American Research Journal of Electrical Engineering

Volume 4, Issue 1, 1-17 Pages
Research Article | Open Access

Implementation of Modified Adaptive Control Strategy for Reduced-Switch PV-DSTATCOM with a T-Connected Transformer for Power Quality Improvement

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ABSTRACT

In this work, a new two-leg three-phase three-wire VSC based reduced-switch PV-DSTATCOM using Modified Adaptive Control Strategy and a T-Connected transformer is proposed for Power Quality Improvement. Two single phase linear transformers are connected in T-Configuration at PCC for reduction of neutral current and the required rating of the system is reduced. The PV-DSTATCOM uses a boost converter circuit operated by IC-MPPT to attain power sharing with grid. The PWM current controller is introduced to drive the DSTATCOM and its reference supply currents are generated based on new modified techniques. The reduced switch PV-DSTATCOM is tested for power factor correction, reactive power compensation, load balancing etc. The neural current is compensated using T-connected transformer which is connected with the third split leg of the VSC via small capacitor as the conventional three-phase four wire six or eight switch DSTATCOM has the problem of producing switching harmonics distortion. The proposed system is replicated in MATLAB/Simulink using Sim-Power-Systems software based environment.

KEYWORDS: *Voltage Source Converter (VSC), Incremental Conductance-Maximum Power Point Tracking (IC-MPPT), Photovoltaic Distribution Static Compensator (PV-DSTATCOM).*

INTRODUCTION

A power system is a complex system, its complexity is increasing day by day. The power system is fairly reliable, but its quality of power supply is not always up to its rated values due to connection of different loads like linear, non-linear and unbalanced loads. These loads severely impact on the grid especially during peak hours. In addition, high neutral current also creates problems due to overloading power feeders, voltage distortion, overloaded transformers and common mode noise. Grid cannot alone compensate for reactive power, I^2R and I_n^2R losses, etc. The unbalanced grid voltage may lead to drawing of negative sequence current which may cause reduction in torque of electro-mechanical energy conversion devices and underneath components of harmonics in the power network

Peerzadah et al. [1] have described a reduced switch VSI based PV-DSTATCOM for power quality improvement. Different loads like linear, non-linear and unbalanced loads have been studied in a three-phase three-wire system to achieve grid unity power factor and zero voltage regulation of power system. The cost of converter, switching and conduction losses are also reduced elegantly. Meenakshi et al [2] proposed the system to address the power quality issues related to load using DSTATCOM and the system is built in MATLAB/Simulink to vindicate the simulation results. Zakaria et al. [3] presented the different techniques of MPPT and a comparative review between Perturb & Observe and Incremental Conductance algorithms is done with a track on Maximum Power Point. Abdelazeem et al. [4] proposed modified DSTATCOM with proposed current controller for Micro-grid application, interfacing of the VSC is done to ensure correct injection of the compensation current and elimination of switching harmonics. Rangaswamy et al. [5] proposed Synchronous Reference Frame Theory based control algorithm for the operation of Four Leg VSC based six switch DSTATCOM with PV-BES for neutral current compensation. Harmonics from the grid side are also eliminated and power quality improvement is done. Binh et al. [6] have introduced a modelized photovoltaic source based on Thevenin Equivalent Circuit and an algorithm is implemented for MPPT by deriving the equivalent model of the PV Panel. Mohammad et al. [7] discussed six-switch topology based three-phase four wire DSTATCOM with T-connected transformer for neutral current mitigation along with load compensation. Fathimathul et al. [8] introduced a comprehensive case study of different VSI based DSTATCOM topologies and a grand focus has been on to three-leg VSI with series, single DC capacitor. Topologies are compared and presented to show neutral current compensation, difference arises in the number of switches used and which directly shows cost and size. Hybrid configuration is selected for load compensation. Shazly et al. [9] discussed in detail the concept of MPPT techniques which increase the efficiency and performance of the solar PV system. Simulation-comparative study has been studied between P&O and Incremental Conductance algorithms to optimize the energy conversion efficiency of the PV system. It is reflected in the work that incremental conductance algorithm rapidly tracks changing irradiance, changing conditions more perfectly than Perturb & Observe method. Yao et al. [10] discussed various STATCOM control methods with many applications of proportional-integral controller gains obtained by trail-and-error approach which is highlighted as ineffective at a different operating point. This challenge has been rectified using adaptive PI control, which self-adjusts the control gains dynamically during disturbances. Singh et al. [11] developed an adaptive control algorithm for estimation of reference supply currents through obtaining the fundamental active power components of three-phase distorted load currents for a four-leg DSTATCOM which performs load compensation. Reddy et al. [12] presented an investigation on five-level Cascaded H-Bridge inverter as DSTATCOM for harmonics elimination and reactive power compensation. D-Q frame theory is implemented for reference supply current generation for VSC and single PI controller is utilized for capacitor DC voltage regulation. Singh et al. [13] proposed a three-phase four-wire six switch DSTATCOM based on VSC and a T-connected transformer which mitigates the neutral current and VSC of DSTATCOM performs load balancing, eliminates the harmonic current and compensates the reactive power.

Due to the increased growth of electrical energy consumption, environmental issues of conventional energy resources increase. Excessive use of fossil fuels for meeting our energy needs results in depletion of fossil fuel reserves. Consequently, the electric power started to be reconfigured with Solar-PV. In the proposed study, solar PV (renewable source) has been integrated with grid via DSTATCOM. It supplies energy to various loads, it is a clean source of energy and PV-DSTATCOM performs dual role in this work it compensates load for various power quality issues and integrates solar-PV with the grid, thus, resulting in power sharing power between grid and solar PV. Thus, the study proposes environmentally friendly solution using solar PV and reduced burden on fossil fuels, in addition to load compensation. Modified PV-DSTATCOM with only four switches in operation acts as a retrofit solution in eliminating the current related power quality issues. The conventional VSC of three-phase four-wire DSTATCOM uses generally six-switches for necessary load compensation which results in conduction and power losses and the cost of the converter is also high. Two inverter switches need elimination so that losses and costs are significantly reduced. The three-phase four-wire DSTATCOM utilizes voltage controller circuit to stabilize the voltage and due to this harmonic distortion get generated in the current signal. So, it is mandatory to develop an efficient circuit so that harmonics distortion plus inverter switching losses can be reduced subsequently. The general adaptive filter approach tested in previous literature based on a four-leg eight-switch VSC topology of DSTATCOM with self-regulated dc bus voltage using single PI regulator needs to be tested on three-phase four-wire system using reduced-switch PV-DSTATCOM with one more additional dc-link feedback loop of split-capacitor voltages. For neutral current compensation, the split-leg of VSC needs to be connected with the neutral wire so that inverter noise, ripples and big harmonic spikes get discharged through neutral. Hence the reduced switch DSTATCOM operation remains perfect. The main contribution of the proposed work is as follows:

i. Presenting a developed design of a three-phase four-wire system in which Incremental Conductance (IC) MPPT provides fast response to reduced-switch PV-DSTATCOM operated on the distribution system.

ii. Connecting a central point of shunt passive ripple filter with the neutral to drain the switching harmonic-noise effect. In the design of reduced switch PV-DSTATCOM the neutral line cannot be connected directly with the third split leg, so, a small capacitance is connected between the system neutral wire and split leg of inverter on negative side.

iii. Neutral of T-connected Transformer need connected with the system neutral to minimize the neutral current.

iv. The total amplitude of active power component of reference supply current is calculated as sum of dc-link PI regulator output plus split capacitor PI regulator output and average value of load active currents.

v. Utilizing the Pulse Width Modulation current controller to obtain the necessary gating pulses to four-switch VSC. The input to PWM current controller is modified two signals only as the summing points connected perform the required summation and subtraction of reference supply currents and actual currents before performing the non-unity feedback system.

SYSTEM DESIGN AND DESCRIPTION

Fig. 1 the detailed power system circuit in which utility grid (V_{sa}, V_{sb}, V_{sc}) is connected at point of common coupling to feed different loads (linear, non-linear and unbalanced loads). L_{sa}, L_{sb}, L_{sc} and R_{sa}, R_{sb}, R_{sc} are connected as source impedances of ac mains. IL_a, IL_b, IL_c are the currents drawn by the three-phase four-wire dynamic load. IL_n is the neutral current drawn by the three-phase load. The point of common coupling voltages is represented as V_{pa}, V_{pb}, V_{pc} for the three phases respectively. At point of common coupling L_{fa}, L_{fb}, L_{fc} are connected on output side of the VSC for mitigation of ripples from PV-DSTATCOM currents. The PV-DSTATCOM currents (I_{fa}, I_{fb}, I_{fc}) are injected by the VSC for compensation of reactive power, reducing the harmonics of load currents and load unbalance compensation at PCC. The modified DSTATCOM consists of two-leg VSC, two DC-link split capacitors, and a small neutral capacitor. The third leg (phase) is obtained from the mid-point of split capacitors on DC-link side of VSC. The DC-link capacitors are denoted as C_{dc1} & C_{dc2}. The small neutral capacitor C_n is connected to the negative terminal of split-leg. The negative terminal of the neutral capacitor is further connected to the neutral of T-connected transformer where the transformer is responsible for minimization/mitigation of neutral current. A low-pass ripple filter is connected at PCC to filter the high-frequency noise at PCC. The mid-point 'n' of ripple filter is also grounded to reduce the ripple factor so that it allows good tracking of reference currents along with unit vectors. A modified adaptive filter-based strategy has been implemented for the three-phase two-leg VSC based reduced-switch DSTATCOM which interfaces grid tied solar-PV system. In the system, Incremental Conductance controlled MPPT boost-converter is used to control the active power allocation between grid and solar-PV. The elements of boost converter are represented as L_{in} as boost inductance, D_{in} as boost circuit diode. C_{in} & R_{in} are in series with each other but connected across the Solar panel for minimization of ripples before connection with the boost-converter circuit.

