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Voltage Controlled DSTATCOM for Power-Quality Improvement with Photovoltaic System

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Abstract:

This paper proposes a new algorithm to generate reference voltage for a distribution static compensator (DSTATCOM) operating in voltage-control mode. In this DSTATCOM is implemented by using renewable energy like solar power system/Photovoltaic system. The main disadvantage of using renewable sources is that which are not connected to grid because of variability in the energy production. The proposed scheme ensures that unity power factor (UPF) is achieved at the load terminal during nominal operation, which is not possible in the traditional method with the renewable solar energy conversion and also used to maintain as DC link voltage to the STATCOM. In order to maintain the power system quality the D-statcom will absorb and provide reactive power to mitigate voltage sag, swell, interruption and improve power factor in various conditions.

Also, the compensator injects lower currents and, therefore, reduces losses in the feeder and voltage-source inverter. Further, a saving in the rating of DSTATCOM is achieved which increases its capacity to mitigate voltage sag. Nearly UPF is maintained, while regulating voltage at the load terminal, during load change. The state-space model of DSTATCOM is incorporated with the deadbeat predictive controller for fast load voltage regulation during voltage disturbances. With these features, this scheme allows DSTATCOM to tackle power-quality issues by providing power factor correction, harmonic elimination, load balancing, and voltage regulation based on the load requirement. Simulation results are presented to demonstrate the efficiency of the proposed algorithm by using MATLAB /Simulink Software.

Index Terms:

Current control mode, power quality (PQ), voltage-control mode, Solar Based voltage-source inverter.

I. Introduction:

Renewable Energy Sources are those energy sources which are not destroyed when their energy is harnessed. Human use of renewable energy requires technologies that harness natural phenomena, such as sunlight, wind, waves, water flow, and biological processes such as anaerobic digestion, biological hydrogen production and geothermal heat. Amongst the above mentioned sources of energy there has been a lot of development in the technology for harnessing energy from the wind. Wind is the motion of air masses produced by the irregular heating of the earth's surface by sun. These differences consequently create forces that push air masses around for balancing the global temperature or, on a much smaller scale, the temperature between land and sea or between mountains. One of the most common power quality problems today is voltage dips. A voltage dip is a short time (10 ms to 1 minute) event during which a reduction in r.m.s voltage magnitude occurs. It is often set only by two parameters, depth/magnitude and duration. The voltage dip magnitude is ranged from 10% to 90% of nominal voltage (which corresponds to 90% to 10% remaining voltage) and with a duration from half a cycle to 1 min. In a three-phase system a voltage dip is by nature a three-phase phenomenon, which affects both the phase-to-ground and phase-to-phase voltages. A voltage dip is caused by a fault in the utility system, a fault within the customer‟s facility or a large increase of the load current, like starting a motor or transformer energizing. Typical faults are single-phase or multiple-phase short circuits, which leads to high currents. The high current results in a voltage drop over the network impedance. At the fault location the voltage in the faulted phases drops close to zero, whereas in the non-faulted phases it remains more or less unchanged. Voltage dips are one of the most occurring power quality problems. Off course, for an industry an outage is worse, than a voltage dip, but voltage dips occur more often and cause severe problems and economical losses.

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Utilities often focus on disturbances from end-user equipment as the main power quality problems. This is correct for many disturbances, flicker, harmonics, etc., but voltage dips mainly have their origin in the higher voltage levels. Faults due to lightning, is one of the most common causes to voltage dips on overhead lines. If the economical losses due to voltage dips are significant, mitigation actions can be profitable for the customer and even in some cases for the utility. Since there is no standard solution which will work for every site, each mitigation action must be carefully planned and evaluated. There are different ways to mitigate voltage dips, swell and interruptions in transmission and distribution systems. At present, a wide range of very flexible controllers, which capitalize on newly available power electronics components, are emerging for custom power applications. Among these, the distribution static compensator and the dynamic voltage restorer are most effective devices, both of them based on the VSC principle. STATCOM is often used in transmission system. When it is used in distribution system, it is called DSTATCOM STATCOM in Distribution system). DSTATCOM is a key FACTS controller and it utilizes power electronics to solve many power quality problems commonly faced by distribution systems.

