



# 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, which occur due to a nonlinear load, environment problem and polluted grid. The performances of the above topologies have been compared for the 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 the 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. The 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 the 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

NOWADAYS 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 some of the examples of a nonlinear load. Customers are very much affected by the financial issue due to power quality problems arise even in one minute 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 that occur in three-phase three-wire and one neutral wire (four-wire) distribution lines. For controlling 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

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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 zigzag 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 the 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 conditions.

This paper has been organized into different sections. The first introduction section describes the problem in the distribution system, various topologies and control schemes for shunt active filter. Section 2 describes the basic circuit configuration of DSTATCOM. Section 3 demonstrates the three topologies of DSTATCOM. Section 4 explains the control scheme for DSTATCOM to extract the reference signal. Section 5 describes the simulation results and analysis of different topologies of DSTATCOM. Last section concludes the paper.

## 2 Basic Circuit Configuration of DSTATCOM

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 the three-phase source and load. The connection point is called the point of common coupling (PCC).  $I_s$  and  $V_s$  represents the source current and the source voltage of three-phase AC mains respectively.  $R_s$  and  $L_s$  are the source resistance and inductance of three-phase source respectively.  $I_c$  denotes the compensating current and  $L_c$  is interfacing inductor connected at the AC side of the voltage source inverter.  $V_{dc}$  is the internal voltage of the DC-link capacitor connected at the DC side of IGBT based voltage source inverter.  $I_c$  is the compensating current injected by IGBT based voltage source inverter to PCC for surpresses the effect of harmonics, the reactive power component of the non-linear load. SPWM based current controller is providing the generation of gate pulse for voltage source inverter.

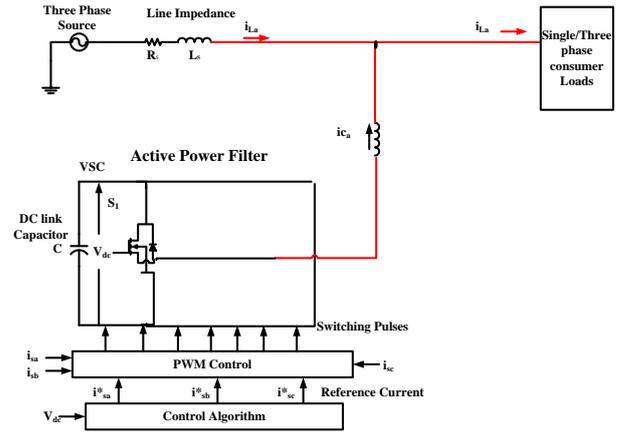


Fig. 1 Pictorial view of DSTATCOM topology.

Table 1 Design parameters of DSTATCOM.

| S. No. | Parameter                       | Design specification   | Value used in simulation        |
|--------|---------------------------------|--|---------------------------------|
| 1      | DC capacitor voltage $V_{dc}$   | $V_{dc} = \frac{2\sqrt{2}}{\sqrt{3}m} V_m$                               | 700V                            |
| 2      | Capacitor $C_{dc}$              | $C_{dc} = \frac{I_0}{2\omega V_{dc}(p-p)}$                               | 3200 $\mu$ F                    |
| 3      | Ripple filter ( $R_f, C_f$ )    | $R_f \times C_f \leq 1/10$   | 19 $\Omega, 10^{-3}$ F          |
| 4      | Interfacing inductor $L_f$      | $mV_{dc} (4af_s i_{cr} (p-p))$   | 2.5mH                           |
| 5      | Load                            | Uncontrolled diode bridge rectifier with parallel combination of R and L | $R = 12\Omega, L = 0.001$ F     |
| 6      | Source impedance ( $R_s, L_s$ ) | Series combination of R and L  | $R = 0.001\Omega, L = 0.003$ mH |
| 7      | Three-phase source              | AC Voltage source  | 415V                            |

## 3 Different Topologies of DSTATCOM

### 3.1 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 represents the grid of the whole distribution system.  $i_{sa}, i_{sb}, i_{sc}$ , and  $i_{sn}$  represent the source current of a, b, c, and neutral phases, respectively.  $i_{La}, i_{Lb}, i_{Lc}$ , and  $i_{Ln}$ , represents the load current of a, b, c, n phases, respectively.  $i_{ca}, i_{cb}, i_{cc}$ , and  $i_{cn}$  represent the inverter current of a, b, c, and n phases, respectively.  $C_{dc}$  is the DC-link capacitor. Three-phase four-wire (3P4W) VSC is interfaced through a compensating impedances in parallel to the load. The VSC is configured by an

