Control of Photovoltaic System with A DC-DC Boost Converter Fed DSTATCOM Using IcosΦ Algorithm

V. Kamatchi Kannan1* and N. Rengarajan2

1Department of Electrical and Electronics Engineering, K.S.R College of Engineering, K.S.R. Kalvi Nagar, Tiruchengode, Tamilnadu, India
2K.S.R. College of Engineering, K.S.R. Kalvi Nagar, Tiruchengode, Tamilnadu, India

Abstract

In this paper, a three-phase three-wire Distribution STATic COMpensator (DSTATCOM) which is fed by Photovoltaic (PV) array or battery operated DC-DC boost converter is proposed for reactive power compensation, source current harmonic reduction and load compensation in the distribution system. The proposed DSTATCOM consists of a three-leg Voltage Source Converter (VSC) with a dc bus capacitor. The PV array or battery operated boost converter is proposed to maintain the dc link voltage of the dc bus capacitor for continuous compensation for the load. This paper presents to evaluate the performance comparison of two control strategies for extracting the reference currents to control the proposed DSTATCOM. The two control methods are Synchronous Reference Frame (SRF) theory and IcosΦ algorithm. The switching of VSC will occur by comparing the source current with the reference current using Hysteresis based Pulse Width Modulation (PWM) current controller. The performance of the DSTATCOM is validated using MATLAB software with its simulink and Power System Blockset (PSB) toolboxes. The simulation results for the two control methods are compared to validate the superior performance of the IcosΦ algorithm. By comparing, the source current THD is reduced to acceptable level 5% of IEEE-519-1992 in IcosΦ method.

Key Words: Distribution STAtic COMpensator, Photo Voltaic Array, Boost Converter, Voltage Source Converter, IcosΦ Controlling Algorithm

1. Introduction

Electricity is a convenient form of energy for lighting, heating, cooling and also produces motive power for number of applications. Hence, the annual consumption of electricity has been increasing rapidly throughout the world. Thus, the increased usage of electricity in the modern day world challenges the economic co-operations of a power system with a greater focus on power quality [1,2]. Many researchers have focused on renewable energy source based power quality improvement in the power distribution system [3–5]. Power quality has caused a great concern to electric utilities with the growing use of electronic and computing equipment such as personal computers, uninterruptible power supplies, printers, etc. and other nonlinear loads such as fluorescent lighting, adjustable speed drives, heating and lighting control etc. These nonlinear loads of power electronic devices create major power problem in the distribution system which tends to power quality problem. The various power electronic based devices called custom power devices used to mitigate the power quality problems have been proposed in the literature survey [6,7]. Among these, DSTATCOM is the most effective device [8,9].

The Distribution STAtic COMpensator (DSTATCOM) is one of the shunt connected custom power device which injects current through the interface inductor at the Point of Common Coupling (PCC) to mitigate the
power quality problems. The different topologies of DSTATCOM are reported in the literature such as a 4-leg VSC (Voltage Source Converter), three single phase VSC, 3-leg VSC with split capacitor DSTATCOM [10, 11]. The proposed DSTATCOM consists of three-leg VSC with a dc bus capacitor. The operation of VSC is supported by a dc bus capacitor with proper dc voltage across it. For controlling DSTATCOM, and hence to generate the reference currents there are number of controllers reported in the literature survey such as instantaneous reactive power theory, adaptive neural network, power balance theory, synchronous reference frame theory and IcosΦ controlling algorithm [4,12–19]. In this paper, the IcosΦ controlling algorithm is compared with Synchronous Reference Frame (SRF) theory to validate the effectiveness of the IcosΦ method. After tracking the reference currents with the help of these controllers and by comparing it with source currents, the switching of VSC will occur and hence cancel out the disturbances caused by the nonlinear loads. The Photo Voltaic (PV) module or battery operated boost converter is proposed to maintain the dc bus capacitor voltage of the VSC for providing continuous reactive power compensation, source current harmonic reduction and load compensation throughout the day. The proposed system is simulated under MATLAB environment using SIMULINK and simpowersystem tool boxes.

