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Neutral Current Compensation in grid tied Solar PV-BES Utility System using Four Leg VSC based DSTATCOM with SRF Control Strategy

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***Abstract-** In this proposed work, Synchronous Reference Frame (SRF) based control algorithm is used in Photovoltaic (PV) grid integration through Distribution Static Synchronous Compensator (DSTATCOM) with Battery Energy Storage (BES) system for simultaneous mitigation of power quality issues and for real power injection. In order to makeover the issues in the quality of power in the system by compensating neutral current, asymmetrical loads in the four wire three phase nonlinear and unbalanced load distribution system. The highest power of PV is tracked using Incremental Conductance (Inc) method and the voltage of DC bus is preserved by Bidirectional DC-DC Converter (BDDC). The proposed system works as PV-DSTATCOM mode which performs DSTATCOM operation by improving power quality with the capability of transferring the generated PV power to the consumers and Grid, and in BES-DSTATCOM mode it supplies power to the utility load. The proposed system is implemented and modeled for 11kV/440V utility system. The results have been obtained using sim power system tools in MATLAB/SIMULINK environment.*

***Keywords:** DSTATCOM, SRF, Voltage Source Converter (VSC) Point of Synchronization (POS), Neutral Current Compensation, Non-Linear Load and Unbalanced Load.*

I. INTRODUCTION

The increasing trend in the use of renewable source energy leads to decline in use of traditional source of energy in all fronts. At present, the majority of the research is concentrating on exploitation of distributed generation instead of traditional methods. Energy production is based on renewable sources due to environmental friendly nature, increasing prices, global warming and there is a fast movement towards clean energy [1,2]. The difficulties associated with the varied nature of solar intensity could be overcome by addition of Battery Energy Storage system into the PV connected utility system. Thereby improving the reliability of the system. For extraction of peak PV power, the Maximum Power Point Tracking (MPPT) algorithm is considered [3]. The incremental conductance method of MPPT algorithm [4] is used in this system to extract the peak PV power through a boost converter. schematic diagram of the power network tied Solar PV-BES-DSTATCOM system is as shown in Fig.1. Integration of distributed generations (DGs') in distribution lines improves the distribution network quality of power due to the constriction of harmonics in fundamental waveforms of voltage and current. Sinusoidal grid current or source current, increment of reactive power requirement by load, unbalanced phase, downturn of power factor, harmonic content are some of the instances of power quality issues [5]. These issues may affect the efficiency and life span of generation, continuity of power supply to the consumers etc,. Power quality issues arise due to connection of nonlinear loads. The unbalanced source voltage may lead to negative sequence current, reduction in torque in case of electric machine, and underneath components of harmonic in the power network [6].

In the present situation in the distribution network, lot of nonlinear loads are connecting everyday due to extensive use of semiconductor devices based electronic equipment. In order to cope up with issues arising due to quality of power several Custom Power Devices (CPDs') are being used. These CPD's are being used to mitigate for almost all the PQ issues for smooth control of voltage and current in the power network. The Custom Power Devices are such as Distributed Voltage Regulator (DVR), Distributed Static Compensator (DSTATCOM), and Unified Power Quality Conditioner (UPQC) [7]. These devices compensate for the issues emerging due to quality of power like voltage sag, swell, current harmonics, voltage imbalance, voltage distortion etc,. An improved version of shunt connected active filter is named as DSTATCOM, mainly focuses on load balancing, retrieval of reactive power and harmonics mitigation at the synchronization point. The active power transfer capability of power networks reduces due to increase in reactive power. It must be reduced by using DSTATCOM control strategy. More successful utilization of DSTATCOM relies on following points. Extraction of reference supply current using control algorithms. The differences in reference current of respective phases are measured and the output taken as different switching signals.

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[5,8]. Several control algorithms have been reported for such operation as per references [9-15]. The reference supply currents are calculated by using SRF control theory (Id-Iq) [9,14], Recursive Digital Filter Based Control Algorithm [10], Adaptive RLS technique[11], The algorithm based on Leaky Least Mean Fourth(LLMF) is given on[12], Variable Step Size - Least Mean Square (VSS-LMS) algorithm is explained in reference [13], Adaptive Linear Neural Network (ADLINE) based Least Mean Square (LMS) for DSTATCOM [15]. The Adaptive Neural Network (ANN) based a four-legged DSTATCOM for counterbalancing the neutral current and linear/non-linear loads by using VSC has been presented in the reference [16].

The literature survey of various techniques to resolve the power quality issues have been done as per the above. The works like ANN based a four legged DSTATCOM for counterbalancing the neutral current using VSC and SRF control theory have motivated to propose this work.

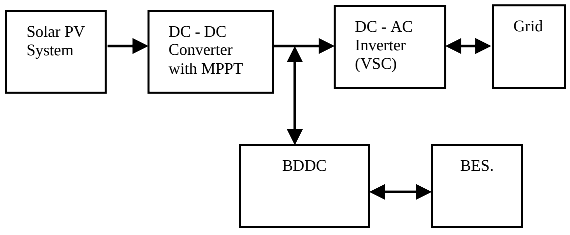

Fig. 1.Block diagram of Solar PV-BES-DSTATCOM system.

In this work, in order to compensate for source and neutral current the DC bus voltage is controlled by using four leg VSC along with BES BDDC. The SRF based algorithm and Proportional Integral Controller (PIC) is utilized in the DSTATCOM. The reactive power, neutral current and harmonics due to unbalanced and nonlinear loads are alleviated by interconnecting the DSTATCOM at Point of Synchronization (POS). In this proposed work 11kV/440V distribution transformer with Delta-Star connection having neutral brought out is taken into consideration for analysis. The proposed methodology uses MATLAB/SIMULINK software for simulation and verifying the results. The organization of this paper is done as follows; system configuration is detailed in Section-II, control strategy is represented in Section-III, the results & discussions are given in Section-IV and the conclusion is narrated in Section-V.

