Comparative Power Quality analysis of Different DSTATCOM Topologies

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Abstract: This paper presents the three topologies of three phase four wire DSTATCOM for reduction of harmonics, reactive power compensation, increasing power factor, occur due to a nonlinear load, environment problem and polluted grid. The performances of above topologies have been compared for magnitude of source current, power factor improvement, DC link voltage regulation and total harmonic distortion. This paper presents a novel work for the new young scientist/industrialist who working in the improvement of power quality in grid. This paper helps to provide the application, designing constraints of shunt active filter in many fields. The First topology which is used in this paper is the three-phase four wire four- pole voltage source converter based DSTATCOM. The second is the three-phase four wire with three leg voltage source converter based DSTATCOM with T-connected transformer and the third topology is the three H-bridge voltage source converter based DSTATCOM. T-connected transformer in the second topology has been used to reduce the rating for voltage source converter. Synchronous reference frame theory based controller has been proposed to generation of the reference current. Reference current generated from the synchronous frame theory is processed to hysteresis current controller loop which produces switching pulses for VSC based DSTATCOM. All these topologies have been implemented in MATLAB/Simulink platform by using different types of loading conditions such as resistive and power electronics load.

Keywords: Distribution Static Compensator (DSTATCOM); Synchronous Reference Frame (SRF); Hysteresis Current Controller (HCC) Total Harmonic Distortion (THD); Voltage Source Converter (VSC).

1 Introduction

Now a day’s various types of distribution load are three phase four wire type load and much of these are occupied with non-linear load in hospitals, Software Park, commercial buildings, air traffic control, processing plant etc. [1-3]. Adjustable speed drives (ASD), cyclo-converter, rectifiers, traction system, household used equipment are the some of the examples of a nonlinear load. Customers are very much affected by the financial issue due to power quality problems arise even a 1 min or more. These are the 24*7 usable types of equipment and creating excessive neutral current, unbalanced the load, high reactive power, harmonics etc. [4-5]. These are the effects caused by power electronics contents load occur in three phase three wire and one neutral wire (four wire) distribution lines. For controlling of these power quality problems many standards are proposed by IEEE like IEEE-519 for harmonic mitigation, IEEE -1159 for voltage swell and voltage sag etc. [4]. Compensating power devices come into the picture for minimization of harmonics produced, compensation of reactive power and balance the load by drawing sinusoidal current which overall minimizes the power quality problems. These devices include DSTATCOM, DVR and UPQC [5]. These devices are the parallel connected, series connected, shunt-series connected respectively [1]. Earlier various types of research have been done on various types of IGBT based DSTATCOM topologies for three phase three wire with one neutral wire(four wire) distribution lines are four pole voltage source converter (VSC)[2], three single-phase VSCs[1], three-pole VSC with two dividing capacitors three-pole VSC [6] with zig-zag transformer [5], and three-pole VSC with neutral terminal at the positive or negative of dc bus [7]. Apart from the above power electronic topologies many strategies for controlling the three-phase three wire with one neutral wire IGBT based DSTATCOM are reported such as IRPT/PQ theory [1][2], power balance theory-based [6], artificial neural network(ANN)[14], wavelet-based approach[5], synchronous detection method(SDM)[8] etc. Due to easy availability of input variables and less computation time, SRF theory is used for the
Control of three phase three wire with one neutral wire (four wire) DSTATCOM. In this paper, the three different topologies for DSTATCOM are presented and compared to different loading condition. This paper has been organized into different sections. The first introduction section is describing the problem in the distribution system, various topologies and control schemes for shunt active filter. Section 2 describes basic circuit configuration of DSTATCOM. Section 3 describes the various parameters design of DSTATCOM. Section 4 demonstrates the three topologies of DSTATCOM. Section 5 explains about the control scheme for DSTATCOM to extract reference signal. Section 6 describes the simulation results and analysis of different topologies of DSTATCOM. Last section 7 concludes the paper.