2. System Configuration

Figure 1 shows the circuit diagram of the three-phase three-wire system which is used to feed the nonlinear load continuously. The nature of the nonlinear load is to cause distortion in the current. After connecting the nonlinear load, suddenly there will be a distortion in the distribution system. In order to eliminate these distortions, the control of DSTATCOM is achieved by using SRF theory and IcosΦ algorithm. The DSTATCOM consists of six Insulated Gate Bipolar Transistor (IGBT) with antiparallel diode based three-leg VSC connected in shunt with the dc bus capacitor. The PV module or battery with the DC-DC boost converter is connected with the dc bus capacitor, which is used to give a desired voltage across the capacitor for continuous compensation. According to the gate pulse given, the switching of VSC will occur which injects currents at the PCC.
through the interface inductor \( L_r \).

3. Photovoltaic Module

Photovoltaic (PV) is one of the major power sources, becoming more affordable and reliable than utilities [20, 21]. Photovoltaic is the method of converting solar radiation into direct current electricity which generates an electric power by using semiconductors that exhibit the photovoltaic effect. PV module is a connected assembly of photovoltaic cells. Hence, it will be connected in parallel to produce high current and in series to produce high voltage. Then, separate diodes and capacitors are connected to avoid the reverse currents. Figure 2 shows the equivalent circuit of a PV cell. It consists of a current source in parallel with a diode which represents the nonlinear impedance of the pn junction and also a small series and a high parallel intrinsic resistance. The output current of the solar cell can be represented as

\[
I = I_{ph} - I_{sat} \left( e^{\frac{q(V - IR_p)}{AKT}} - 1 \right) - \left( \frac{V - IR_s}{R_p} \right)
\]

where, \( I \) = Output current of solar cell, \( I_{ph} \) = Photocurrent, \( I_{sat} \) = Saturation current of the diode (10\(^{-4}\) A), \( q \) = Electron charge (1.6 \times 10\(^{-19}\) C), \( V \) = Voltage on the load, \( R_s \) = Series intrinsic resistance, \( R_p \) = Parallel intrinsic resistance, \( k \) = Boltzman’s constant (1.38 \times 10\(^{-23}\) J/K), \( T \) = Cell temperature (K), \( A \) = Ideality factor.

To model the PV module in MATLAB-SIMULINK, the parameters are obtained from SHANSHAN ULICA UL-175D photovoltaic module [22]. The solar irradiance (G) and temperature (T) were taken as standard test conditions which are 1000 Watt/m\(^2\) and 25 °C respectively.

The proposed DSTATCOM has three operating modes. They are (i) Day time excess power mode, (ii) Day time mode, (iii) Night time mode.

i. Day time excess power mode

The PV array output drives the boost converter fed DSTATCOM for compensating the source as well as it charges the 35V battery.

ii. Day time mode

To provide continuous compensation, if the PV output voltage is equal to the boost converter input, the PV array drives the boost converter so as to step-up the voltage and match the dc link requirement of the DSTATCOM. The battery is not charged in this mode.

iii. Night time mode

During the night time the PV array output is absent, the battery supplies the boost converter for providing compensation at the night time.

4. Control of DC Capacitor Voltage with Boost Converter

Boost converter also called as high efficiency step-up converter which has an output DC voltage greater than its input DC voltage. It consists of two semiconductor switches and one storage element [23,24]. Figure 3 shows the circuit diagram of a boost converter. When the switch is closed, the inductor gets charged by the PV or battery and stores the energy. The diode blocks the current flowing, so that the load current remains constant which is being supplied due to the discharging of the capacitor. When the switch is open the diode conducts and the energy stored in the inductor discharges and charges the capacitor. Therefore, the load current remains constant throughout the operation.

The output voltage of the boost converter can be written as

\[
V = V_g - IR_p
\]
\[ V_0 = V_i \left( \frac{1}{1 - D} \right) \]  

(2)

The boost converter which is used to maintain the output voltage constant for all the conditions of temperature and variations in solar irradiance. The input to the boost converter is 35 V and the boosted output voltage will be 670 V. The switching frequency is chosen to 25 KHz. The inductance used in the boost converter is 0.0191 mH.