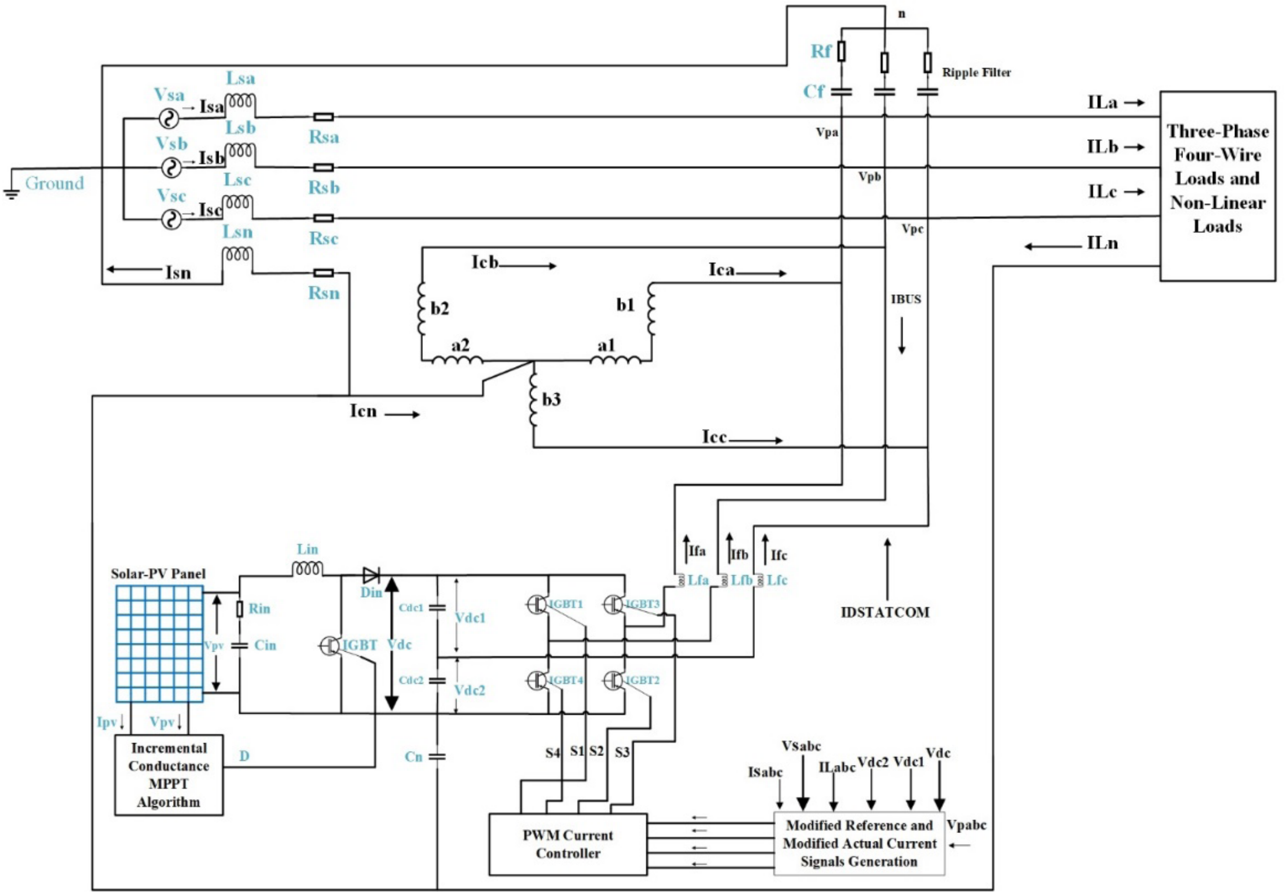

Fig. 1. Schematic Power Circuit with PV-DSTATCOM connection and T-Connected Transformer at PCC

Modelling of Solar-PV

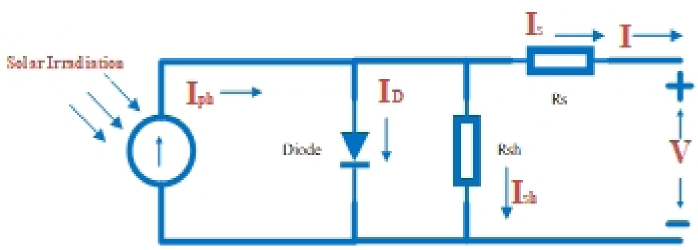

Fig. 2. *Equivalent circuit of a Solar Cell*

Fig. 2 shows model for solar-PV panel designed with single equivalent circuit using mathematical equations as

$$I_{PVCell} = I_{ph} - I_D - I_{sh} \tag{1}$$

where $I_{pv\,Cell}$ is the output current (A), I_{ph} is the photogenerated current (A), I_D is the diode current (A), I_{sh} is the shunt current (A). The current that flows through the diode can be calculated using Shockley diode equation as

$$I_D = I_o\left(e^{\frac{q(V+IR_S)}{mK\,T_C}} - 1\right) \tag{2}$$

And current across shunt resistance R_{sh} is given as

$$I_{sh} = \frac{V + IR_s}{R_{sh}} \tag{3}$$

Using (2) & (3) in (1) we obtain

$$I_{PVCell} = I_{ph} - I_o\left[\left(e^{\frac{q(V+IR_S)}{mK\,T_c}} - 1\right)\right] - \frac{V + IR_s}{R_{sh}} \tag{4}$$

where I_o is the diode reverse saturation current (A), q is the charge of electron (1.6×10^{-19}C), K is the Boltzmann's gas constant ($1.38\times10^{-23}\, J/K$), T_c is the absolute temperature in Kelvin, m is the diode ideality factor, V is PV-cell output voltage, R_{sh} is the shunt-resistance of the cell (Ω), R_s is the series resistance of the cell (Ω). Thus, using single-diode-model for analysis of solar-PV, the current at maximum power point I_{mp} can be calculated as

$$I_{mp} = I_{ph} - I_o\left[\left(e^{\frac{q(V_{mp}+I_{mp}R_S)}{mK\,T_c}} - 1\right)\right] - \frac{V_{mp} + I_{mp}R_s}{R_{sh}} \tag{5}$$

However, power at maximum power point P_{max} is given by

$$P_{max} = V_{mp} \times I_{ph} - I_o\left[\left(e^{\frac{q(V_{mp}+I_{mp}R_S)}{mK\,T_c}} - 1\right)\right] - \frac{V_{mp} + I_{mp}R_s}{R_{sh}} \tag{6}$$

Incremental Conductance MPPT Algorithm

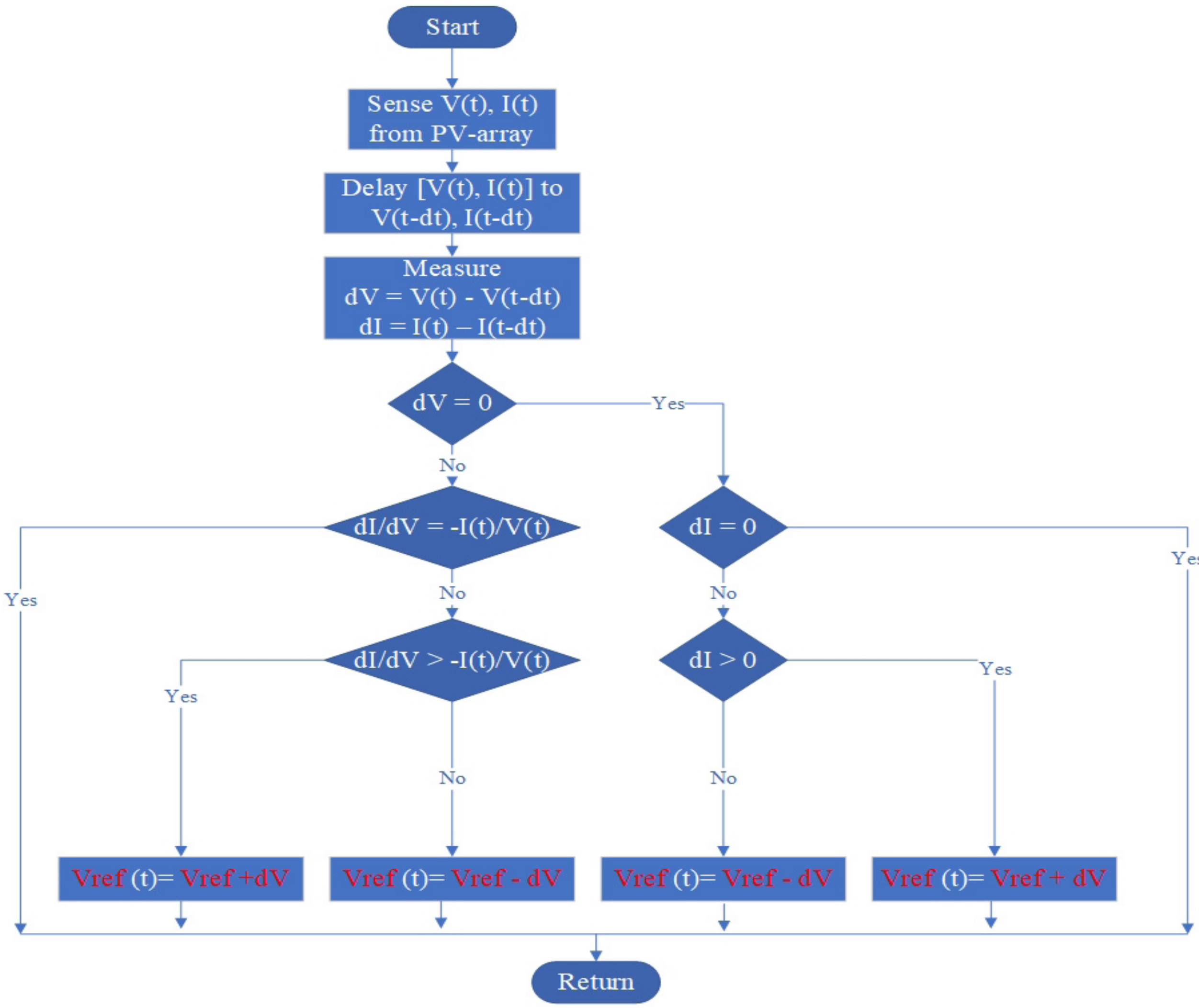

Fig. 3. Flow Chart of Incremental Conductance Algorithm

In the control algorithm, incremental changes in voltage and current are measured by the controller in PV-array. Maximum power point is calculated by comparing the incremental conductance of $\frac{dI}{dV}$ with PV-array conductance $\frac{I}{V}$. When $\frac{dI}{dV} = \frac{I}{V}$ the output voltage is at maximum power point voltage. This is maintained until the irradiance changes and the process is repeated. The incremental conductance MPPT works on $\frac{dP}{dV} = 0$ and $P=VI$. Fig. 3 shows the exhibits the flow chart of the incremental conductance algorithm. The output power of PV-array is given as $P=VI$ watts and the mathematical chain rule for derivation of the products with respect to voltage is given as

$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I\frac{dV}{dv} + V\frac{dI}{dV} = I + V\frac{dI}{dV} = 1(V)\frac{dP}{dV} = \left[\frac{I}{V}\right] + \frac{dI}{dV} \tag{7}$$

Therefore, from (7) this method searches for the voltage operating point at which the conductance is equal to the incremental conductance. The incremental conductance algorithm relies on the slope of the P-V curve. Table 1 depicts the parameters of solar-PV and Fig. 4 depicts the design of PV-Curve.