II. SYSTEM CONFIGURATION

The circuit configuration of 3-phase 4-wire distribution network having PV-BES system is depicted in Fig.2. The Solar PV array of 118 kW tied to grid through 4-leg VSC with interconnecting inductors feeding 3-phase unbalanced and nonlinear loads. The voltage ripples are reduced by connecting ripple filters. The PV-BES system with boost converter is used for tracking MPP, the BDDC is to control the charging and discharging of battery, and also to control the DC link voltage of VSC. The development of system parameters with PV array have been done by adopting the methods as mentioned in [5,17] with Incremental Conductance as MPPT algorithm.

D-STATCOM is connected to the 3-phase AC source and loads (nonlinear & unbalanced) in parallel. The nonlinear loads consisting of 3-phase uncontrolled diode rectifier with resistive and inductive components. This load increases the harmonic content, reactive power consumption, unbalance in all the phases and power factor deterioration. L_s and R_s represent the source inductance and source resistance ofAC mains. The value of Ls and Rs should be kept low because it can draw large current. AC 3-phase source voltages are V_{sa}, V_{sb} and V_{sc} and 3-phase source currents are i_{sa}, i_{sb} and i_{sc}. The nonlinear load currents are I_{La}, I_{Lb} and I_{Lc} . They have been modeled as uncontrolled bridge rectifiers and set of resistance and inductance. V_{dc} is the internal DC bus capacitor voltage, connected at the DC side of an IGBT based VSC. L_f (Interfacing inductors) is connected at the AC side of IGBT based VSC for decreasing voltage and current ripple in the compensating current coming through VSC. Ripple filter modeled with R_f & C_f (R_f and C_f are connected in series) is connected at the POS in parallel with load. The bus voltage switching noises have been filtered using ripple filters at the POS. I_{ia}, I_{ib} and I_{ic} are the compensating current injected by IGBT based VSC to POS for surpassing the effect of harmonics and reactive power component of non-linear load. The eight IGBT switches of 4-leg VSC based DSTATCOM are S1, S2, S3, S4, S5, S6, S7 and S8. In order to regulate the DSTATCOM, SRF based control algorithm is utilized. The SRF control algorithm extracts the reference source current and further this current is compared with the source current. The PWM (Pulse Width Modulation) controller is incorporated to produce switching pulses to IGBT.

III. CONTROL STRATEGY

The present system comprises of MPPT control for PV, BDDC control for Battery Energy Storage and SRF control algorithm for DSTATCOM. All these control strategies have been discussed in this section.

A. *The MPPT Control*

Here, the most important consideration in the system is to elite the peak power from the PV array corresponding to the changes in the level of irradiation. In this present system an Incremental Conductance (Inc) based MPPT control strategy has been adopted for MPP tracing. The mathematical formulation of this control strategy is presented using the below mentioned expressions.

$$\frac{dP}{dV} * MPP = \frac{d(VI)}{dV} \quad (1.1)$$

$$\frac{dI}{dV} * MPP = -\frac{I}{V} \quad (1.2)$$

In this algorithm two sensors are used for the measurement of solar PV arrays voltage and current. The PV curve slope comes to zero at the point of MPP.

The PV array instantaneous conductance is at the left hand side. The MPP has been attained only when the instantaneous conductance matches with the conductance of the solar. The error due to change in solar intensity is almost decresed to zero, as both voltage and currents are sensed.

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B. *SRF Theory based Control Technique for Four Leg VSC*

In this work, to control the 3-phase 4-leg VSC based DSTATCOM the SRF control technique has been used and is shown in Fig.3.

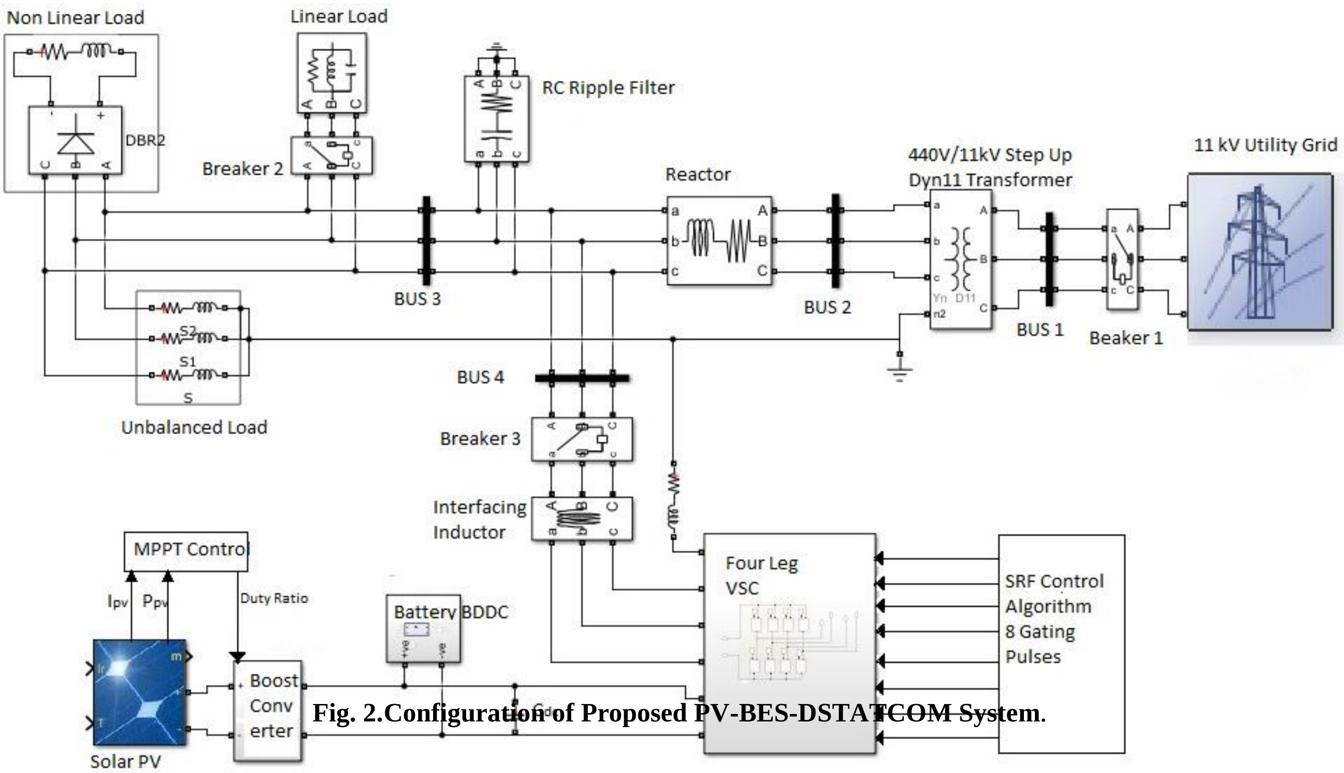

Fig. 2.Configuration of Proposed PV-BES-DSTATCOM System.