5. Synchronous Reference Frame Theory

The block diagram of Synchronous Reference Frame (SRF) theory [4] is shown in Figure 4. From this algorithm, the reference source current is generated to control the proposed DSTATCOM. The load currents, PCC voltages and dc bus voltage are sensed as a feedback signal. The load currents from the a-b-c frame are first converted to α-β-0 frame and then to d-q-0 frame. The equation used for conversion is given below

\[ \begin{bmatrix}
  i_q \\
  i_d
\end{bmatrix} = \frac{2}{3} \begin{bmatrix}
  \cos \theta & -\sin \theta \\
  \cos \left( \theta - \frac{2\pi}{3} \right) & -\sin \left( \theta - \frac{2\pi}{3} \right) \\
  \cos \left( \theta + \frac{2\pi}{3} \right) & \sin \left( \theta + \frac{2\pi}{3} \right)
\end{bmatrix} \begin{bmatrix}
  i_a \\
  i_b \\
  i_c
\end{bmatrix} \]  

(3)

The input to the first PI controller is the error between the reference dc bus voltage \( V_{dc}^* \) and the sensed dc bus voltage \( V_{dc} \) of DSTATCOM. The loss component of the current \( i_{loss} \) is the output of the PI controller.

\[ i_{loss(n)} = i_{loss(n-1)} + K_{pd}(V_{dc(n)} - V_{dc(n-1)}) + K_{id}v_{dc(n)} \]  

(4)

where, \( K_{pd} \) and \( K_{id} \) are the proportional and integral gains of the dc bus voltage PI controller. Therefore the reference source current is

\[ i_s^* = i_{dc} + i_{loss} \]  

(5)

The actual and reference PCC voltage are fed to another PI controller for regulating the PCC voltage. The reference quadrature current \( i_q^* \) is the output of the PI controller. This \( i_q^* \) is added to the dc component of \( i_q \).

\[ i_{qr(n)} = i_{qr(n-1)} + K_{pq}(V_{te(n)} - V_{te(n-1)}) + K_{iq}v_{te(n)} \]  

(6)

where, \( K_{pq} \) and \( K_{iq} \) are the proportional and integral gains of the PCC voltage PI controller. The generated reference quadrature axis current is

\[ i_q^* = i_{ph} + i_{qr} \]  

(7)

Therefore the resultant d-q-0 current are again converted back to the reference source current using reverse park transformation. A PWM controller is used for generating the gate pulse to the DSTATCOM by using the reference and sensed source current.

6. Proposed ICOSΦ Algorithm

The block diagram of IcosΦ controlling algorithm is shown in Figure 5 is used to extract the reference currents [25]. The source currents \( i_{sa}, i_{sb} \) and \( i_{sc} \), the load currents \( i_{La}, i_{Lb} \) and \( i_{Lc} \), the ac terminal voltages \( v_a, v_b, v_c \) and the dc bus voltage \( V_{dc} \) are sensed. The IcosΦ controlling algorithm is used to generate only the active component of the load currents i.e. \( I_{cos}(\Phi) \) (where I = amplitude of fundamental load current and \( \Phi = \) displacement angle of load current). Hence by combining the in-phase and quadrature component, the reference current can be generated.

The three-phase nonlinear load current can be expressed as

\[ i_{qr(n)} = i_{qr(n-1)} + K_{pq}(V_{te(n)} - V_{te(n-1)}) + K_{iq}v_{te(n)} \]  

(6)
where, $I_{abc}^n$ and $\Phi_{abc}^n$ = amplitude and phase angle of $n^{th}$ harmonic current in a, b and c phases, $I_{Load}^{abc}$ = load current in a, b and c phases.