Table 1. Parameters of Solar-PV

S No	Parameter	Value
1	No of parallel connected strings	8
2	Series-connected modules per string	31
3	Module Connected: User-defined	280.1657W
4	Cells per module (N_{cell})	72
5	Open-circuit voltage (V_{oc})	50V
6	Short-circuit current (I_{sc})	8.14A
7	Voltage at maximum power point (V_{mp})	37.01V
8	Current at maximum power point (I_{mp})	7.57A
9	Temperature Coefficient of V_{oc}	-0.35001%/^{0}C
10	Temperature Coefficient of I_{sc}	0.05%/^{0}C
11	Light generated current I_L	8.1535A
12	Diode saturation current I_0	1.9128e^{-10}
13	Diode ideality factor	1.1048
14	Shunt Resistance R_{sh}	670.5032Ω
15	Series Resistance R_s	0.97495Ω
16	Variable Solar Irradiance	300-1000W/m^2
17	Panel Temperature	25^{0}C

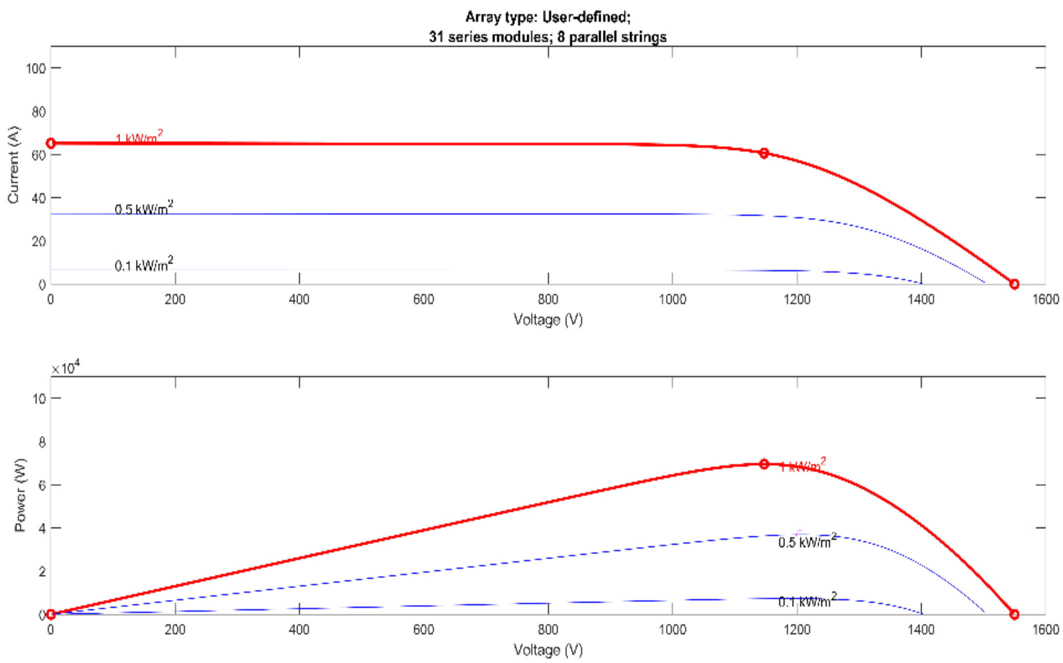

Fig. 4. PV-Curve

The PV-array is user defined with 31 series modules and 8 parallel strings. The slope will become zero at MPP, increases (positive) on the left side of MPP and decreases (negative) on the right side of the MPP. The equations of this control strategy are as follows:

$$\frac{dP}{dV} > 0, \quad Left\ side\ of\ MPP \tag{8}$$

$$\frac{dP}{dV} = 0, \quad at\ the\ MPP \tag{9}$$

$$\frac{dP}{dV} < 0, \quad Right\ side\ of\ the\ MPP \tag{10}$$

The incremental conductance algorithm is derived by differentiating output power of PV module with respect to voltage and setting the result equal to zero. The relation between the incremental conductance $\frac{dI}{dV}$ and instantaneous conductance $\frac{I}{V}$ can be derived based on (7) as follows

$$\frac{dI}{dV} = -\frac{1}{V}\ at\ the\ MPP \tag{11}$$

$$\frac{dI}{dV} \geq -\frac{1}{V}\ Left\ side\ of\ MPP \tag{12}$$

$$\frac{dI}{dV} \leq -\frac{1}{V}\ Right\ side\ of\ MPP \tag{13}$$

Design of set up DC to DC Boost Converter

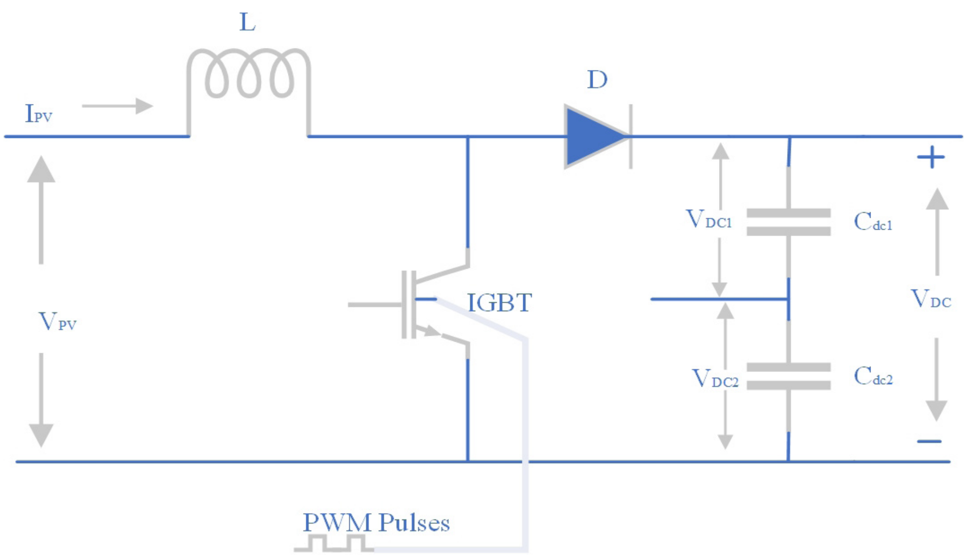

Fig. 5. Boost Converter Circuit

The solar-PV output is required to contain a DC-DC converter that steps up the solar modules voltage up to the DC-Link voltage level, which relies on the duty ratio (α). Fig. 5 shows the DC-DC boost converter of the proposed system. The parameters for the circuit are I_{PV} as the input solar-PV current, V_{PV} the input solar-PV voltage and I_{DC} & V_{DC} as output DC-Link current and voltage respectively. The relationship between V_{PV} and V_{DC} conversion ratio can be expressed as

$$V_{PV} \times T_{ON} - (V_{DC} - V_{PV})T_{OFF} = 0.0 \tag{14}$$

Therefore,

$$V_{PV} \times \alpha \times T = (V_{DC} - V_{PV})(1 - \alpha)T \tag{15}$$

Where $\alpha = \frac{T_{ON}}{T}$ is the duty cycle (0<α<1). T = T_{ON}+ T_{OFF} is the switching period.

$$\frac{V_{DC}}{V_{PV}} = \frac{T_{ON} + T_{OFF}}{T_{OFF}} = \frac{1}{1-\alpha} \tag{16}$$

The output voltage is quite sensitive to changes in duty cycle α. The duty ratio synchronizes the PV voltage with the DC-Link voltage and is calculated

$$\alpha = 1 - \left(\frac{V_{PV}}{V_{DC}}\right) = 1 - \left(\frac{1338}{1408}\right) = 0.0497 \tag{17}$$

where V_{PV} is the solar-PV array output voltage which is found equal to 1338V and V_{DC} is the DC-Link voltage equal to 1408V respectively. If switching period T = 50μs, and I_{PV} is calculated as 18.14A, then value of L is calculated as

$$L = \frac{V_{PV} \times \alpha \times T}{d \times I_{PV}} \tag{18}$$

$$L = \frac{V_{PV} \times \alpha \times T}{(0.1) \times I_{PV}} = \frac{1338 \times 0.0497 \times 50 \times 10^{-6}}{0.1 \times 18.14} = 1.8329\,mH \tag{19}$$

The filter capacitor C_{in}=1000e^6 and resistor Ri_n=0.001Ω connected across PV-array module are required for filtration of harmonics, ripples and noise from PV-module.

Design of DC-Link VSC Voltage and Split-Capacitor Voltages

The DC-Link VSC voltage V_{DC} of PV-DSTATCOM should be greater than twice of the peak amplitude of the phase voltage of the system. The DC-Link voltage is calculated as

$$V_{DC} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}} \tag{20}$$

where, V_{LL} is the line-to-line output voltage of PV-DSTATCOM. 'm' is the modulation index and is taken as 1. Hence, V_{DC} is obtained as 700V for V_{LL} of 415V grid and V_{ref} is selected as 1400V and across each capacitor the voltage is taken similar as

$$V_{DC} = V_{DC_1} + V_{DC_2} = 700 + 700 = 1400V \tag{21}$$

Design of DC-Link Split-Capacitors

The value of split-capacitors is determined by decrement in DC-Link voltage upon load connection and increment in DC-Link voltage upon deletion of the loads. The equation used for calculation is

$$C_{DC_1} = C_{DC_2} = \frac{I_c}{2\omega V_{DC_{(ripp)}}} \tag{22}$$

Hence, the obtained values of C_{DC1} and C_{DC2} are 12954μF each. So, the value is rounded-off to a standard value of 13000μF each.

AC Interfacing Inductor L_f

The AC interfacing inductance L_f of VSC relies on the current ripple $i_{cr(p-p)}$, switching frequency f_s, dc-bus voltage V_{DC}, and L_f is given by the formula as

$$L_f = \frac{\sqrt{3} m V_{dc}}{12 a f_s i_{cr(p-p)}} \tag{23}$$

Where *'m'* is the modulation index and a is the overloading factor. Considering, $i_{cr(p-p)}$=6%, f_s=10KHz, m=1, V_{dc}=1400V, a=1.2, the L_f is calculated to be 2.80mH.

Ripple Filter

For 10KHz switching frequency, the ripple connected at PCC is designed to filter out the high-frequency noise from voltage at PCC. The Ripple Filter is also connected with neutral wire for draining the high frequency spikes, ripples and harmonics from PCC. A resistance R_f= 10Ω is connected in the series with the capacitor C_f=5.5μF at PCC. The impedance is found at fundamental frequency, which is sufficiently large, and thus, ripple filter draws negligible fundamental current.