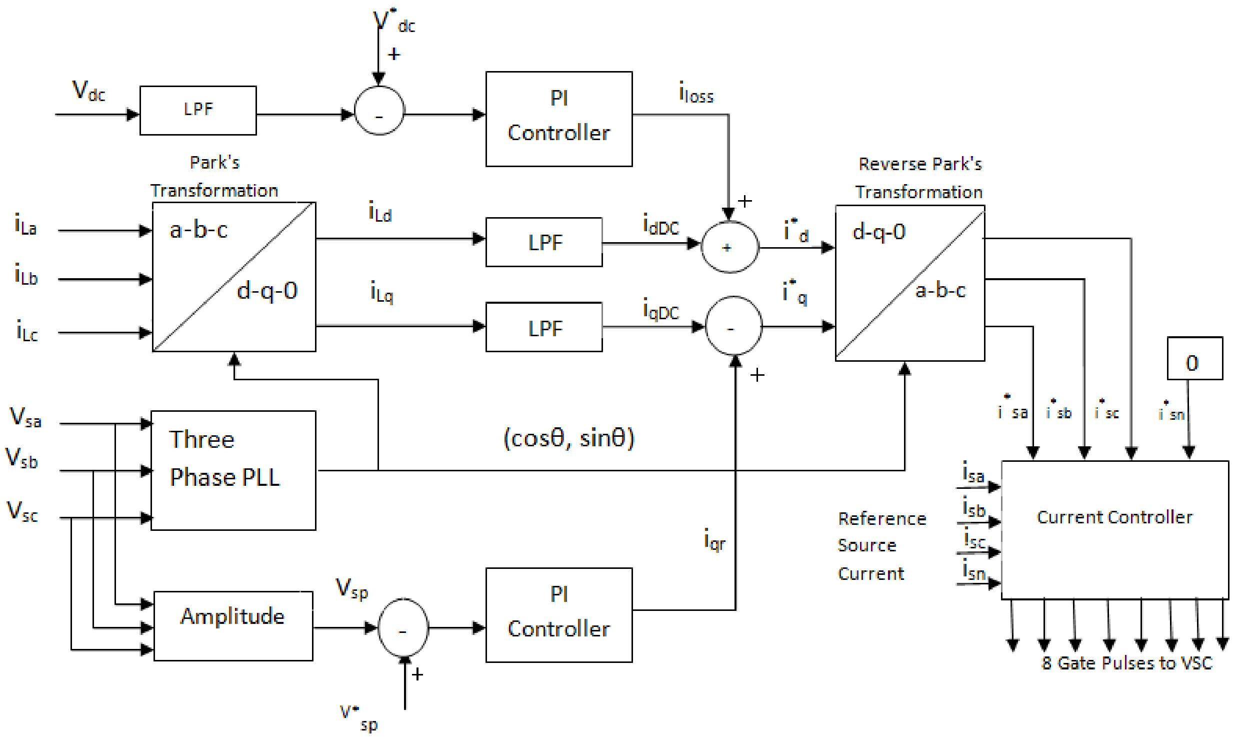

Fig. 3.Block diagram of SRF Control algorithm.

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With this technique The DSTATCOM can be used for regulating POS voltage with set value and supply side Power Factor Correction (PFC). When the DSTATCOM is operated for PFC mode, the source current is in phase with the supply voltage. Similarly in voltage regulation, the DSTATCOM supplies a current in such a way that the BUS2 voltage i.e. at POS (V_{ma}, V_{mb}, V_{mc}) and source voltage (V_{sa}, V_{sb}, V_{sc}) are equal in magnitude. The load currents (i_{La}, i_{Lb}, i_{Lc}), the BUS2 voltages (V_{ma}, V_{mb}, V_{mc}) and dc bus voltage (V_{dc}) have been measured and given as response signals. The 3-phase load currents are converted into the d-q-0 currents by exercising the Park's transformation as shown below.

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_{L0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos\left(\theta-\frac{2\pi}{3}\right) & -\sin\left(\theta-\frac{2\pi}{3}\right) & \frac{1}{2} \\ \cos\left(\theta+\frac{2\pi}{3}\right) & \sin\left(\theta+\frac{2\pi}{3}\right) & -\frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \qquad (2.1)$$

A 3-phase Phase Locked Loop (PLL) is employed to synchronize these d-q-0 signals with the BUS2 voltages. The part of DC current (iLd and iLq) have been extracted by passing d-q-0 current components in the Low Pass Filters (LPF). The DC parts are extracted from the reference signal and Non-DC parts such as harmonics are segregated by the SRF controller with LPF. The fundamental and harmonic components of d-axis and q-axis currents are,

$$i_{Ld} = i_{dDC} + i_{dAC} \qquad (2.2)$$

$$i_{Lq} = i_{qDC} + i_{qAC} \qquad (2.3)$$

Control strategy of the DSTATCOM is that, the source must supply the DC parts of the direct-axis load current (i_{dDC}) in line with the active power current portions, for regulating the dc link and to meet the losses (i_{loss}) in D-STATCOM. However, the source must supply the dc part of the quadrature axis load current (i_{qDC}) and the output of the PIC (i_{qr}) used for controlling the voltage at BUS2. For meeting the current loss (i_{loss}) the component obtained from PIC at the DC bus is considered.

$$i_{loss}(n) = i_{loss}(n-1) + K_{pd}\left(V_{de}(n) - V_{de}(n-1)\right) + K_{id}V_{de} \qquad (2.4)$$