Potential applications of D-STATCOM include power factor correction, voltage regulation, load balancing and harmonic reduction. Comparing with the SVC, the D-STATCOM has quicker response time and compact structure. It is expected that the D-STATCOM will replace the roles of SVC in nearly future. D-STATCOM and STATCOM are different in both structure and function, while the choice of control strategy is related to the main-circuit structure and main function of compensators, so D-STATCOM and STATCOM adopt different control strategy. At present, the use of STATCOM is wide and its strategy is mature, while the introduction of D-STATCOM is seldom reported. Many control techniques are reported such as instantaneous reactive power theory (Akagi et al., 1984), power balance theory, etc. In this paper, an indirect current control technique (Singh et al., 2000a, b) is employed to obtain gating signals for the Insulated Gate Bipolar Transistor (IGBT) devices used in current controlled voltage source inverter (CC-VSI) working as a DSTATCOM. This paper considers the operation of DSTATCOM in VCM and proposes a control algorithm to obtain the reference load terminal voltage by using Photovoltaic system. This algorithm provides the combined advantages of CCM and VCM. The UPF operation at the PCC is achieved at nominal load, whereas fast voltage regulation is provided during voltage disturbances. Also, the reactive and harmonic component of load current is supplied by the compensator at any time of operation. The deadbeat predictive controller is used to generate switching pulses. The control strategy is tested with a three-phase four-wire distribution system. The effectiveness of the proposed algorithm is validated through detailed simulation and experimental results.

II. Overview of a photovoltaic (PV) module :

To understand the PV module characteristics it is necessary to study about PV cell at first. A PV cell is the basic structural unit of the PV module that generates current carriers when sunlight falls on it. The power generated by these PV cell is very small. To increase the output power the PV cells are connected in series or parallel to form PV module. The electrical equivalent circuit of the PV cell is shown in Fig 1.

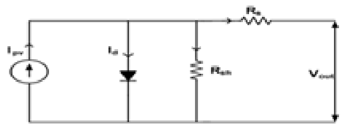

Fig 1: Electrical equivalent circuit diagram of PV cell

The main characteristics equation of the PV module is given by

$$I = I_{pv} - I_o\left[\exp\left(\frac{q(V+IR_s)}{\alpha KT}\right)-1\right]-\frac{V+IR_s}{R_{sh}} \quad (1)$$

$$I_o = I_{o,n}\left(\frac{T_n}{T}\right)^3 \exp\left[\frac{qE_g}{\alpha K}\right]\left(\frac{1}{T_n}-\frac{1}{T}\right) \quad (2)$$

$$I_{pv} = [I_{sc} + K_i(T-T_n)]\frac{G}{G_n} \quad (3)$$

Where,
I and V - cell output current and voltage;
Io - cell reverse saturation current;
T - Cell temperature in Celsius;
K - Boltzmann’s constant;
q - Electronic charge;
Ki- short circuit current/temperature coefficient;
G - Solar radiation in W/m2;
Gn- nominal solar radiation in W/m2;
Eg - energy gap of silicon;
Io,n - nominal saturation current;
Rs - Series resistance;

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Rsh - shunt resistance;

I-V characteristic of a PV module is highly non-linear in nature. This characteristics drastically changes with respect to changes in the solar radiation and cell temperature. Whereas the solar radiation mainly affects the output current, the temperature affects the terminal voltage. Fig.2 shows the I-V characteristic of the PV module under varying solar radiations at constant cell temperature (T = 25 ºC).

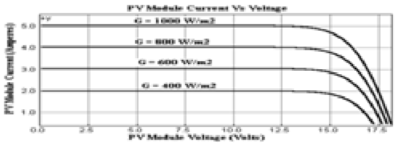

Fig 2: Current versus voltage at constant cell temperature T = 25 ºC.

Fig.3 shows the I-V characteristics of the PV module under varying cell temperature at constant solar radiation (1000 W/m2).

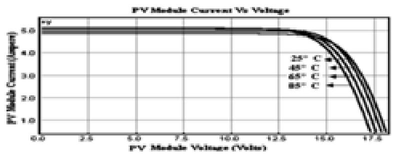

Fig 3: Current versus voltage at constant solar radiation G = 1000 W/m2

III. PROPOSED CONTROL SCHEME:

Circuit diagram of a DSTATCOM -compensated distribution system is shown in Fig. 4. It uses a three- phase, four-wire, two-level, neutral-point-clamped VSI. This structure allows independent control to each leg of the VSI. Fig. 5 shows the single-phase equivalent representation of Fig. 1. Variable is a switching function, and can be either or depending upon switching state. Filter inductance and resistance are and , respectively. Shunt capacitor eliminates high-switching frequency components.First, discrete modeling of the system is presented to obtain a discrete voltage control law, and it is shown that the PCC voltage can be regulated to the desired value with properly chosen parameters of the VSI. Then, a procedure to design VSI parameters is presented. A proportional-integral (PI) controller is used to regulate the dc capacitor voltage at a reference value. Based on instantaneous symmetrical component theory and complex Fourier transform, a reference voltage magnitude generation scheme is proposed that provides the advantages of CCM at nominal load. The overall controller block diagram is shown in Fig. 6. These steps are explained as follows.