Design of the T-connected Transformer

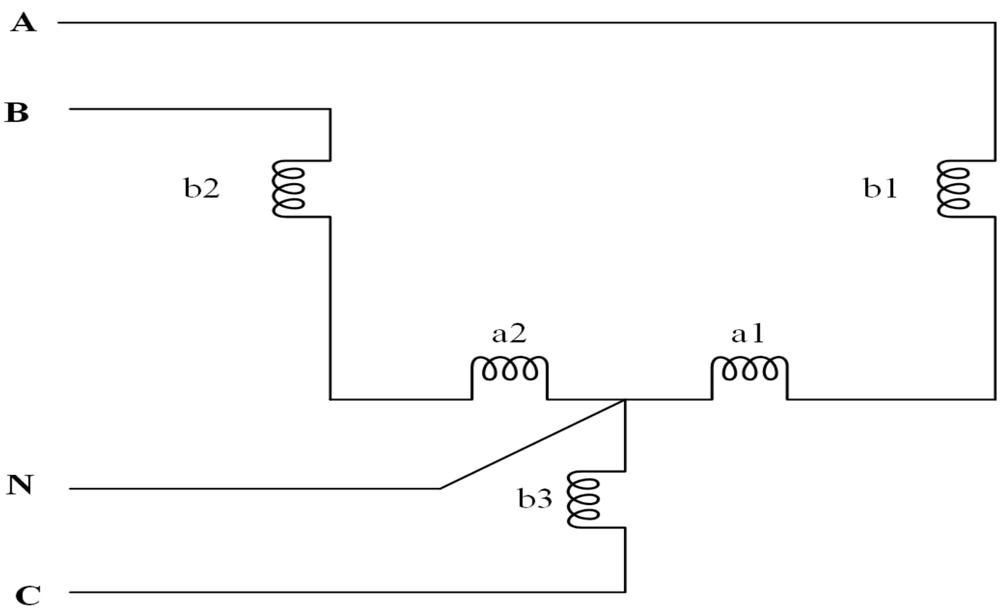

Fig. 6. T-Configuration Transformer

Fig. 6 shows the connection of two single-phase linear transformers connected in T-configuration for interfacing with the three-phase four-wire system. The T-configuration Transformer not only offers a path/ mitigation for the neutral current but also provides a path for the zero-sequence fundamental current and harmonic currents. Under the connection of different loads at PCC including unbalanced one, the current divides equally into three currents and takes a path through the T-connected winding of the transformer.

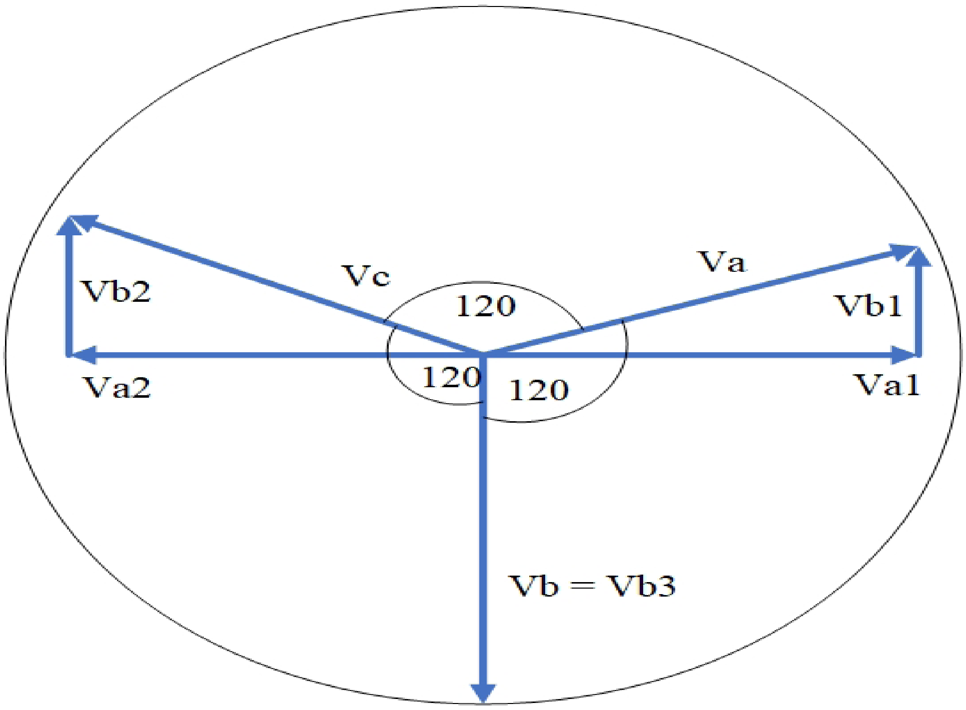

Fig. 7. Phasor Diagram

The phasor diagram shown in Fig. 7 gives the following relation to the turn's ratio of windings as

$$V_{a1} = K_1 V_a \tag{24}$$

$$V_{b1} = K_2 V_a \tag{25}$$

Where K_1 and K_2 are fractions of winding in the phases. Considering $|V_a| = |V_b| = V$ and $V_{a1} = V_a \cos 30°$, $V_{b1} = V_a \sin 30°$, using (24) and (25), K_1=0.866 and K_2= 0.5. The grid line voltage is V_{ca}=415V, thus,

$$V_a = V_b = V_c = \frac{415}{\sqrt{3}} == 239.7\text{V} \tag{26}$$

$$V_{a1} = 207.43V \tag{27}$$

$$V_{b1} = 119.81V \tag{28}$$

Thus, two single-phase linear transformers of rating 5kVA, 240V/120V/120V and 5kVA, 208V/208V are selected.

Selection of neutral capacitor

The design ofneutralcapacitor relies on the neutral source which will be compensated by the modified PV-DSTATCOM. This two-leg topology of DSTATCOM is designed to work on a three-phase four-wire power system. Its neutral capacitor C_n can be calculated by

$$C_n = \frac{X_{cn}}{2\pi f} \tag{29}$$

where X_{cn} is the capacitive reactance.

CONTROL STRATEGY

Fig. 8 shows the schematic diagram of Proposed new Modified adaptive Control Algorithm for control of PV-DSTATCOM. The point of common coupling voltages V_{ap}, V_{bp}, V_{cp} and load currents i_{La}, i_{Lb}, i_{Lc} are sensed for computation of the currents i_{Lpa1}, i_{Lpb1}, i_{Lpc1} respectively. These currents i_{Lpa1}, i_{Lpb1}, i_{Lpc1} are called active power components of Phase a, b, c. The components of nonlinear load current at PCC include active power, ripples, various components of harmonics with dc quantities, etc. These active power components of load current are differentiated from distorted load currents for production of current error components and both in-phase components of supply voltages (V_{ap}, V_{bp}, V_{cp}) and these current errors are multiplied. These components are passed through the respective low pass filters before integration. After integration, the components are again multiplied with in phase components of three-phase grid voltages V_{ap}, V_{bp}, V_{cp} respectively. Then i_{Lpa1}, i_{Lpb1}, i_{Lpc1} are sent to three rms blocks wherein computation of root mean square value are done so that arithmetic mean is calculated to define the continuous function signals. Then amplification with suitable gains is performed on the active power components. After extraction of distorted components of load currents, their peak amplitude is estimated with the help of gain factor (k). It is declared as I_{LAP}.

The actual sensed DC-Link voltage is feedbacked and compared with the calculated reference DC-Link voltage V_{dc}^*. The DC-Link voltage error of the PV-DSTATCOM at the nth sample instant is

$$V_{DC_e}(n) = V_{DC}^*(n) - V_{DC}(n) \tag{30}$$

For maintaining the DC-Link voltage of PV-DSTATCOM constant, this error is given to the PI regulator. At the nth sampling instant, the output of DC-Link Proportional Integral (PI) Regulator is given by

$$I_{lp}(n) = I_{lp}(n-1) + K_{pd}\{V_{DCe}(n) - V_{DCe}(n-1)\} + K_{id}V_{DCe}(n) \tag{31}$$

In addition to it, the Voltage balancing of split capacitors for VSC, the two DC-bus capacitor voltages are sensed and their difference is compared with reference value of zero to balance the capacitor voltages. The difference of the split capacitors is feedbacked and compared with zero, it generates an error signal and is given to the PI regulator I_{tdp} given by

$$I_{tdp}(n) = I_{tdp}(n-1) + K_{pd1}\left\{V_{DC_{diff}}(n) - V_{DC_{diff}}(n-1)\right\} + K_{id1}V_{DC_{diff}}(n) \tag{32}$$

where $V_{DC_{diff}}(n) = \{0 - (V_{dc_1}(n) - V_{dc_2}(n))\}$ is the error signal obtained and K_{pd1} and K_{id1} are the proportional and integral gains of the PI regulator for dc-link of voltage source converter.