Here, k_{pd} and k_{id} are the DC bus voltage proportional and the integral gains for PIC. The difference in error among the reference (V^*_{dc}) and measured (V_{dc}) dc voltage at the n[th] sampling moment is $V_{de}(n) = V^*_{dc} - V_{dc}(n)$. The reference direct axis source current,

$$i^*_d = i_{d\,DC} + i_{loss} \qquad (2.5)$$

By application of Inverse Park's Transformation the reference source currents are obtained . These are in line with the BUS2 voltages without zero sequence components.

$$\begin{bmatrix} i^*_{sa} \\ i^*_{sb} \\ i^*_{sc} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & \\ \cos\left(\theta-\frac{2\pi}{3}\right) & \sin\left(\theta-\frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta+\frac{2\pi}{3}\right) & \sin\left(\theta+\frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} i^*_d \\ i^*_q \\ i^*_0 \end{bmatrix} \qquad (2.6)$$

In order to achieve Zero Voltage Regulation (ZVR) the source must supply the same direct-axis portion i^*_d throughout the dissimilarity of quadrature-axis current i_{qDC}. The output of PIC (i_{qr}) component is used for controlling the BUS2 voltages.

The PIC output is taken as the reactive portion of current (i_{qr}) for ZVR operation of BUS2 voltage. The AC terminal voltage magnitude (V_{SP}) at BUS2 is regulated to its set voltage (V_{dc}^*) and is obtained by,

$$V_{sp} = \sqrt{\frac{2}{3}\left(V_{sa}^2 + V_{sb}^2 + V_{sc}^2\right)} \qquad (2.7)$$

The output of PIC is obtained as,

$$i_{qr}(n) = i_{qr}(n-1) + K_{pq}\left(V_{te}(n) - V_{te}(n-1)\right) + K_{iq}V_{te} \qquad (2.8)$$

Here, K_{pq} and K_{iq} are the proportional and integral gain constants of the PIC respectively. The difference in error among voltages of reference value V^*_{sp} and actual value $V_{sp}(n)$, the amplitudes of terminal voltage a the n[th] sampling moment is $V_{te}(n) = V^*_{sp} - V_{sp}(n)$.

The reference quadrature-axis source current is,

$$i^*_q = i_{qr} - i_{qDC} \qquad (2.9)$$

By Inverse Park's transformation with equation (1.6) in i^*_d, i^*_q and i^*_q=0, reference currents are obtained.

The measured supply currents (i_{sa}, i_{sb}, i_{sc}) and reference supply currents (i^*_{sa}, i^*_{sb}, i^*_{sc}) are estimated and errors are intensified by a PIC and gating signals are generated by comparing with the triangular carrier signal. These gating signals are used to regulate the IGBT switches to induce a current to see that the measured supply currents match with the reference supply currents.

The 4[th] leg of VSC is employed for mitigation of neutral current [14, 16]. In hysteresis controller the reference neutral current (i^*_{sn}) is differentiated with compensating neutral current (i_{sn}) and the differentiated signals are intensified with PIC to produce the gating signals to the neutral limb of IGBT switches.

$$i_{sn} = -\left(i_{sa} + i_{sb} + i_{sc}\right) \qquad (2.10)$$

$$i^*_{sn} = 0 \qquad (2.11)$$

This hysteresis controller is simple implementation, greater stability, and fast response to signals.

C. *Control of BDDC*

The BES BDDC control scheme is depicted in Fig.4. Current Control DC/DC Bidirectional Converter is operating on MPP voltage to control the DC bus voltage. For battery charging and discharging , BDDC has been utilized [18].

This converter operates on the DC bus voltage and the battery system voltage. The proportional and integral gains of PIC is K_p and K_i equal to 0.02 and 110 successively, have used to obtain reference current signal in the charging mode.

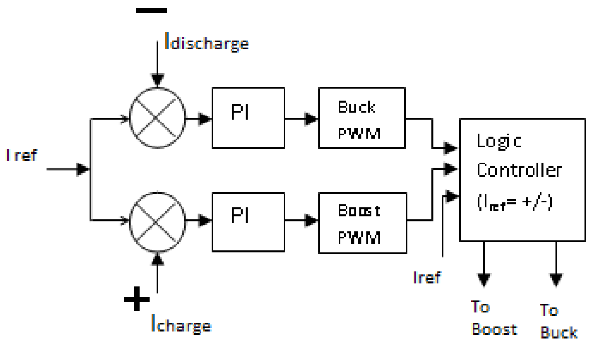

Fig. 4.Control signals for BDDC.

In discharging operation K_p and K_i is of 0.02 and 3, successively. For battery charging and discharging, charge controller may respond to power/current reference signal, or DC bus voltage is in islanded mode. The error signal between the measured and reference battery current, is fed to the PIC. The output of PIC is the duty cycle in the form of 0's and 1's. These signals are generated using PWM strategy by estimating the available duty ratio with a sawtooth signal, which is then fed to the BDDC. Based on the logic that the controller should decide whether to work in boost or buck operation. For the current reference -ve the controller works in boost mode, i.e. in the upper logic, and for the current reference +ve, the controller works buck mode, i.e. in the lower logic.

IV. RESULTS AND DISCUSSIONS

The suggested PV-BES 4-Leg VSC based DSTATCOM prototype has been developed and executed in MATLAB/SIMULINK software using sim-power components with SRF control theory. With non-linear and un-balanced load conditions, the present model has been verified . The above said model is well suited for compensation of unbalanced load, alleviation of harmonics, PFC at the point of synchronization. The simulation duration from 0.4s to 0.6s is taken for clear observation. The SRF based DSTATCOM performance has evaluated in different conditions.