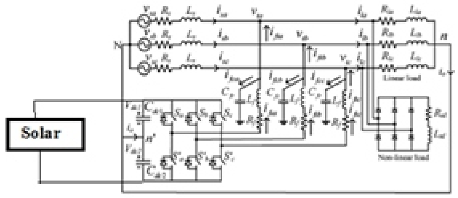

Fig 4: Circuit diagram of the DSTATCOM-compensated distribution system.

System Modeling and Generation of the Voltage-Control Law

The state-space equations for the circuit shown in Fig. 5 are given by

$$\dot{x} = A\,x + B\,z \quad (4)$$

Where,

$$A = \begin{bmatrix} 0 & \frac{1}{C_{fc}} & 0 \\ -\frac{1}{L_f} & -\frac{R_f}{L_f} & 0 \\ -\frac{1}{L_s} & 0 & -\frac{R_s}{L_s} \end{bmatrix},$$

$$B = \begin{bmatrix} 0 & -\frac{1}{C_{fc}} & 0 \\ \frac{V_{dc}}{L_f} & 0 & 0 \\ 0 & 0 & \frac{1}{L_s} \end{bmatrix},$$

$$x = [v_{fc} \quad i_{fi} \quad i_s]^t, \quad z = [u \quad i_{ft} \quad v_s]^t$$

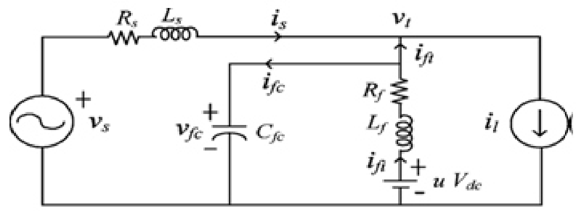

Fig5: Single-phase equivalent circuit of DSTATCOM

The general time-domain solution of (4) to compute the state vector x(t) with known initial value x(t0) , is given as follows:

$$x(t) = e^{A(t-t_0)}\,x(t_0) + \int_{t_0}^{t} e^{A(t-\tau)}B\,z(\tau)\,d\tau. \quad (5)$$

The equivalent discrete solution of the continuous state is obtained by replacing and as follows:

$$x(k+1) = e^{AT_d}\,x(k) + \int_{kT_d}^{T_d+kT_d} e^{A(T_d+kT_d-\tau)}B\,z(\tau)\,d\tau. \quad (6)$$

In (6), k and Td represent the Kth sample and sampling period, respectively. During the consecutive sampling period, the value of Z(t) is held constant, and can be taken as Z(k). After simplification and changing the integration variable, (6) is written as

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$$x(k+1) = e^{AT_d}\, x(k) + \int_0^{T_d} e^{A\lambda} B\, d\lambda\, z(k). \quad (7)$$

Equation (6) is rewritten as follows:

$$x(k+1) = G\, x(k) + H\, z(k) \quad (8)$$

Where, G and H are sampled matrices, with a sampling time of Td. For small sampling time, matrices G and H are calculated as follows:

$$G = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{bmatrix} = e^{AT_d} \approx I + AT_d + \frac{A^2 T_d^2}{2}$$
$$H = \begin{bmatrix} H_{11} & H_{12} & H_{13} \\ H_{21} & H_{22} & H_{23} \\ H_{31} & H_{32} & H_{33} \end{bmatrix} = \int_0^{T_d} e^{A\lambda} B\, d\lambda$$
$$\approx \int_0^{T_d} (I + A\lambda)\, B\, d\lambda. \quad (9)$$

From (9),
$G_{11} = 1 - T_d^2/2L_f C_{fc}$, $G_{13} = 0$, $H_{11} = T_d^2 V_{dc}/2L_f C_{fc}$, Hence, the capacitor voltage using (8) is given as

$$v_{fc}(k+1) = G_{11} v_{fc}(k) + G_{12} i_{fi}(k) + H_{11} u(k) + H_{12} i_{ft}(k)$$
(10)