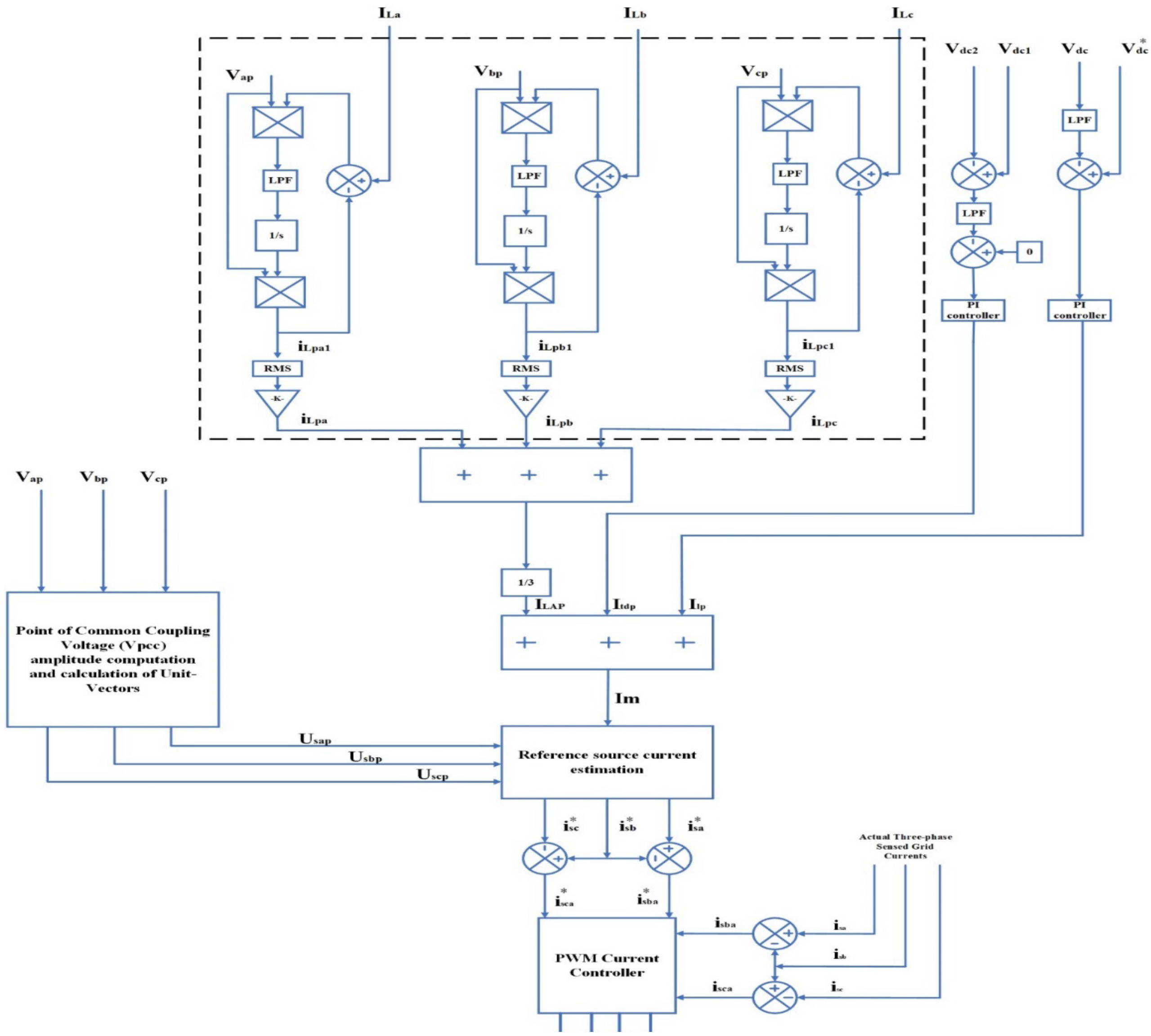

Fig. 8. Modified Adaptive Control Strategy

Thus, total amplitude of active power component of reference supply current I_m is calculated by a sum of output of DC-link PI regulator (I_{lp}), output of second dc-bus PI regulator (I_{tdp}) and average value of load active currents (I_{LAP}) is formulated as

$$I_m = I_{lp} + I_{tdp} + I_{LAP} \tag{33}$$

Therefore, active power component of reference supply current I_m is multiplied with three in-phase unit-vectors U_{spa}, U_{spb}, U_{spc}. These unit-vectors are given by computation of amplitude as

$$V_{pcc} = \sqrt{\frac{2}{3}} \times \sqrt{V_{pa}^2 + V_{pb}^2 + V_{pc}^2} \tag{34}$$

Where V_{pa}, V_{pb} *and* V_{pc} are phase PCC voltage. Hence, the three unit-vectors are as

$$U_{spa} = \frac{V_{pa}}{V_{pcc}}, U_{spb} = \frac{V_{pb}}{V_{pcc}}, U_{spc} = \frac{V_{pc}}{V_{pcc}} \tag{35}$$

From (33) and (35) we get the three-phase reference currents as given by

$$i_{sa}^* = I_m \times U_{spa} \tag{36}$$

$$i_{sb}^* = I_m \times U_{spb} \tag{37}$$

$$i_{sc}^* = I_m \times U_{spc} \tag{38}$$

REFERENCE SUPPLY CURRENT GENERATION

The reference supply currents are generated by utilizing i_{sa}^*, i_{sb}^* and i_{sc}^*. Two summing points analyze the reference source currents to generate modified reference supply currents at the output, using (36), (37) and (38) as

$$i_{sba}^* = i_{sa}^* - i_{sb}^* \tag{39}$$

$$i_{sca}^* = i_{sb}^* - i_{sc}^* \tag{40}$$

The generated modified supply currents i_{sba}^* and i_{sca}^* are further fed to the next two summing points inside PWM current controller. On the other side of control strategy, actual source currents are sensed by current sensors and are analyzed by another two summing points as given by

$$i_{sba} = i_{sa} - i_{sb} \tag{41}$$

$$i_{sca} = i_{sb} - i_{sc} \tag{42}$$

The actual modified currents i_{sba} and i_{sca} are fed to the summing points inside PWM current controller wherein i_{sba}^* and i_{sca}^* are connected, finally derived reference supply currents are compared. The PWM controller generates four gating pulses to the IGBTs of H-bride inverter.

RESULTS AND DISCUSSION

The new modified adaptive control of PV-DSTATCOM performance is evaluated in five different conditions as

Under linear and unbalanced loading conditions (0 to 0.35s)

Under heavy nonlinear loading condition (0.2 to 0.35s)

Under Varying Solar-Irradiance (0.3 to 0.35s)

Neutral current compensation

Analysis of Total Harmonic Distortion (THD)

The system is subjected to a balanced linear load and an unbalanced load (see table 2). The loads are connected constantly to the system from 0s to 0.35s. It can be observed that initially grid current was lagging the grid voltage, and all excess reactive power demand of the load was fulfilled by the grid. The grid power factor deteriorated and not unity.

The solar PV-DSTATCOM is connected in the system at PCC at 0.04s and all reactive power demand of load is compensated locally by the DSTATCOM and not by the grid plus there is also a power exchange between Solar-PV and grid. The load is fully satisfied, no condition of poor distribution bus-voltage, voltage sag, swell, etc. with this burden on grid is reduced and grid power factor becomes equal to unity, thus, ideal condition is achieved and power quality is improved.

Table 2. System Simulation Parameters

S No	Parameter	Value
1	Supply Voltage V_s	415V
2	Supply Frequency f	50Hz

3	Line Impedance $R_s + jX_s$	0.001Ω + j 0.01mH
4	Interfacing Inductance L_f	2.80mH
5	DC Link split capacitors value	$C_{DC1} = C_{DC2} = 13000e^{-6}$
6	DC Link voltage of split capacitors	$V_{CD1} = V_{CD2} = 700V$
7	DC Link total reference voltage	$V_{DC} = 1400V$
8	Peak amplitude of PCC AC reference Voltage	325V
9	Switching Frequency	10 kHz
10	Three-phase parallel RLC load	• Active power P (W): 10000 watts • Inductive reactive Power QL: 9000 var • Capacitive reactive power Qc: 105 var
11	Unbalanced Load	a = 2 Ω +4mH, b = 3 Ω + 15mH, c = 4 Ω + 2.3mH
12	Non-linear Load (front-end AC to DC rectifier)	36 Ω + 100mH

The same system is subjected to excursion of heavy non-linear load from 0.2s onwards. During this time duration, the non-linear load generates harmonics at PCC, demands bitter reactive power demand and tries to distort the fundamental component of voltage and current at PCC. But as PV-DSTATCOM is connected at PCC before non-linear load excursion, the DSTATCOM actively eliminates harmonics effectively which are generated by the non-linear load and fulfils all load reactive power demand. Any power which is dissipated by the non-linear load is fulfilled through Solar-PV. Hence the grid remains unaffected during thistime period. Power factor stands equal to unity and power quality remains improved during dynamic load conditions.

Thus, PV-DSTATCOM performs here a dual role as it eliminates harmonics, compensates for reactive power, load unbalancing compensation, compensates for I^2R and I_n^2R losses produced by the non-linear load plus integrates Solar-PV with grid. Hence, the proposed work shows the validation on the modified adaptive control strategy.

The system is verified under Variable Solar Irradiance Condition also. For the PV-array at the irradiance port, repeating sequence stair case mask has been connected in which vector output values are set as 300 W/m^2 and 1000 W/m^2 with sample time of 0.3 seconds onwards. It is observed from the simulation results that Solar-PV mean power was initially 6400 Watts which received step increase up to 6800 watts at t = 0.3s onwards due to variation of solar irradiance, with the result the mean power of grid also changes from 16000 watts to 16500 Watts. Load demand also received an increment from 119931 Watts to 22600 Watts by switching of heavy non-linear load from 0.2s onwards. Therefore, the variation of Solar Irradiance results in more power sharing of Solar-PV system with the grid at PCC. Moreover, this extra power generated by Solar-PV is also used to compensate for the losses created by the Load.

The three-phase four-wire system using two-leg VSC and a T-connected transformer is analyzed for neutral current compensation noise, ripples and harmonics suppression etc. The split leg of VSC is connected to the neutral wire using a small capacitor C_n for minimization of harmonics, ripples, spikes created between ac and dc sides of the VSC whereas the T-connected transformer is reducing the neutral current under linear, non-linear and unbalanced loads. In addition, T-connected transformer is also utilized for triplen harmonic current reduction.

The system was checked for THD with and without PV-DSTATCOM. The THD of grid current without DSTATCOM was about 13% and when new modified adaptive controlled PV-DSTATCOM is connected at PCC the grid current THD is subsequently reduced to 3.18% which is well below IEEE 519 Standard.

The proposed reduced switch PV-DSTATCOM has been built and executed in MATLAB/Simulink software using sim-power components with modified adaptive control. With Linear, nonlinear and unbalanced loading conditions the model has been verified. The work validated in MATLAB/Simulink confirms for reactive power compensation, elimination of harmonics, Load unbalance compensation, grid power factor correction and neutral current compensation simultaneously. The results were observed in a simulation time duration of 0 to 0.35s. In this short time duration PV-DSTATCOM is connected to PCC at 0.04s, dynamical load response has been studied from 0.2s onwards and results are obtained. This proves the efficient tunning and response of the system.

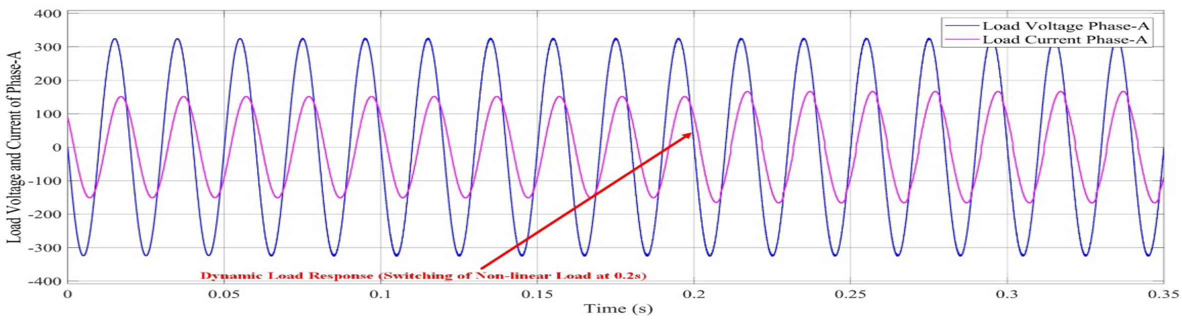

Fig. 9. Load Voltage and Current of Phase-A

Fig. 9 the load voltage and current of phase-A, it can be observed that load current lags the load voltage which results in lagging power factor. Three loads are connected to the system on the distribution side i.e., Parallel RLC load, unbalanced load and dynamic non-linear load with step time of 0.2s. The initial condition for non-linear load is kept 0 and final value is set 1 for its operation, the heavy non-linear load is connected on distribution side that injects harmonics into the system and the demand of load current increases. In addition, unbalanced load and parallel RLC loads have their neutral point connected with neutral wire which results in protection against surges, spikes etc. Reactive power drawn by the loads results in excessive current demand (from 0 to 0.04s) which results in burdening on grid voltage. The PV-DSTATCOM is connected to the system at 0.04s at PCC as a shunt active filter that performs Load Compensation using its new modified adaptive control algorithm.