2. Basic Circuit Configuration of DSTATCOM

![Pictorial view of DSTATCOM topology](image)

Fig 1: Pictorial view of DSTATCOM topology

Fig 1 shows the basic topology of DSTATCOM. The component of DSTATCOM has IGBT based voltage source converter, DC capacitor, ripple filter, SPWM and SRF based control scheme. Sinusoidal pulse width modulation technique is used to provide switching pulses for the IGBT switches. The input to the SPWM is reference three phase compensating current which is obtained from SRF based control scheme. DSTATCOM is connected between three phase source and load. The connection point is called point of common coupling (PCC). Is and VS represents the source current and source voltage of three phase AC mains respectively. Rs and Ls are the source resistance and inductance of three phase source respectively. Ic denotes the compensating current and Lc is interfacing inductor connected at the AC side of voltage source inverter. Vdc is the internal voltage of DC link capacitor connected at the DC side of IGBT based voltage source inverter. Ic are the compensating current injected by

3. Design of DSTATCOM parameters

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Parameter</th>
<th>Design Specification</th>
<th>Value used in simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DC Capacitor Voltage Vdc</td>
<td>$V_{dc} = \frac{2\sqrt{2}}{3} V_{m}$</td>
<td>700V</td>
</tr>
<tr>
<td>2</td>
<td>Capacitor Cdc</td>
<td>$C_{dc} = \frac{I_0}{2\omega V_{dc(p-p)}}$</td>
<td>3200 $\mu$F</td>
</tr>
<tr>
<td>3</td>
<td>Ripple Filter (Rf, Cf)</td>
<td>$R_f \times C_f \leq 1/10$</td>
<td>19 $\Omega$, 10c-3F</td>
</tr>
<tr>
<td>4</td>
<td>Interfacing InductorLf</td>
<td>$mV_{dc}(4af_{s}l_{e}(p-p))$</td>
<td>2.5 mH</td>
</tr>
<tr>
<td>5</td>
<td>Load</td>
<td>Uncontrolled diode bridge rectifier with parallel combination of R and L</td>
<td>R=12 $\Omega$, L=0.001F</td>
</tr>
<tr>
<td>6</td>
<td>Source Impedance (Rs, Ls)</td>
<td>Series combination of R and L</td>
<td>R=0.001 $\Omega$, L=0.003mH</td>
</tr>
<tr>
<td>7</td>
<td>Three Phase Source</td>
<td>AC Voltage source</td>
<td>415V</td>
</tr>
</tbody>
</table>

4. Different Topologies of DSTATCOM

4.1 Four- Pole Voltage Source Converter Based DSTATCOM

![Four-pole voltage source converter based DSTATCOM](image)

Fig.2: Four -pole voltage source converter based DSTATCOM
Fig. 2 represents the four-pole VSC based DSTATCOM for minimizing the problems of power quality issues arising in three phase four wire distribution lines. Three-phase four-wire AC main line represent the grid of the whole distribution system. \( i_{sa}, i_{sb}, i_{sc}, i_{sn} \) represents the source current of a, b, c and neutral phase respectively. \( i_{la}, i_{lb}, i_{lc}, i_{ln} \) represents the load current of a, b, c, n phase respectively. \( i_{ca}, i_{cb}, i_{cc}, i_{cn} \) represents the inverter current of a, b, c and n- phase respectively, \( C_{dc} \) is the DC link capacitor. Three- phase four-wire (3P4W) VSC is interfaced through the compensating impedances in parallel to the load. The VSC is configured by an insulated gate bipolar transistor (IGBT) in a four -pole along with a dc-side capacitor for voltage regulation. Four- pole VSC is comprised as 8 switches of IGBT and the same amount of diode in anti-parallel direction.