As seen from (8), the terminal voltage can be maintained at a reference value depending upon the VSI parameters Vdc, Cfc, Lf , Rf , and sampling time Td . Therefore, VSI parameters must be chosen carefully. Let Vt* be the reference load terminal voltage. A cost function is chosen as follows

$$J = [v_{fc}(k+1) - v_t^*(k+1)]^2 \quad (11)$$

The cost function is differentiated with respect to u(k) and its minimum is obtained at

$$v_{fc}(k+1) = v_t^*(k+1) \quad (12)$$

The deadbeat voltage-control law, from (10) and (12), is given as

$$u^*(k) = \frac{v_t^*(k+1) - G_{11} v_{fc}(k) - G_{12} i_{fi}(k) - H_{12} i_{ft}(k)}{H_{11}}.$$
(13)

In (13), u*(K+1) is the future reference voltage which is unknown. One-step-ahead prediction of this voltage is done using a second-order Lagrange extrapolation formula as follows:

$$v_t^*(k+1) = 3\,v_t^*(k) - 3\,v_t^*(k-1) + v_t^*(k-2). \quad (14)$$

The term u*(K+1) is valid for a wide frequency range and when substituted in (13), yields to a one-step-ahead deadbeat voltage-control law. Finally u*(k) is converted into the ON/OFF switching command to the corresponding VSI switches using a deadbeat hysteresis controller.

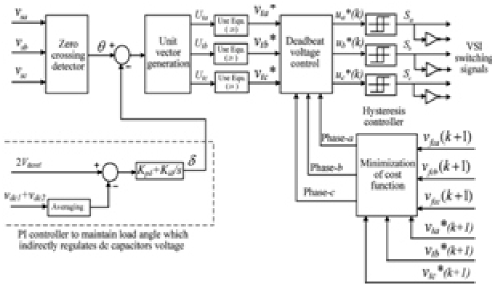

Fig 6: Overall block diagram of the controller to control DSTATCOM in a distribution system.

b.Proposed Method To Generate Reference Terminal Voltages:

Reference terminal voltages are generated such that, at nominal load, all advantages of CCM operation are achieved while DSTATCOM is operating in VCM. Hence, the DSTATCOM will inject reactive and harmonic components of load current. To achieve this, first the fundamental positive-sequence component of load currents is computed. Then, it is assumed that these currents come from the source and considered as reference source currents at nominal load. With these source currents and for UPF at the PCC, the magnitude of the PCC voltage is calculated. Let three-phase load currents Ila,Ilb,Ilc, and be represented by the following equations:

$$i_{lj}(t) = \sum_{n=1}^{m} \sqrt{2}\, I_{lj\,n} \sin(n\,\omega t + \phi_{lj\,n}) \quad (15)$$

where j= a,b,c represent three phases, n is the harmonic number, and m is the maximum harmonic order. Represents the phase angle of the th harmonic with respect to reference in phase- and is similar to other phases. Using instantaneous symmetrical component theory, instantaneous zero-sequence , positive-sequence , and negative-sequence current components are calculated as follows:

$$\begin{bmatrix} i_{la}^0(t) \\ i_{la}^+(t) \\ i_{la}^-(t) \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \begin{bmatrix} i_{la}(t) \\ i_{lb}(t) \\ i_{lc}(t) \end{bmatrix} \quad (16)$$

where is alpha a complex operator
The fundamental positive-sequence component of load current , calculated by finding the complex Fourier coefficient, is expressed as follows

$$\bar{I}_{la1}^+ = \frac{\sqrt{2}}{T} \int_0^T i_{la}^+(t)\, e^{-j(\omega t - 90^\circ)}\, dt \quad (17)$$

Ila1 is a complex quantity, contains magnitude and phase angle information, and can be expressed in phasor form as follows:

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$$\bar{I}^{+}_{la1} = |\bar{I}^{+}_{la1}| \angle \bar{I}^{+}_{la1}. \quad (18)$$

Hence, the instantaneous fundamental positive-sequence component of load current in phase ila1(t) , is expressed as

$$i^{+}_{la1}(t) = \sqrt{2}\,|\bar{I}^{+}_{la1}| \sin\left(\omega t + \angle \bar{I}^{+}_{la1}\right) \quad (19)$$

The fundamental positive-sequence component of load currents must be supplied by the source at nominal load. Hence, it will be treated as reference source currents.