### 6.1 In-Phase Component of Reference Source Currents

The amplitude of active power component of fundamental load currents are given as

$$I_{a} = \sum I_{a} \sin(n \omega t - \Phi_{a}^n) \quad \text{for} \quad n = 0, 1 \text{ to } \infty$$  \hspace{1cm} (8)

$$I_{b} = \sum I_{b} \sin(n \omega t - \Phi_{b}^n) \quad \text{for} \quad n = 0, 1 \text{ to } \infty$$  \hspace{1cm} (9)

$$I_{c} = \sum I_{c} \sin(n \omega t - \Phi_{c}^n) \quad \text{for} \quad n = 0, 1 \text{ to } \infty$$  \hspace{1cm} (10)

The unit vector in phase with $v_a$, $v_b$ and $v_c$ are derived as

$$u_a = \frac{v_a}{V_f} \quad ; \quad u_b = \frac{v_b}{V_f} \quad ; \quad u_c = \frac{v_c}{V_f}$$  \hspace{1cm} (18)

In-phase component of reference source currents are estimated as

$$i_{a\text{ref}} = I_{a} u_a \quad ; \quad i_{b\text{ref}} = I_{b} u_b \quad ; \quad i_{c\text{ref}} = I_{c} u_c$$  \hspace{1cm} (19)

### 6.2 Quadrature Component of Reference Source Currents

The unit vectors ($w_a$, $w_b$ and $w_c$) in quadrature with ($v_a$, $v_b$ and $v_c$) can be calculated using the in-phase unit vectors ($u_a$, $u_b$ and $u_c$) given as

$$w_a = \frac{-u_b + u_c}{\sqrt{3}}$$  \hspace{1cm} (20)
The amplitude of reactive power component of fundamental load currents are given as

\[ w_1 = \frac{3u_a}{2} + \frac{(u_b - u_c)}{2\sqrt{3}} \]  

\[ w_e = -\frac{\sqrt{3}u_e}{2} + \frac{(u_b - u_c)}{2\sqrt{3}} \]  

(21)

(22)

The amplitude of reactive power component of fundamental load currents are given as

\[ I_{Ia1} = |I_{Ia1}| \sin \Phi_a = |\text{Im} \{I_{Ia1}\}| \]  

\[ I_{Ib1} = |I_{Ib1}| \sin \Phi_b = |\text{Im} \{I_{Ib1}\}| \]  

\[ I_{Ic1} = |I_{Ic1}| \sin \Phi_c = |\text{Im} \{I_{Ic1}\}| \]  

(23)

(24)

(25)

Thus, the amplitude of reactive power component of fundamental load current is extracted at zero crossing of the unit template in-phase of PCC voltages.

For balanced source currents, the magnitude of reactive component of reference currents can be given as

\[ I_{sq} = \left| \frac{I_{Ia1} \sin \Phi_a + I_{Ib1} \sin \Phi_b + I_{Ic1} \sin \Phi_c}{3} \right| + I_{imq} \]  

(26)

where, \( I_{imq} \) = output of the ac terminal voltage PI controller.

The error in amplitude of ac terminal voltage at \( n^{th} \) sampling instant is given as

\[ V_{w(n)} = V_{r(n)} - V_{r(e)} \]  

(27)

where, \( V_{r(n)} \) = reference ac terminal voltage, \( V_{r(e)} \) = three-phase ac terminal voltage.

The output of the PI controller for maintaining the amplitude of ac terminal voltage at the \( n^{th} \) sampling instant is given as

\[ I_{mq(n)} = I_{mq(n-1)} + K_{pa} (V_{w(n)} - V_{w(n-1)}) + K_{ia} V_{w(e)} \]  

(28)

where, \( K_{pa} \) and \( K_{ia} \) = proportional and integral gain of the ac terminal voltage, \( V_{de(n)} \) and \( V_{de(n-1)} \) = voltage errors in \( n^{th} \) and \( (n-1)^{th} \) instant.

The quadrature component of reference source currents are estimated as

\[ i_{sq} = I_{sq} \cos \phi_a \] ; \( i_{jq} = I_{jq} \cos \phi_b \) ; \( i_{qc} = I_{qc} \cos \phi_c \]  

(29)

6.3 Reference Source Currents

The reference source currents can be extracted by the sum of in-phase and quadrature components of the reference source currents and it is given as

\[ i_{sa} = i_{sq} + i_{jq} \]  

(30)

\[ i_{sb} = i_{sq} + i_{jq} \]  

(31)

\[ i_{sc} = i_{sq} + i_{jq} \]  

(32)

Thus, these reference source currents \( (i_{sa}, i_{sb}, \text{and } i_{sc}) \) are compared with the source currents \( (i_{sa}, i_{sb} \text{ and } i_{sc}) \) in hysteresis based PWM current controller for generating gate signals for IGBT switches in DSTATCOM.