1. Under Nonlinear Loads
2. Under Unbalanced Loads
3. Under Varying Solar Irradiance
4. Neutral current compensation
5. Analysis Total Harmonic Distortion (THD)

A. *Performance under Nonlinear Loads.*

Fig. 5 & Fig. 6 represents the behavior of the PV-BES power network tied system with nonlinear load condition. The Dynamic Performance of PCC Current, Load Current, Grid Current, PCC & Grid Voltages without PV-DSTATCOM and with PV-DSTATCOM integration is as shown in Fig.5 & Fig.6 respectively. The behavior of solar PV-BES-DSTATCOM is deliberated for solar insolation of 1000W/m2. The highest PV power is produced by adjusting the DC bus voltage with MPP. In the grid tied operation, the load supplied by the generated PV power and its excess power is transmitted into the grid. The VSC power (118 kW) is the total of load power (28kW), and the power which is sent to the grid (90kW), as shown in Fig.7. The nonlinear loads affects the load current waveform and it is having the total harmonic distortion (THD) of 21.73%, shown in Fig.5(b). Even, when the load current is disturbed, the quality of grid current is recovered by the suitable injection of DSTATCOM counterbalancing currents as shown in Fig.6(c). The source voltage harmonics is 0.19% and current harmonics is 3.36%. These values are in the permissible limits, as per the IEEE-519 standards. Before compensation, the grid current THD was 17.66%. Under UPF condition the source currents are balanced.

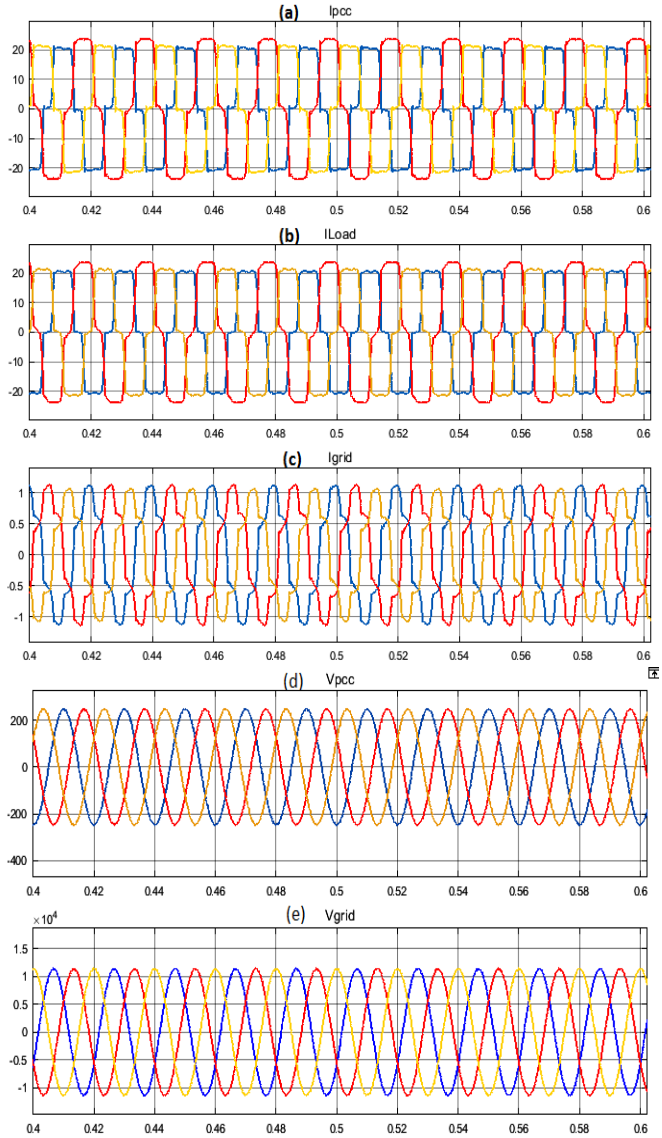

Fig. 5.Dynamic Performance of PCC Current, Load Current, Grid Current, PCC & Grid Voltages without PV-DSTATCOM under non linear load condition.

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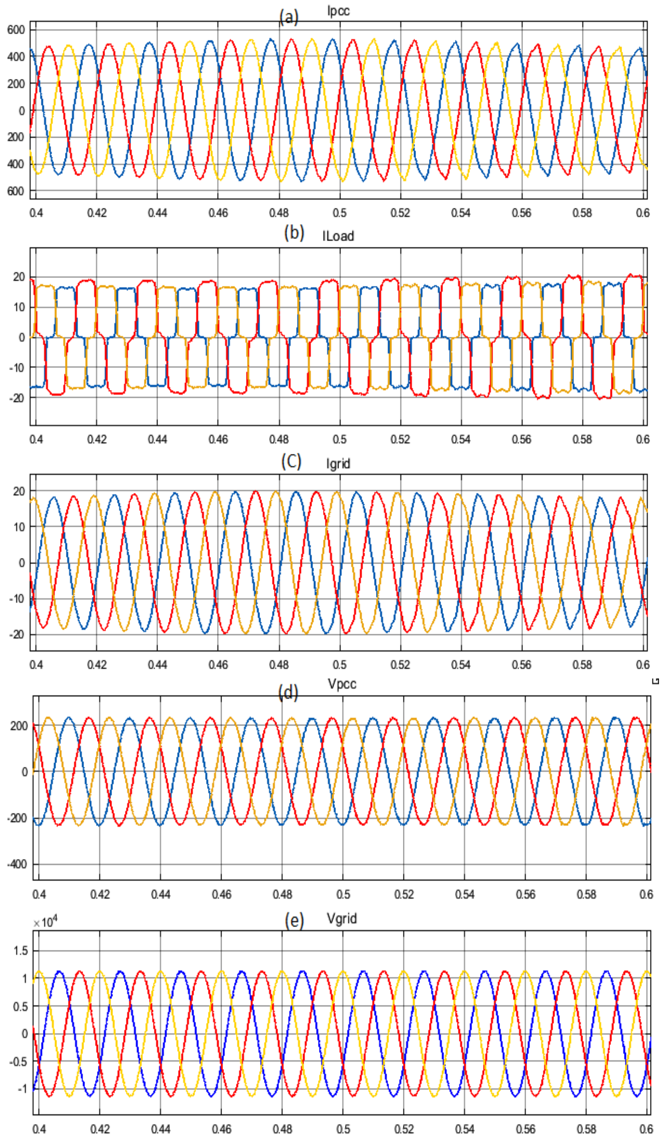

Fig. 6.Dynamic Performance of PCC Current, Load Current, Grid Current, PCC & Grid Voltages with PV-DSTATCOM under non linear load condition.