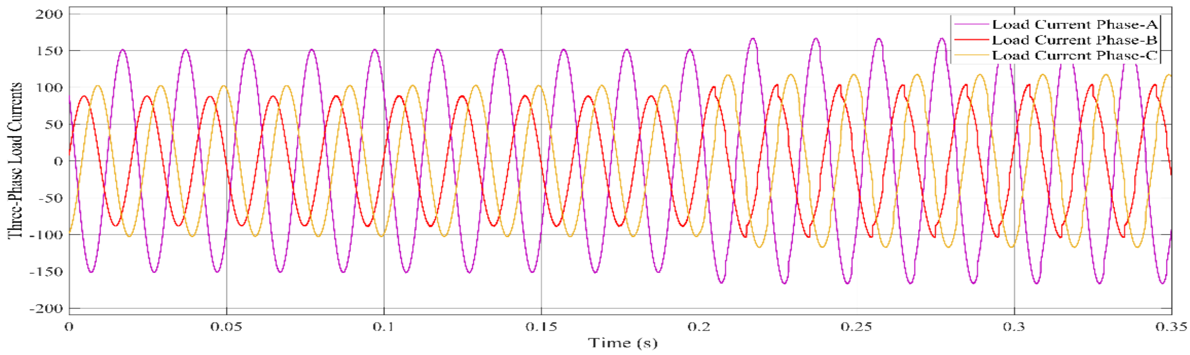

Fig. 10. Three-Phase Load Currents

Fig. 10 the three-phase unbalanced and distorted load currents. The three different types of heavy loads are connected on the distribution side at PCC that result in unbalance, excessive neutral current, reactive power demand, generation of losses, harmonics, ripples etc. As it can be seen that from the figure that at t=0.2s there is high consumption of load currents due to connection of non-linear load. Harmonics are also injected by the non-linear load due to their properties. By the connection PV-DSTATCOM at PCC (0.04s onwards) satisfies all reactive power demand locally, cancels the harmonics at PCC produced by the non-linear load whereas excessive neutral current is eliminated by the T-connected transformer. Thus, the system configuration performs a dual role, one using PV-DSTATCOM performs load compensation, second T-connected transformer compensates the neutral current.

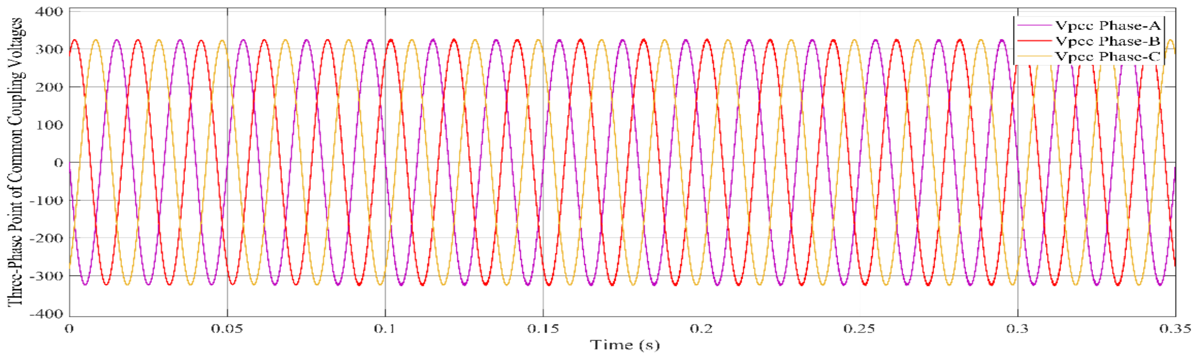

Fig. 11. Sinusoidal Point of common coupling voltages

Fig. 11 sinusoidal PCC voltages corrected by PV-DSTATCOM. All reactive power demand of load is satisfied by DSTATCOM plus harmonics cancellation at PCC. The noise from PCC voltages is drained and cancelled by the RC ripple filter. The Ripple filter has its mid-point connected with neutral wire of the system, so, all unwanted noise and switching ripples at PCC are bypassed towards neutral. Hence, PCC voltages become purely sinusoidal.

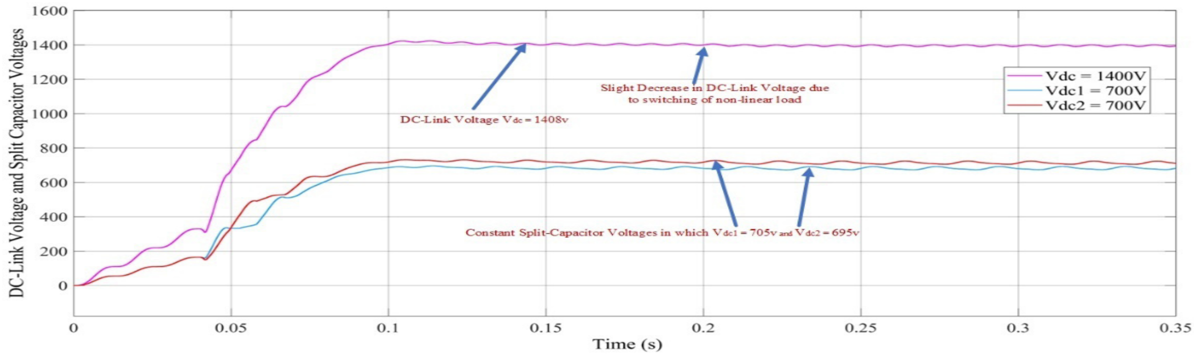

Fig.12. DC Link Voltage and Split-Capacitor Voltages of PV-DSTATCOM

Fig. 12 the dc link voltage and split capacitor voltages of the VSI for PV-DSTATCOM. The dc-link voltage of the inverter results in a slight drop due to switching of the heavy non-linear load but the new modified adaptive control of the DSTATCOM keeps DC link voltage constant (1400V) near to its reference value. With the result, split capacitor voltages also reach near to their reference value of 700V each by keeping their difference equal to zero.

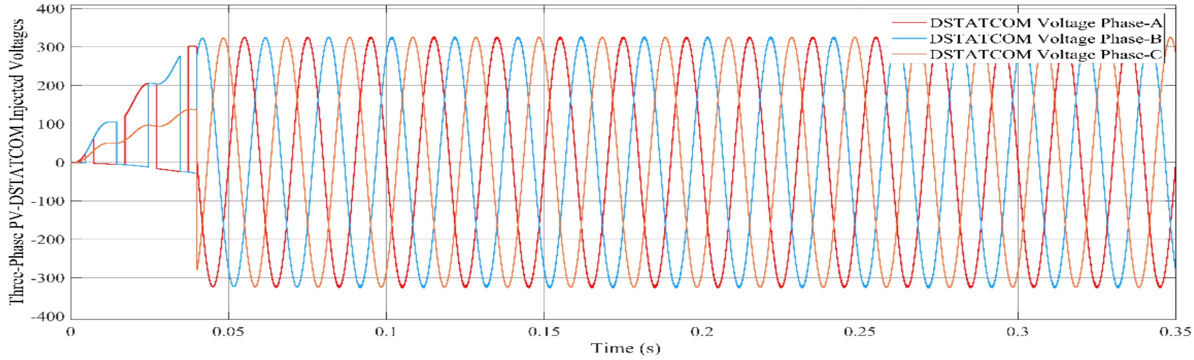

Fig. 13. Three-Phase PV-DSTATCOM Injected Voltages at PCC

Fig. 13 PV-DSTATCOM is connected at PCC at 0.04s and before the short period of time 0 to 0.03 the grid was under severe burden due to unbalance effect, excess reactive power demand, nonlinearities, harmonic effect of the dynamic load. After 0.04s the Load Compensation is done by PV-DSTATCOM and injects sinusoidal voltages at PCC. The magnitude of DSTATCOM voltage and current (leading or lagging) is automatically adjusted by the modified adaptive control algorithm through feedback system. The DSTATCOM voltages are not distorted because the reason is that there is also neutral current compensation done using the split-leg of H-Bridge inverter which results in discharge of harmonic spikes, noise etc. via neutral wire of three-phase four-wire system.

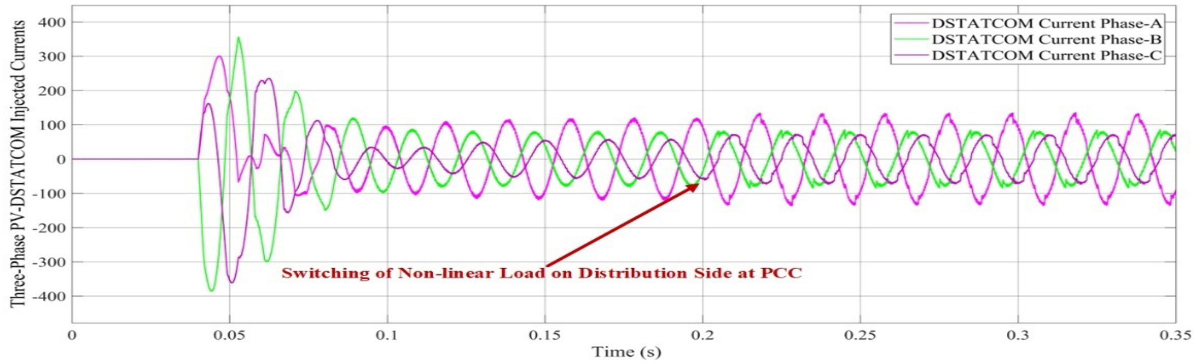

Fig. 14. Three-Phase PV-DSTATCOM Injected Currents

Fig. 14 three-phase PV-DSTATCOM injected currents, unbalance components from 0.1 to 0.2s are injected at PCC for compensation of load unbalance effect and reactive power but as on 0.2s onwards when non-linear load is switched on at PCC the PV-DSTATCOM injects harmonics also to cancel the dynamical load effect. The ripples and noise are discharged towards neutral via small capacitor, hence, the system remains free of such disturbances and PV-DSTATCOM fully performs the Load Compensation.