$$\begin{aligned} i^{*}_{sa} &= i^{+}_{la1}(t) = \sqrt{2}\,|\bar{I}^{+}_{la1}| \sin(\omega t - \delta_0) \\ i^{*}_{sb} &= i^{+}_{lb1}(t) = \sqrt{2}\,|\bar{I}^{+}_{la1}| \sin\left(\omega t - \frac{2\pi}{3} - \delta_0\right) \\ i^{*}_{sc} &= i^{+}_{lc1}(t) = \sqrt{2}\,|\bar{I}^{+}_{la1}| \sin\left(\omega t + \frac{2\pi}{3} - \delta_0\right) \end{aligned} \quad (20)$$

When reference source currents derived in (20) are supplied by the source, three-phase terminal voltages can be computed using the following equations:

$$v_{tj}(t) = v_{sj}(t) - L_s \frac{di^{*}_{sj}}{dt} - R_s i^{*}_{sj}. \quad (21)$$

Let the rms value of reference terminal and source voltages be Vt* and V , respectively. For UPF, the source current and terminal voltage will be in phase. However, to obtain the expression of independent of V* , we assume the PCC voltage as a reference phasor for the time-being. Hence, phase- quantities, by considering UPF at the PCC, will be

$$\begin{aligned} v_{ta}(t) &= \sqrt{2}\,V_t^{*} \sin \omega t \\ i^{*}_{sa} &= \sqrt{2}\,|\bar{I}^{+}_{la1}| \sin \omega t \\ v_{sa}(t) &= \sqrt{2}\,V \sin(\omega t + \delta_0) \end{aligned} \quad (22)$$

Substituting (22) into (21), the phasor equation will be

$$V_t^{*}\angle 0 = V\angle \delta_0 - (R_s + jX_s)\,|\bar{I}^{+}_{la1}| \angle 0. \quad (23)$$

Simplifying the above equation

$$V_t^{*} = V\cos\delta_0 + jV\sin\delta_0 - |\bar{I}^{+}_{la1}|\,R_s - j\,|\bar{I}^{+}_{la1}|\,X_s \quad (24)$$

Equating real and imaginary parts of both sides of (24), the following equation is obtained:

$$\begin{aligned} V\cos\delta_0 &= V_t^{*} + |\bar{I}^{+}_{la1}|\,R_s \\ V\sin\delta_0 &= |\bar{I}^{+}_{la1}|\,X_s. \end{aligned} \quad (25)$$

To remove from (25), both sides are squared and added to obtain the following:

$$V^2 = \left(V_t^{*} + |\bar{I}^{+}_{la1}|\,R_s\right)^2 + \left(|\bar{I}^{+}_{la1}|\,X_s\right)^2 \quad (26)$$

After rearranging (26), the expression for reference load voltage magnitude will be

$$V_t^{*} = \sqrt{V^2 - \left(|\bar{I}^{+}_{la1}|\,X_s\right)^2} - |\bar{I}^{+}_{la1}|\,R_s. \quad (27)$$

Finally, using from (27), the load angle, and the phase-source voltage as reference, three-phase reference terminal voltages are given as

$$\begin{aligned} v^{*}_{ta}(t) &= \sqrt{2}\,V_t^{*} \sin(\omega t - \delta) \\ v^{*}_{tb}(t) &= \sqrt{2}\,V_t^{*} \sin\left(\omega t - \frac{2\pi}{3} - \delta\right) \\ v^{*}_{tc}(t) &= \sqrt{2}\,V_t^{*} \sin\left(\omega t + \frac{2\pi}{3} - \delta\right) \end{aligned} \quad (28)$$

IV. Simulation Results :

The below figure shows that simulation circuit diagram and the respective waveforms as shown with the MAT-LAB/Simulink software.