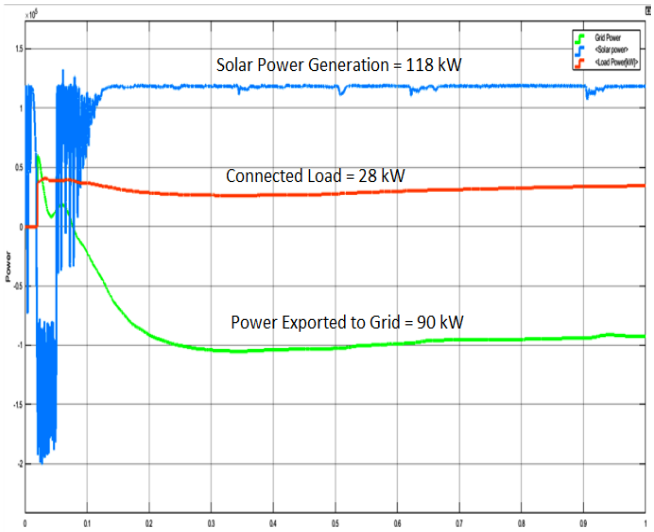

Fig. 7. Distribution of power: Solar power generation, load connected and excess power exported to grid.

B. *Performance under Unbalanced Loads*

Fig.8 exemplifies the dynamic performance of system signals among unbalance load conditions. The harmonics are induced to the distribution network and also grid currents are distorted due to unbalanced loads as shown in Fig.8(c). Further as shown in Fig.8(a) the harmonics affects the BUS2 current waveforms when the DSTATCOM is not connected. In Fig.9 it is seen that the BUS2 (point of synchronization) and BUS1 (source current) remains fundamental, when the unbalanced loads are connected with DSTATCOM as shown in Fig.9(b).

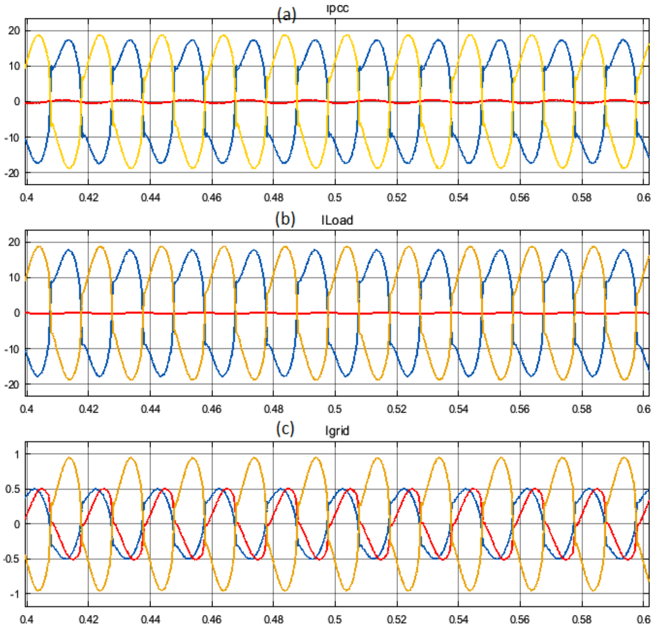

Fig. 8.Dynamic Performance of Unbalanced Load, PCC & Grid Currents without PV-BES-DSTATCOM.

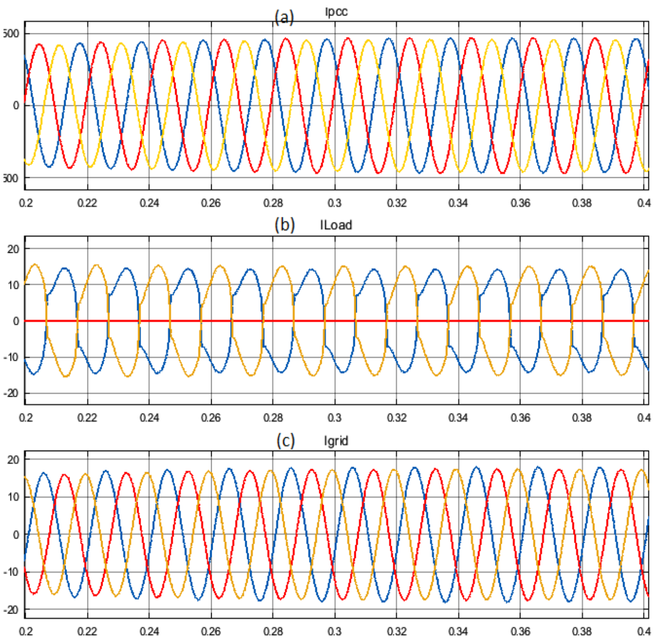

Fig. 9.Dynamic Performance of Unbalanced Load, PCC & Grid Currents with PV-BES-DSTATCOM.

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C. *Performance under Varied Solar Irradiance*

Behavior of the system under varying solar insolation is shown in Fig.10(a-f). It shows that change in PV Power (Ppv), Grid Power (Pgrid), PV Current (I_PV), Battery Power (P_Battery) and PV Voltage on varying solar intensity from 1000 W/m^2 to 200 W/m^2. From the waveform, it is seen that as the solar radiation reduces from 1000W/m^2 to 200W/m^2, there is a deduction in P_PV and I_PV. Similarly, the variation in solar intensity from 200 W/m^2 to 1000 W/m^2 reflects the changes in P_PV and I_PV occurred, as shown in Fig.10(b,d). The change in PV power reflects the corresponding increase or decrease in grid power exported, thereby power delivered to the load/ grid will change correspondingly, it is as shown in Fig.10(c). When there is PV power , the battery is charged from the remaining PV power after meeting the loads demand as shown in the Fig.10(e). The Fig.10(f) shows the variation in solar intensity, when the highest solar power is obtained without disturbing V_{dc}. When there is no PV power or low, the battery gets discharged and delivers the load. . Battery current will change from charging to discharging during solar insolation variation and vice-versa is as shown in Fig.11.The Fig.12 shows VSC voltage, battery voltage and state of charge (SOC) of battery, when there is PV power. The supply currents with UPF are maintained by regulating the VSC.