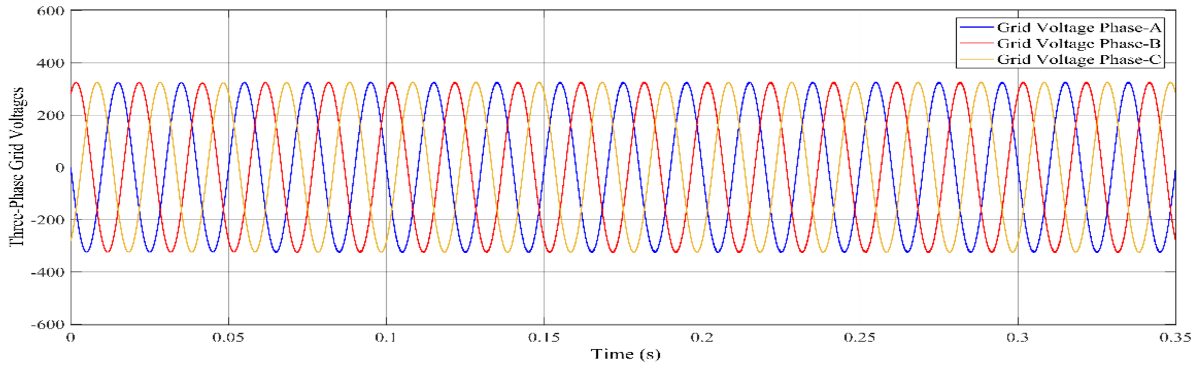

Fig. 15. Three-Phase Grid Voltages

Fig. 15 the three-phase grid voltages which are sinusoidal as PV-DSTATCOM performs the perfect load compensation at PCC and there is no effect in grid voltages, hence, are sinusoidal in nature. The grid continuously feeds the load and there is no disconnection to grid at PCC.

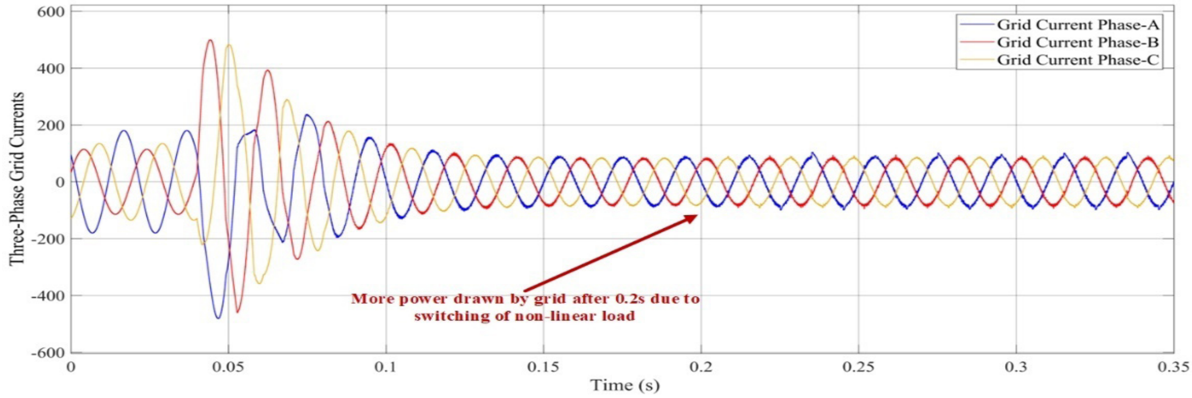

Fig. 16. Three-phase Grid Currents

Fig. 16 the three-phase sinusoidal grid currents. All reactive power demand of the load is satisfied locally by the PV-DSTATCOM at PCC including elimination of harmonic drawn by the non-linear load. Thus, grid currents attain sinusoidal form and hence power quality is improved.

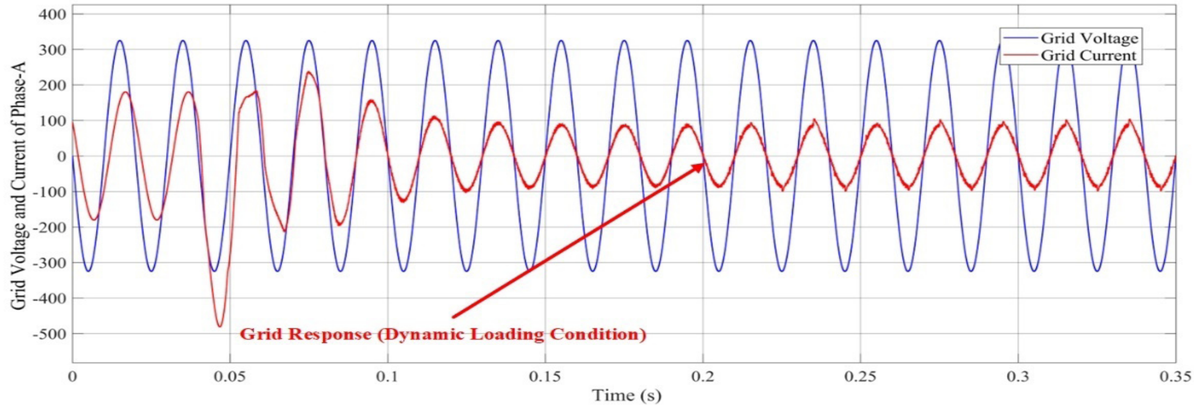

Fig. 17. Grid Voltage and Current of Phase-A

Fig. 17 the grid voltage and current of phase-A, the grid current linearly follows the grid voltage and there is no irrelevant phase shift in voltage or current after 0.1s, thus, power factor becomes equal to unity under dynamical loading conditions. Hence power quality is improved with the newly proposed work.

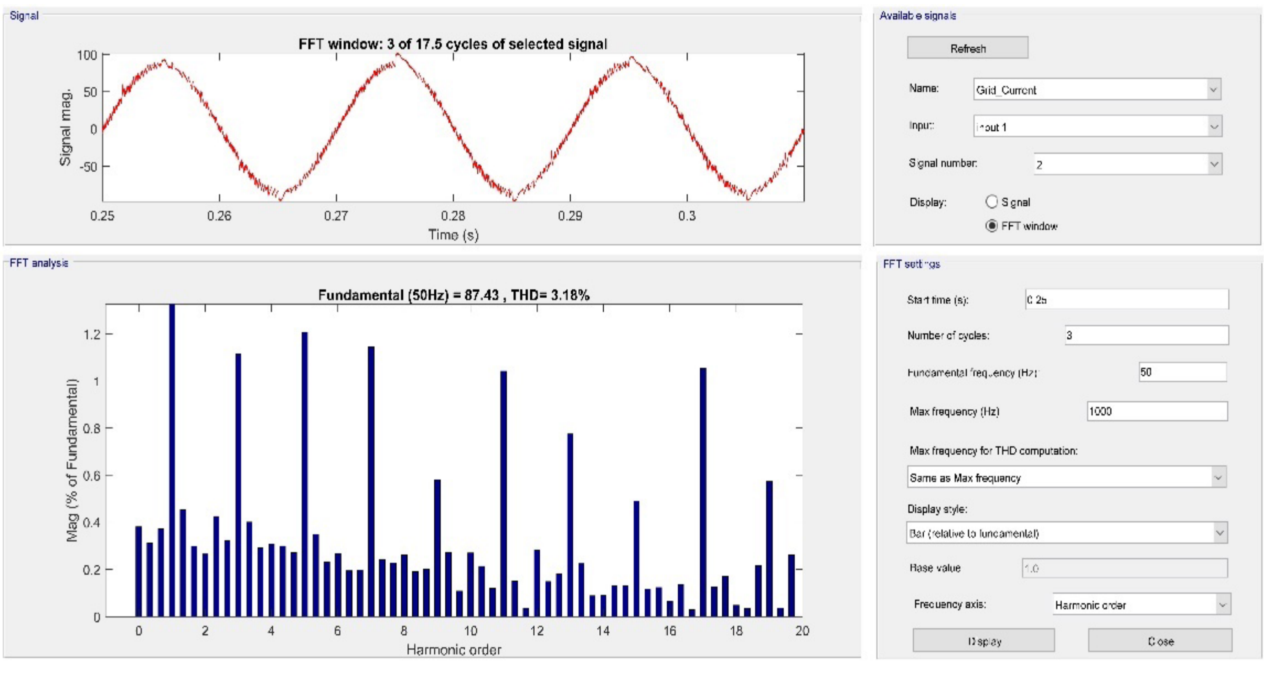

Fig. 18. THD FFT Analysis of Grid Current with PV-DSTATCOM

Fig. 18 the harmonic spectrum of grid current. THD of grid current for 3 cycles is only 3.18% which well below the Standard-519.

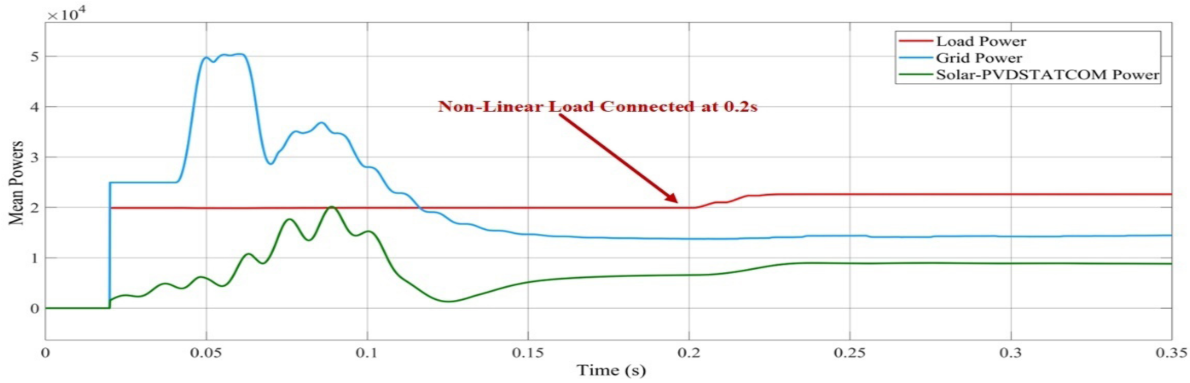

Fig. 19. Mean Powers of Load, Grid and Solar-PVDSTATCOM

Fig. 19 the mean powers of Load, Grid and Solar PV-DSTATCOM. Initially before 0.04s grid was feeding the load fully and all reactive power was drawn by the load from grid, when PV-DSTATCOM at 0.04s is connected at PCC the load reactive power demand is locally compensated plus with elimination of harmonics. In the grid-tied operation, the load is supplied by Solar-PV and grid. Solar-PV is integrated with grid via DSTATCOM and it supplies energy to different types of loads thereby reducing burden on the grid. The operation of Solar-PV is meant with solar insolation of 1000W/ and the highest power is produced (6500 Watts to 9000 watts) by adjusting the DC-link voltage with MPP. Grid power from 0.15s to 0.2s was 14000 watts after 0.2s of non-linear load switching grid power becomes equal to 19000 watts at 0.23s onwards. Load demand initially was constant about 20000 watts which later becomes 22600 watts due to non-linear load connection at PCC on distribution side. Some extra power generated by solar-PV is lost due to losses created by heavy dynamic load, but the system is still stable. Thus, the work proposes environmentally friendly solutions using solar PV and reduced burden on fossil fuels, in addition to load compensation.