### 4.2 Three-Pole Voltage Source Converter with T-Connected Transformer Based DSTATCOM

Fig. 3 represents the three -pole voltage source converter with T-connected transformer based DSTATCOM. T- Connected transformer is used for neutral current compensation by providing a path for current in the neutral wire and reduces the rating of voltage source converter. Three- phase four-wire (3P4W) VSC is interfaced through the compensating impedances in parallel to the load. T –connected transformer are constructed using two single-phase isolated transformer connected in T- shape. Three –pole VSC is configured by 6-IGBT switches and an anti-parallel diode.

### 4.3 Three H-bridge Based DSTATCOM

The above figure represents three H-bridge based DSTATCOM with linear and non-linear loads. In this configuration power electronic converter based three single-phase H-bridge are connected to single DC link capacitor. The source impedance is represented by \((Z_s)\). By maintaining the value of DC link capacitor voltage loss due to 12 switches are minimized. \( i_{sa}, i_{sb}, i_{sc} \) and \( i_{sn} \) represents the source current of a, b, c, and n-phase respectively. Three single phase H-bridge are connected by an isolated transformer to the common point of coupling. Each phase of the system can be controlled independently irrespective of other phases. Compensator current is injected at the common point of coupling via RC filter. DC link capacitor value is maintained by regulation of PI controller. Stability of DC link voltage capacitor plays a major role in the working of DSTATCOM.DC link capacitor is the only source of active power and reactive power .When non-linear load is changing its characteristics in real time situation then it is much more important for capacitor that to provide reactive power burden .At the real time discharging and charging of capacitor should be maintained. Capacitor can also act as an energy storage device and known as buffer.
<table>
<thead>
<tr>
<th>Topologies</th>
<th>No. of Switches</th>
<th>Voltage Rating</th>
<th>Capacitor Required</th>
<th>Transformer Required</th>
<th>DC link Voltage</th>
<th>Capacitor Current Rating</th>
<th>Switching States</th>
<th>Types of Load</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four Leg Voltage source converter</td>
<td>8M</td>
<td>Vdc</td>
<td>1</td>
<td>0</td>
<td>3.4 (Vm/N)</td>
<td>Low</td>
<td>16</td>
<td>3-phase/1-Phase Loads</td>
<td>Data Communication Automation Industry, Military Equipment</td>
</tr>
<tr>
<td>Three Leg Voltage source converter with T-connected transformer</td>
<td>6M</td>
<td>Vdc</td>
<td>1</td>
<td>1</td>
<td>1.6 (Vm/N)</td>
<td>Low</td>
<td>8</td>
<td>3-phase/1-Phase Loads</td>
<td>UPS, Asynchronous speed drives (ASD), VFD, Wireless Power transfer</td>
</tr>
<tr>
<td>Three H-bridge</td>
<td>12M</td>
<td>Vdc</td>
<td>1</td>
<td>0</td>
<td>3.7 (Vm/N)</td>
<td>High</td>
<td>8</td>
<td>3-phase/1-Phase Loads</td>
<td>Distributed Generated system, Motor drives, Household Inverter</td>
</tr>
</tbody>
</table>

Note: Vm = Peak value of supply voltage
Vdc = DC bus voltage
M = No. of Secondary
N = No. of turns
5. Synchronous Reference Frame Theory

Working of SRF theory is based on the reference signal produced by the feedback signal to load current, PCC voltage and DC link capacitor. PCC voltage Vsa, Vsb and Vsc and load current Ila, Ilb and Ilc are the input of the controller. These signals are coming from the distribution system in which controller is connected. Firstly, three phase stationary signal is converted into corresponding synchronously rotating d-q-o reference signal by Clarke transformation, and then low pass filter is used for extracting ripples. Voltage component of a positive sequence is used for obtaining synchronizing angle [1]. These signals are processed by three-phase PLL for production of sine and cosine signals. Now the amount which is subtracted from DC bus reference voltage (Vdc *) and the voltage of DC capacitor (Vdc) of DSTATCOM is given to a PI controller. The output of PI controller is review while the drop ingredient of current (Iloss) and is summed to the dc ingredient of load current (ILd) to produce (id*). A PI controller is used also to regulate the dc bus voltage to its reference value and compensates for the inverter losses [2]. The PWM gating pulses for the IGBTs in VSI of APF are generated by indirect current control using sinusoidal pulse width modulation technique followed by synchronous reference frame theory [8].