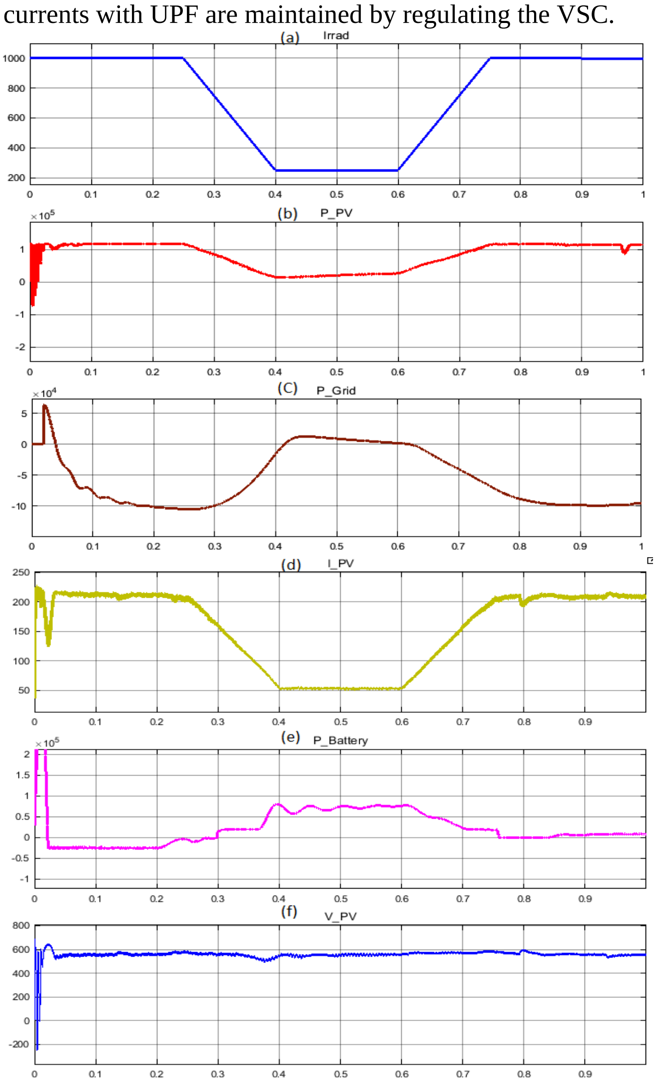

Fig. 10.Dynamic Performance of PV array under varied solar irradiance

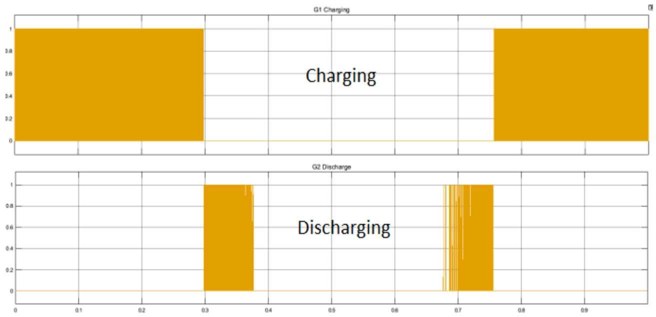

Fig. 11.Battery Charging and Discharging with varied solar irradiation.

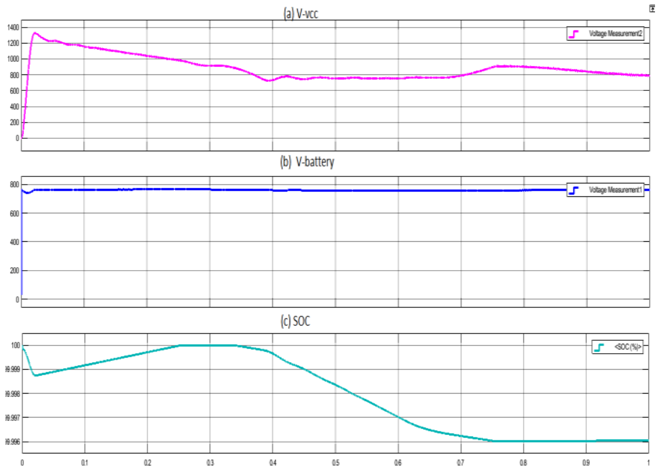

Fig. 12.Waveform VSC voltage, battery voltage and state of charge(SOC) of battery.

D. *Compensation of Neutral current*

In the 3-phase 4-wire distribution network there is a possibility of entry of neutral current when the loads are unbalanced. Fig.13 shows the flow of neutral current due to these unbalanced loads. This unwanted neutral current is alleviated by providing appropriate control algorithm compensation along with DC link capacitor in supply neutral wire and the neutral current is decreased after compensation is observed as shown in Fig.14. Hence successful compensation is achieved for phase and neutral current with this 4 legged VSC based DSTATCOM.

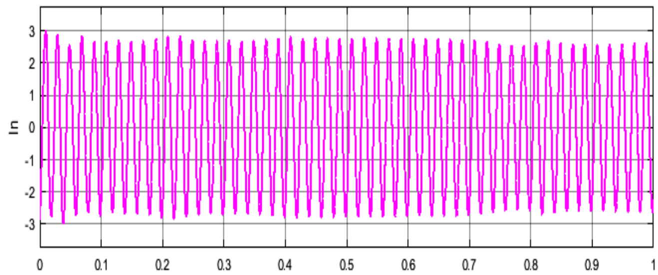

Fig. 13.Waveform of Neutral Current due to Unbalance load without PV- BES-DSTATCOM.

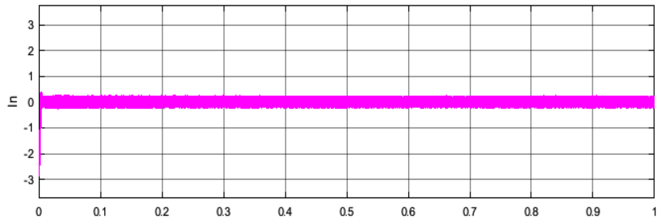

Fig. 14.Waveform of Neutral Current due to Unbalanced load with PV-BES-DSTATCOM.