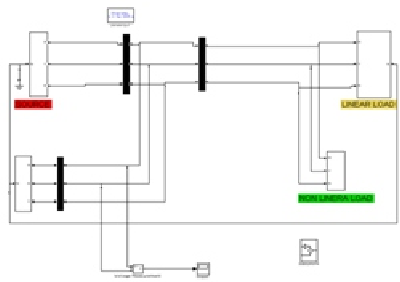

Fig7: Simulation circuit diagram of a proposed converter system

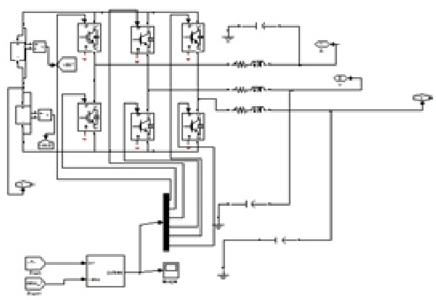

Fig 8: Simulation circuit diagram of a shunt active power filter

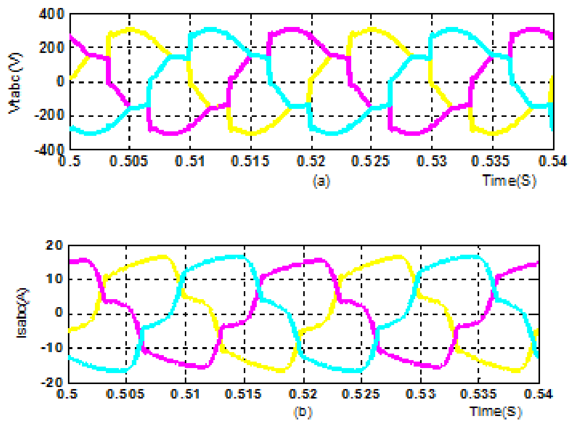

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Fig 9: Before compensation. (a) Terminal voltages. (b) Source currents.

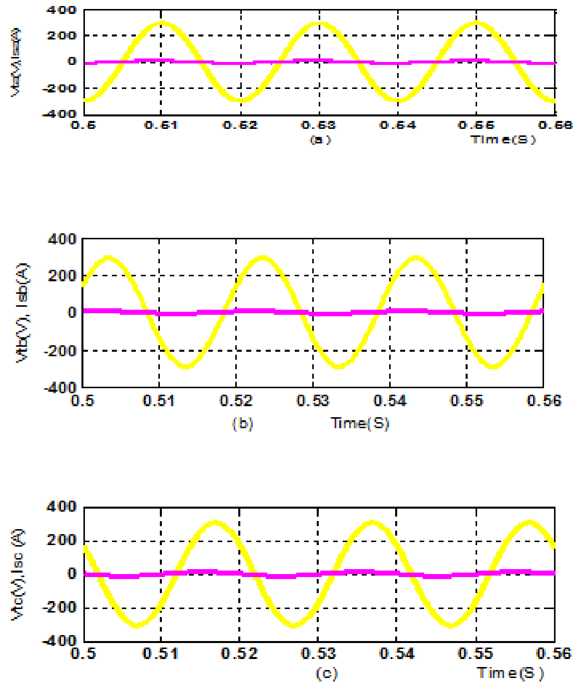

Fig10: Terminal voltages and source currents using the proposed method. (a)Phase a (b) Phase b (c) Phase c

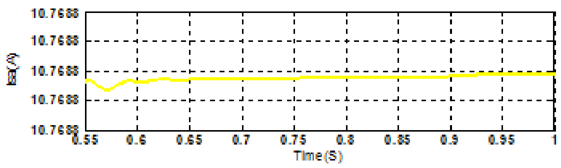

Fig 11: Phase- source rms currents.

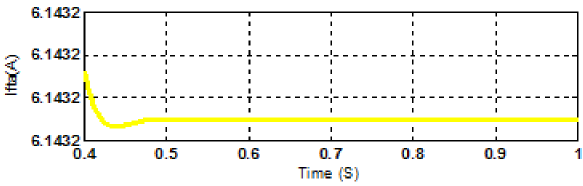

Fig 12: Phase- compensator rms currents.

V. CONCLUSION:

In this paper, a control algorithm has been proposed for the generation of reference load voltage for a voltage-controlled DSTATCOM by using Photovoltaic system. The performance of the proposed scheme is compared with the traditional voltage-controlled DSTATCOM.

Hysteresis loss current control algorithm utilizes the error signal which is the difference between the reference voltage and actual measured load voltage to trigger the switches of an inverter using a Pulse Width Modulation (PWM) scheme. The DSTATCOM handled the situation without any difficulties and injected the appropriate voltage component to correct rapidly any changes in the supply voltage there by keeping the load voltage balanced and constant at the nominal value. The proposed method provides the following advantages: 1) at nominal load, the compensator injects reactive and harmonic components of load currents, resulting in UPF; 2) nearly UPF is maintained for a load change; 3) fast voltage regulation has been achieved during voltage disturbances; and 4) losses in the VSI and feeder are reduced considerably, and have higher sag supporting capability with the same VSI rating compared to the traditional scheme. The simulation shows that the proposed scheme provides DSTATCOM, a capability to improve several PQ problems (related to voltage and current).

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