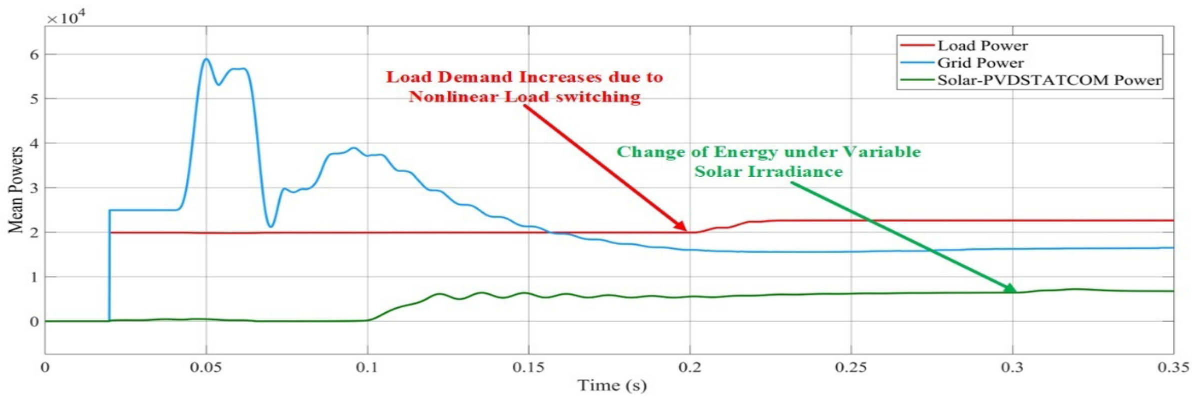

Fig.20. Mean Powers under Variable Solar Irradiance

Fig. 20 the mean powers under Variable Solar Irradiance conditions. Load Demand is constant 20000 watts up to 0.2s and it increases above 20000 watts to 22600 watts due to increment in load, Grid power increases initially because solar PV-DSTATCOM is connected at 0.04s and remains almost constant after 0.2s.

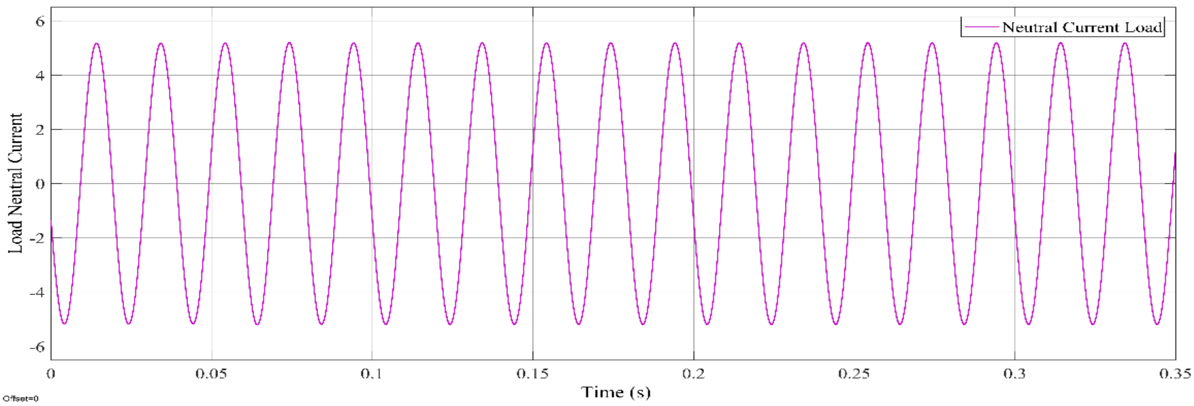

Fig. 21. Load Neutral Current

Fig. 21 the load neutral current. The unwanted neutral current is alleviated by the proposed system and this neutral current is about 5A. This neutral current occurs because of unbalanced loads, due to neutral grounding of parallel RLC loads and due to connection of single-phase loads to the three-phase for-wire system.

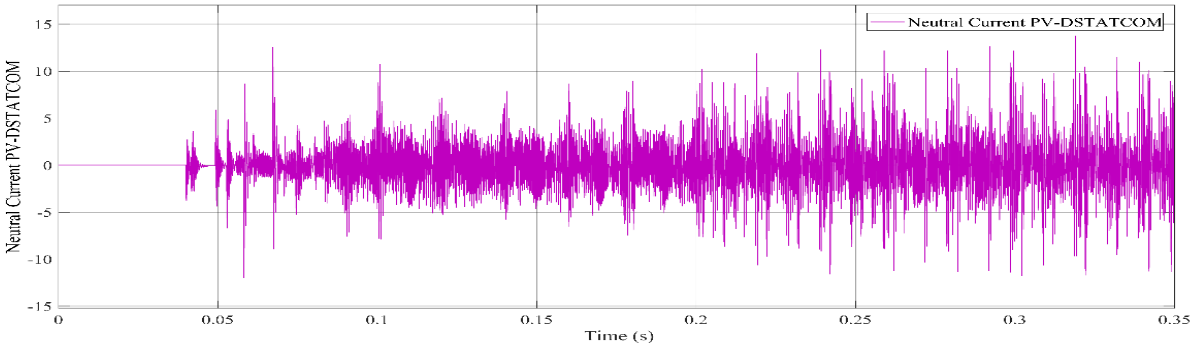

Fig. 22. Neutral current from PV-DSTATCOM

Fig. 22 the neutral current from PV-DSTATCOM, it is having distortions because the split-leg of H-Bridge inverter (DSTATCOM) is connected via a small capacitance to the neutral wire of the system. This current was zero initially up to 0.04s because PV-DSTATCOM was not connected, after 0.04s we can observe the spikes in neutral current due to discharge of switching noise and ripples from the inverter during compensation of reactive power, elimination of harmonics etc. The current is having high noisy magnitude after 0.2s as nonlinear load is compensated by the system, thus, the proposed work elegantly performs inverter neutral current compensation.

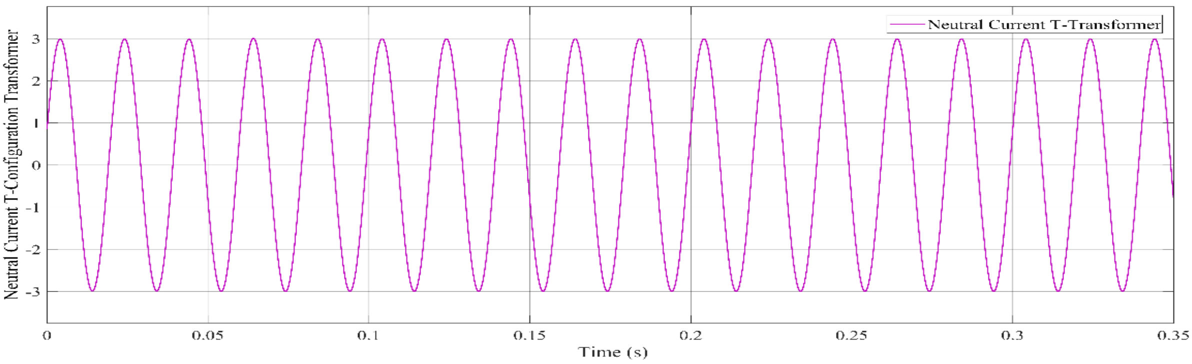

Fig. 23. Neutral current from T-Configuration Transformer

Fig. 23 the neutral current compensation done by T-Connected Transformer and the neutral current is only around 3A, it means the T-Connected transformer performs better elimination of neutral current. Thus, source neutral current should be very low.

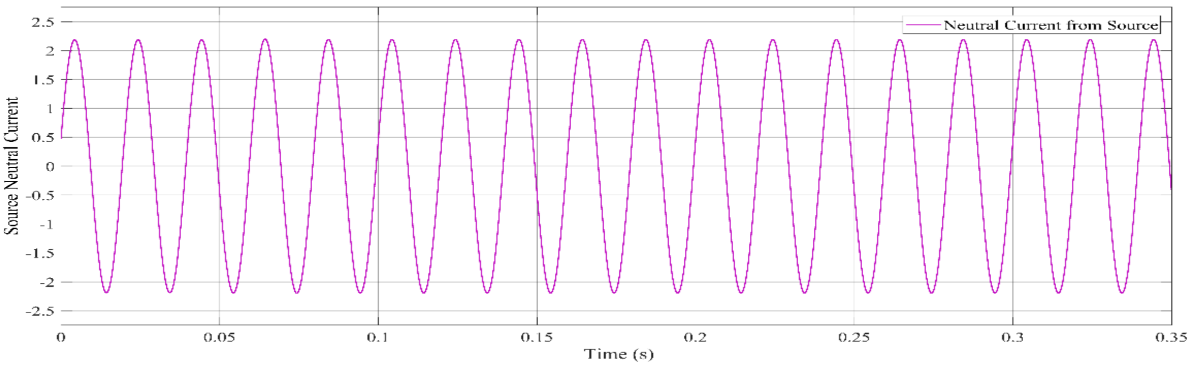

Fig. 24. Depicts compensated neutral current source/grid.

CONCLUSION

This work proposes IC-MPPT boost converter circuit based reduced switch PV-DSTATCOM which is connected to a three-phase four-wire system at PCC. The modified adaptive control strategy successfully performs load compensation under dynamic conditions. Grid power factor is brought equal to unity under heavy load. The neutral current is compensated by the T-Connected transformer. Inverter harmonic spikes, noise, ripples are also drained via split-leg of reduced switch DSTATCOM using small capacitor. The grid-tied Solar PV-DSTATCOM performs power sharing with grid under heavy dynamic loading conditions. The DC-link voltage and split capacitor voltages of the PV-DSTATCOM are regulated to their reference bus voltages under all varying loads by the modified adaptive control strategy. The size and cost of the converter, conduction and switching losses are reduced by the elimination of two IGBTs. Reactive power compensation, harmonics elimination and unbalance compensation are elegantly done by the PV-DSTATCOM and improve the overall performance of the system.

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Citation: Ehsanul Haque Peerzadah, Rehana Perveen, Abdul Hamid Bhat, "Implementation of Modified Adaptive Control Strategy for Reduced-Switch PV-DSTATCOM with a T-Connected Transformer for Power Quality Improvement", American Research Journal of Electrical Engineering, Vol 4, no. 1, 2025, pp. 1-17.

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