6. Results and Discussion

6.1 Three-Phase Four wire four leg Voltage Source Converter

Fig 6: Performance of Four Leg Voltage source Converter based DSTATCOM

Fig.6 represents the Performance of Four leg Voltage source converter based DSTATCOM. From top to bottom the waveform represents the Is, Vdc, Ic, Vs and IL. It have seen that from 0 to 0.1 sec performance of DSTATCOM is uncompensated. It is done by connecting a three phase breaker for on and off. Is is sinusoidal after 0.2 sec. There is a transient period of 0.1 sec to 0.2 sec. After 0.2 sec transient period end steady state system comes. Thus we have seen that in the steady state Is is sinusoidal, it means that DSTATCOM works and effect of non-linear load is not seen. Regulation of DC bus voltage (Vdc) constant throughout in the steady state period of
0.2 sec to 0.7 sec. Vs seems to be constant throughout of magnitude 415V in period from 0.2 sec to 0.7 sec. From the waveform of Is and Vs, it is seen that both are in phase. Waveform of IL is distorted due to the effect of non-linear load. Hence from above performance of four-leg voltage source converter is able to mitigate the effect of non-linear load from the source current and source voltage, and also it able to balancing the phase.

Fig 7: THD of Isa

Fig 8: THD of Isb

Fig 9: THD of Isc

Fig.7 to 9 represent the THD of all three phases of source current. According to IEEE-519, THD of source side current is below 5%. From fig it is seen that THD of Isa, Isb, and Isc is 4.52%, 4.70% and 4.55%. THD of all three phase is within the stipulated limit of IEEE-519 of THD consideration.

6.2 Three-Pole Voltage Source Converter with T-Connected Transformer Based DSTATCOM

Fig 10: Performance of Three-Pole Voltage Source Converter with T-Connected Transformer Based DSTATCOM
Fig. 10 represents the performance of three-pole voltage source converter with T-connected transformer based DSTATCOM in the uncompensated, transient and steady state mode. Three leg consisting of 6 switch of IGBT/diode and T-connected transformer is also used in this topology of DSTATCOM. Waveform of Is, Vdc, Ic, Vs, and IL can be seen from the fig. 10. It is seen that Is is non-sinusoidal in 0 sec to 0.1 sec, transient in the interval of 0.1 sec to 0.2 sec and after 0.2 sec sinusoidal which indicates that operation of DSTATCOM is successfully and it neglects the effect of non-linear load. Voltage of DC bus capacitor Vdc is regulates after 0.2 sec. It is seen that Vdc is almost constant and its magnitude is approaches to 700V after transient time. Source voltage is Vs constant after 0.2 sec. Phase of Is and Vs is constant. IL is deteriorated due to non-linear load.

Fig. 11, 12, and 13 represent the Total harmonic distortion of all three phases of source current Is. THD of Isa, Isb and Isc is 4.44%, 4.41%, and 4.44% respectively. It is seen that THD of all three phases of source current is within the stipulated limit of IEEE-519. Transformer is used for neutral current compensation by providing a path for current in the neutral wire and reduces the rating of voltage source converter. Zig-zag transformer can be used a T-connected transformer. Transformer plays an important role in providing neutral current path and compensate them. From above analysis and performance of DSTATCOM it is seen that three–pole voltage source converter with T-connected transformer is able to eliminate the harmonics from the source current, reactive power compensation and balance the phases. T-connected transformer is designed for integrating the DSTATCOM by its secondary winding. Transformer also reduces the rating of switch as we can see from figure that there is no any increment of THD even it uses less number of switch.
6.3 Three H-bridge Based DSTATCOM

