improvement is THD is observed to be equal to 92.28% during the event of grid integration of Solar PV plant and minimum equal to 37.63% during the event of outage of solar PV plant from the grid.

5 | VALIDATION OF RESULTS IN REAL TIME

The RTDS of OPAL-RT, performs simulation of complex energy conversion systems using averaged MATLAB models in real time. The output results are comparable to the results obtained by the hardware prototype. It effectively validates the results in real time with high accuracy compared to the results obtained by hardware set-ups. RTDS uses fixed step integration technique and capable to achieve accuracy for a time step which ranges from $10 \mu s$ to $100 \mu s$. RTDS interacts with human interface device (HID) (Laptop in present study) in this experimental set up. The HID is an input device of the RTDS. The configuration of the Laptop used as HID has operating system of 64-bit, 4 GB RAM, processor of Intel (I) Core (TM) i5-3230M CPU@2.60 GHz. Figure 7 presented the experimental setup utilized in this work.

The IEEE-13 node test feeder interfaced with solar PV plant and DSTATCOM supported BESS is modelled on HID using MATLAB/Simulink 2011b software and uploaded in RTDS on ML605 target. This modelled network is processed and run on the RTDS (in hardware synchronization mode) with ML605 target which operates in real time scenario and gives results which

**FIGURE 7** Developed experimental set up**FIGURE 8** Real time results of active power flow during the event of solar PV outage

are as good as hardware results. Data are recorded using the OpWrite module of RT-Lab in the ML605 target and again send back to the HID devices. To communicate between HID (laptop) and RTDS, ethernet communication is utilized. The real time results recorded can be analysed using the laptop in offline mode. MATLAB plot window is utilized to plot recorded data. This is inferred that results in real time are close to corresponding simulation results.

Figure 8 describes the real time results of active power supplied by the source, solar PV system, consumed by the load and exchange with the DSTATCOM supported by BESS

TABLE 5 Comparison of Real Time and Simulation Results based on THD

Case studies	THD_v (%)		Percentage error (%)
	With DSTATCOM (Simulation)	With DSTATCOM (Real time)	
Outage of solar PV generator	3.43	3.42605109	0.115
Grid synchronization of solar PV system	0.20	0.19640827	1.796
Change in solar insolation	3.73	3.72016207	0.264

during the event of solar PV system outage in the availability of DSTATCOM. It is established that these real time results are very close to the respective simulation results for this event described in Figure 4(c). Further, the algorithm is also tested for the synchronization event and variations of the solar insolation. It is observed that real time results are close to the simulation results for these events. Therefore, proposed DSTATCOM can effectively be implemented for harmonic mitigation and PQ improvement along with compensation of active and reactive powers in the distribution network.

THD_v of voltage measured on bus 632 is obtained for all the cases of study using RTDS in the availability of DSTATCOM supported by BESS and presented in Table 5. Comparison of results obtained from RTDS with simulation results are presented and error percentage amid results is calculated. Error percentage, E , is calculated by the equation as given below:

$$E = \left(\frac{SR - RT}{SR} \right) * 100\% \quad (10)$$

where SR indicate simulation results, and RT represented results in real time.

From the table 5, it is clear that results in real time are similar to respective results of simulation. Error percentages for THD_v results are less than 1% for the cases of PV plant outage and abrupt changes in insolation of solar radiation. Similarly, percentage of error for THD_v is less than 2% for the case of grid integration of the PV system. Closeness of real time results with the simulation results establishes the effectiveness of the proposed method. Therefore, it is concluded that SRF theory depended control algorithm for DSTATCOM associated with the BESS is effective for improving PQ at the grid level with the PV integration during the events like grid synchronization, PV system outage and sudden variation in insolation of solar radiation.

6 | PERFORMANCE COMPARISONS

The maximum THD_v is recorded with outage of solar PV plant which is equal to 5.5%. This is compared with the study reported in [12] where THD_v recorded at PCC of test system was also 5.5%. Hence, the study proposed in this paper is validated by the study reported in [12]. Further, proposed SRF controlled DSTATCOM supported by BESS is effective in reduction of THD as low as 0.20% in the event of grid synchronization. This is low compared to the THD reported at

PCC in reference [3] by the use of an efficient energy management approach with grid integrated electric vehicle battery (EVB) charging system, solar PV system an energy storage system (ESS) equal to 3.1%. Further, by the use of DSTATCOM the improvement in THD level is achieved up to 60% with RE penetration in reference [23]. However, the THD improvement up to 90% has been achieved in the present study. Hence, it is established that the proposed method of SRF controlled DSTATCOM supported by BESS is effective in harmonic mitigation and PQ improvement in utility grid where solar energy is penetrated.