E. *Analysis of Total Harmonic Distortion (THD)*

The THD of the BUS2 and BUS1 grid currents waveform for this present arrangement, with and without PV-BES-DSTATCOM integration is illustrated in the Fig. 15 to Fig.18. The THD of the system with nonlinear & unbalanced loads connected outside PV-BES-DSTATCOM is shown in Fig.15 & Fig.16. It is seen from Fig.15 that, 22.13% THD for BUS2 currents. The THD of BUS1 grid currents is 17.66%, as shown in Fig.16. By the integration of PV-BES-DSTATCOM to the present arrangement, the harmonics of current distortion at the BUS-2 comes down to 3.03% as shown in Fig.17.The harmonic distortion in source current is reduced to 3.36%, as shown in Fig.18. These THD values are within the bounds of specified IEEE-519 standard

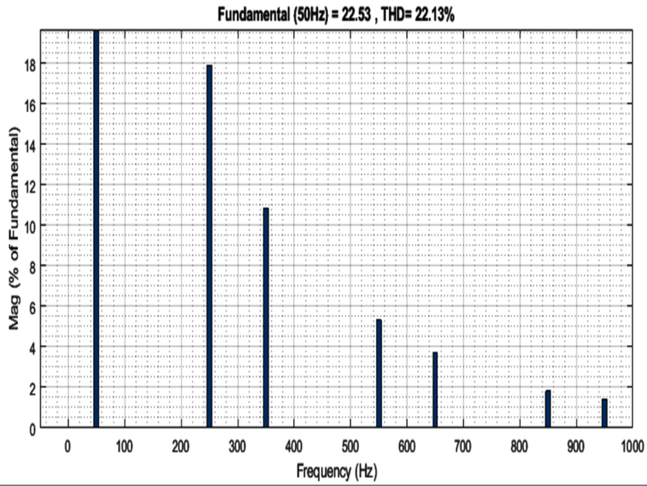

Fig. 15.THD of POS Current without PV-BES-DSTATCOM.

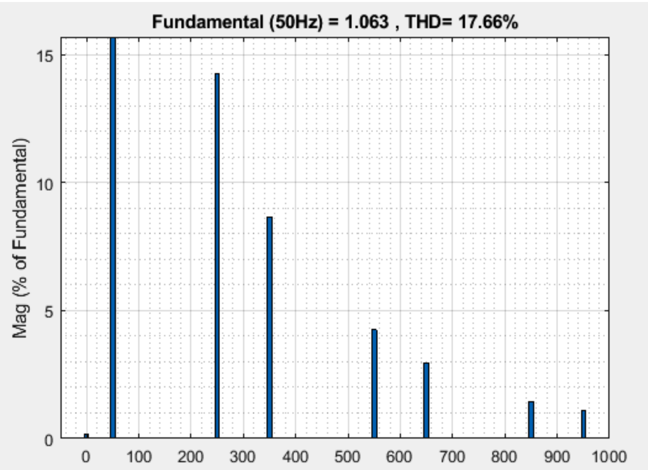

Fig. 16.THD of Source Current without PV-BES-DSTATCOM.

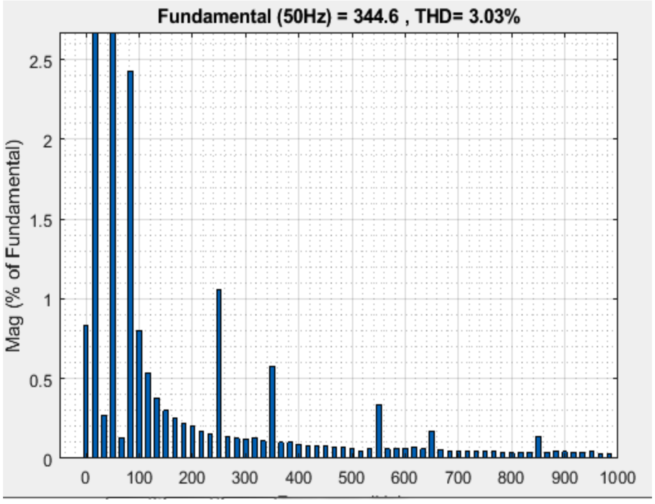

Fig. 17.THD of POS Current with PV-BES-DSTATCOM.

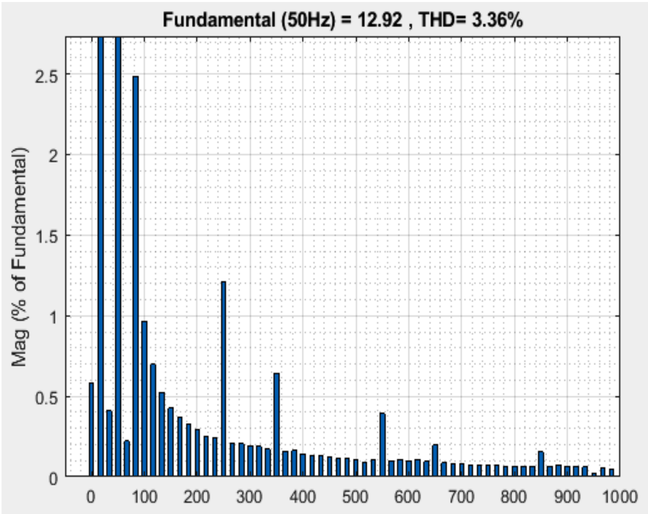

Fig. 18.THD of Source Current with PV-BES-DSTATCOM.

V. CONCLUSION

In this work, the performance of 4-Leg VSC based PV-BES-DSTATCOM supported by DC link capacitor has been examined and implemented using SRF theory. Contrasted to their solitary performance, DC link capacitor with 4-Leg inverter provides better neutral current, PCC current and grid current compensation and also reduced the filters requirement. The suggested SRF control strategy on the 11kV/440V distribution system having Solar PV-BES System with a capacity of 118kW has been modeled and validated for its satisfactory working condition and came up with better harmonic relief at the POS and grid side. The Sim-power components in MATLAB/SIMULINK software environment is used to obtain the simulation results.

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