Fig 14 represents the Performance of Three H-Bridge Based DSTATCOM in the uncompensated, transient and steady state mode. Waveform of \( I_s \), \( V_{dc} \), \( I_c \), \( V_s \), and \( I_L \) can be seen from the fig. 14. It is seen that \( I_s \) is non-sinusoidal in 0 sec to 0.1 sec, transient in the interval of 0.1 sec to 0.2 sec and after 0.2 sec sinusoidal which indicates that operation of DSTATCOM is successfully and it neglects the effect of non-linear load.

Voltage of DC link capacitor \( V_{dc} \) connected at the DC side of inverter is regulates after 0.2 sec. It is seen that \( V_{dc} \) is almost constant and its magnitude is 700V after transient time. Source voltage is \( V_s \) constant after 0.2 sec. Phase of \( I_s \) and \( V_s \) is same which indicates that Three H-bridge based DSTATCOM is able to eliminate the harmonics form source current and makes it sinusoidal, balances the phases and reactive power compensation. Fig 15, 16, and 17 represent the THD of source current. THD of \( I_{sa} \), \( I_{sb} \), and \( I_{sc} \) is 2.13%, 2.41, and 2.30% respectively. THD of all three phases is well within the limit of IEEE-519 of THD consideration on grid side.
Result analysis of Different topologies of DSTATCOM

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Topologies</th>
<th>Source Current (RMS) Isa (A)</th>
<th>Source Current (THD) %</th>
<th>Source Current (RMS) Isb (A)</th>
<th>Source Current (RMS) Isc (A)</th>
<th>Source Voltage Vs (V) Vsa</th>
<th>Vsb</th>
<th>Vsc</th>
<th>Power Factor</th>
<th>DC capacitor voltage (V) Vdc</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Four-pole</td>
<td>10.8</td>
<td>53.52</td>
<td>45.24</td>
<td>4.52</td>
<td>4.70</td>
<td>11.02</td>
<td>7.48</td>
<td>3.537</td>
<td>266.2</td>
</tr>
<tr>
<td>2</td>
<td>Three-pole T-Connected transformer</td>
<td>36.87</td>
<td>20.04</td>
<td>56.91</td>
<td>4.44</td>
<td>4.41</td>
<td>4.44</td>
<td>40.52</td>
<td>25.54</td>
<td>14.98</td>
</tr>
<tr>
<td>3</td>
<td>Three H-Bridge</td>
<td>11.66</td>
<td>40.49</td>
<td>52.15</td>
<td>2.13</td>
<td>2.30</td>
<td>2.41</td>
<td>14.13</td>
<td>8.211</td>
<td>5.914</td>
</tr>
</tbody>
</table>

Table 1: Comparison of different parameter of DSTATCOM topologies

Table 1 depicts comparative arrangements of different parameter of DSTATCOM topologies and Fig. 18 indicates its chartable representation.

7. Conclusion

Three different topologies of DSTATCOM is proposed for mitigation of power quality problem like load balancing, harmonic elimination, reactive power compensation.

From above comprehensive analysis, it can be found that:

1. Total harmonic distortion of Three H-bridge based DSTATCOM is fairly better within all three topologies.
2. DC link capacitor value is regulating in steady state by tuning the gains of PI controller.
3. SRF controller makes all the topologies as a backbone of creating reference current by minimization of error to DC link capacitor which helps to eliminate harmonics and balance the voltage of bus bar.
4. Switch in the Three H-bridge helps to minimize the loss of inverter by DC link capacitor.
5. Regulation of DC bus capacitor in case of Three H-bridge is fast and almost 700 V throughout time interval.
6. The overall performance of Three H-bridge based DSTATCOM is the best among all the three topologies.

REFERENCES


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