7 | CONCLUSION

This paper investigated the PQ disturbances related with DN during the operations of PV plant like grid integration, PV system outage, and abrupt variation in the insolation of solar radiation. A grid is developed using IEEE-13 node test network by incorporating DSTATCOM supported by energy storage, solar PV plant and conventional power plant to depict the scenario of RE integration to the Indian power system. For harmonic mitigation and improvement in the quality of electrical power in above discussed events, the DSTATCOM incorporated with energy storage (BESS) is developed and interfaced to developed IEEE-13 bus grid. SRF theory supported controlling of DSTATCOM is established to be efficient for harmonic mitigation and improving PQ of electrical power at the grid level during the investigated events. Based on the presented study, it is concluded that DSTATCOM associated with BESS using SRF controlling can be efficiently used for harmonic mitigation and improving PQ in the DN integrated with PV plant. RTDS is utilised to prove the simulation results in real time environment and to compute the results as close as hardware results. Minimum error between the real time and simulation results as low as 1.7% indicates the effectiveness of the algorithm. Performance of the algorithm is compared with the existing methods in terms of recognition as well as mitigation of the harmonics and PQ disturbances. It is observed that harmonic levels have been improved up to 90% by implementing the proposed method with solar energy penetration in the utility grid. Hence, based on the real time results which are in close proximity to results of simulation and better performance compared to methods reported in the literature, it is concluded that proposed DSTATCOM incorporated with energy storage (BESS) using SRF controlling strategy is effective in harmonic mitigation and improving PQ in distribution network integrated with

PV plants. Hardware, validation of results would be considered as the future work.

NOMENCLATURE

kW	kilo-watt
MVA	mega volt-ampere
Hz	hertz
kV	kilo-volt
kVAr	kilo volt-ampere reactive
Ω	ohm
km	kilo meter
μH	micro-henry
V_c	inverter voltage
α	angle between PCC and converter voltages
X	reactance
V_{pcc}	voltage at PCC
P	active power
Q	reactive power
mH	milli-henry
μF	micro-farad
cm	centi-meter
θ	angle
THD_v	total harmonic distortion of voltage
THD_i	total harmonic distortion of current
C_{dc}	dc link capacitor
t	time
L	inductance
a	overload factor
f	frequency
m	modulation index

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APPENDIX A

The capability of VSC to control the voltage during transients decides the design of DC link capacitor (C_{dc}). For maintaining the load at the time of transients, DC link capacitor supplies or absorbs active power. Factors such as minimum and maximum battery voltages and instantaneous energy available to the DSTATCOM at the time of transients decide the value of the capacitor. Energy conservation principal is follow during the selection of DC link capacitor values and it is presented by the following relation:

$$\frac{1}{2}C_{dc}[V_{dc}^2 - V_{dc1}^2] = 3V_aIt. \quad (\text{A.1})$$

Where, V_{dc1} represents the value of DC bus minimum voltage, V represents the phase voltage, t represents the time required to recover the DC voltage, and I represents the current of phase. By selecting $V_{dc1} = 6970V$, $V_{dc} = 7000V$, $V = 2.402kV$, $I = 486A$, $t = 350\mu s$, and $a = 1.2$, the DC capacitor computed value is approximately $7000 \mu F$.

Interfacing inductor (L_f) is placed in circuit on AC side of 3-leg VSC among VSC and PCC. Voltage drop across the interfacing inductor is kept higher than 8%, for making operation of DSTATCOM successful. The following relation presented the design value of L_f .

$$L_f = \frac{\sqrt{3}mV_{dc}}{12af_sI_{cr(p-p)}} \quad (\text{A.2})$$

where, f_s represents average switching frequency, V_{dc} represents voltage of DC bus, a represents over voltage factor, and $I_{cr(p-p)}$ represents the peak to peak current ripple. By selecting, $I_{cr(p-p)} = 2.5\%$, $V_{dc} = 7000V$, $f_s = 10kHz$, $a = 1.2$, and $m = 1$, the computed value of L_f is $34mH$.

In this work, ripple filter consists of high pass first order filter, tuned at half of the switching frequency and integrated series resistor (R_f) and capacitor (C_f). In the system, it is connected in parallel and filtered out the noises from voltage at PCC. As compared to the fundamental time constant (T), the time constant of the ripple filter is very small and represented by the following relation

$$R_fC_f \ll T/10. \quad (\text{A.3})$$

Design values of $R_f = 0.1\Omega$ and $C_f = 10\mu F$ are used in this study. Vdc of DSTATCOM is given by the following relation

DC link voltage (V_{dc}) of DSTATCOM is given by the following relation.

$$V_{dc} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} \quad (\text{A.4})$$

where, m represents the modulation index and AC line voltage at PCC is represented by the V_{LL} . Calculated magnitude of V_{dc} is $6793V$ for $m = 1$ and $V_{LL} = 4.16kV$. For the satisfactory operation of the system, DC link voltage is kept higher as compared to the twice of the peak value of the phase voltage of AC system.