7. Simulation Results and Discussion

The analysis of PV or battery interfaced to boost converter operated DSTATCOM for a three-phase three-wire system has been done using MATLAB software using SIMULINK and Power System Blockset (PSB) toolboxes. The power system simulation parameters considered for simulation is shown in Appendix. The proposed DSTATCOM is connected in shunt with the nonlinear load. Firstly, the polluted source current waveform created by nonlinear load is shown in Figure 6(a). The injected current waveform for IcosΦ algorithm is shown in Figure 6(b). The matlab simulation has been done for

![Figure 6. (a) Source current without compensation, (b) Injected current with IcosΦ algorithm.](image)
two different controlling methods. The controlling methods are synchronous reference frame theory and IcosΦ algorithm. The compensated source current waveform for SRF theory and IcosΦ algorithm are shown in Figures 7(a) & (b). From Figure 7, the source current with IcosΦ algorithm is made pure sinusoidal when compared with source current with SRF theory. The simulation results of Phase A current for without DSTATCOM, with SRF theory based DSTATCOM and IcosΦ based DSTATCOM are shown in Figure 8. When nonlinear load is connected continuously to the power system, the Total Harmonic Distortion (THD) of about 23.98% is presented in the system. This THD is reduced to 5.38% when SRF theory is used to generate the firing pulse. Similarly, when IcosΦ is employed, then the THD is further reduced to 1.22%. Therefore after compensation, source current THD is reduced to acceptable level 5% of IEEE-519-1992 standard. Thus proves the efficiency of IcosΦ based DSTATCOM. The THD comparison for SRF and IcosΦ methods is shown in Table 1. The real power and reactive power waveforms for IcosΦ controller are shown in Figures 9 and 10. The transient response of the boost converter is shown in Figure 11.

8. Conclusion

The simulation of the Photovoltaic (PV) array or battery operated DC-DC boost converter fed three-leg VSC based DSTATCOM has been carried out for reactive power compensation, source harmonic reduction and load current compensation in the distribution system. The boost converter is used to step up the voltage so as to match the dc link voltage of the three-leg VSC based DSTATCOM for continuous compensation. The DSTATCOM was controlled by SRF theory and IcosΦ algorithm.

![Figure 7. Source current waveform (a) SRF theory, (b) IcosΦ algorithm.](image)

![Figure 8. Current harmonics and its THD waveform for without and with controlling algorithms.](image)

<table>
<thead>
<tr>
<th>Table 1. Comparison of THD values of DSTATCOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>THD in all three phases</td>
</tr>
<tr>
<td>-------------------------</td>
</tr>
<tr>
<td>Phase A</td>
</tr>
<tr>
<td>Phase B</td>
</tr>
<tr>
<td>Phase C</td>
</tr>
</tbody>
</table>
When comparing SRF theory with IcosΦ method, the IcosΦ method is found effective because the source current THD is reduced below the (IEEE-519-1992) permissible limit of 5%. The MATLAB software with its simulink and Power System Blockset (PSB) toolboxes has been used to validate the proposed system.

Appendix

AC line voltage: 415 V, 50 Hz
Non-linear load: Three phase bridge rectifier with R = 20Ω
AC inductor: 2.5 mH
DC bus capacitance of DSTATCOM, Cdc: 7000 µF
DC bus voltage of DSTATCOM: 670 V
DC voltage PI controller: Kpd = 0.1, Kid = 1

Figure 9. Real power waveform (a) Source, (b) Injected, (c) load for IcosΦ controller.

Figure 10. Reactive power waveform (a) Source, (b) Injected, (c) Load for IcosΦ controller.

Figure 11. Transient response of boost converter voltage.
PCC voltage PI controller: $K_{pq} = 0.1$, $K_{iq} = 1$

References


*Manuscript Received: May 1, 2012
Accepted: Oct. 3, 2012*