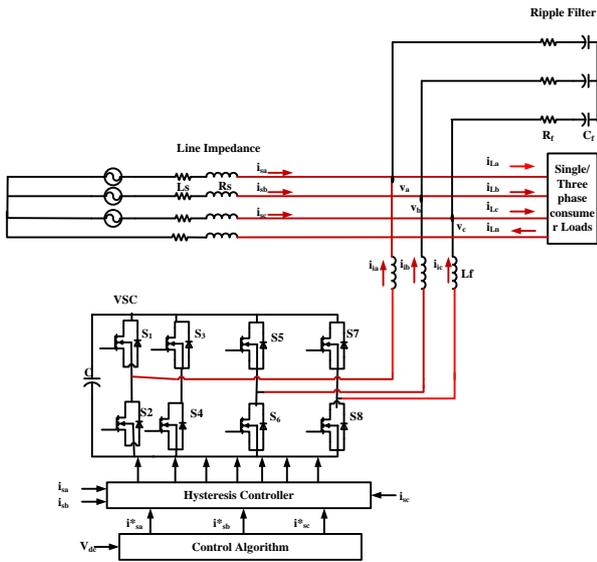


Fig. 2 Four-pole voltage source converter based DSTATCOM.

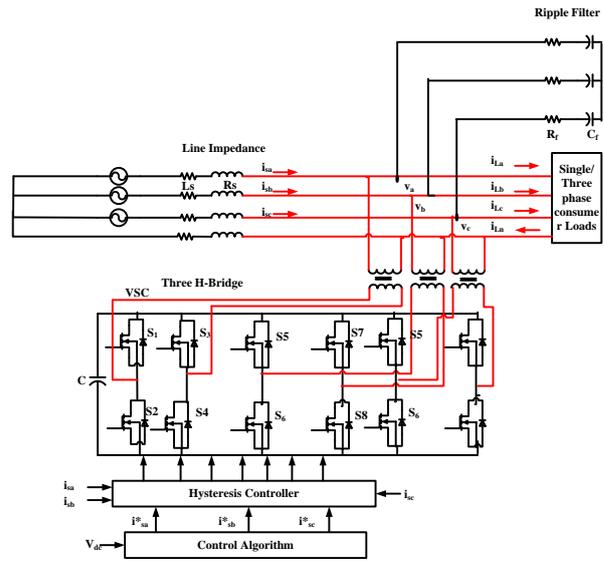


Fig. 4 Three H-bridge based DSTATCOM.

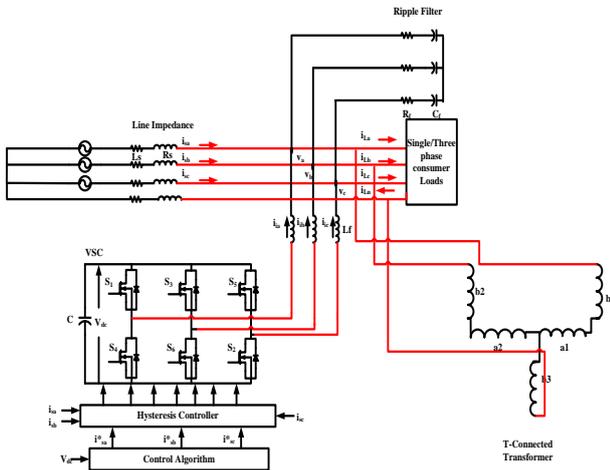


Fig. 3 Three-pole voltage source converter with T-connected transformer based DSTATCOM.

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 antiparallel direction.

### 3.2 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 is 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.

### 3.3 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 converters based three single-phase H-bridge are connected to a single DC-link capacitor. The source impedance is represented by  $Z_s$ . By maintaining the value of DC-link capacitor voltage power loss due to 12 switches are minimized.  $i_{sa}$ ,  $i_{sb}$ ,  $i_{sc}$ , and  $i_{sn}$  represent the source current of a, b, c, and n phases, 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 the regulation of PI controller. The stability of the 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 the non-linear load is changing its characteristics in real-time situation then it is much more important for the capacitor that provides reactive power burden. At the real-time discharging and charging of capacitor should be maintained. The capacitor can also act as an energy storage device and known as a buffer.

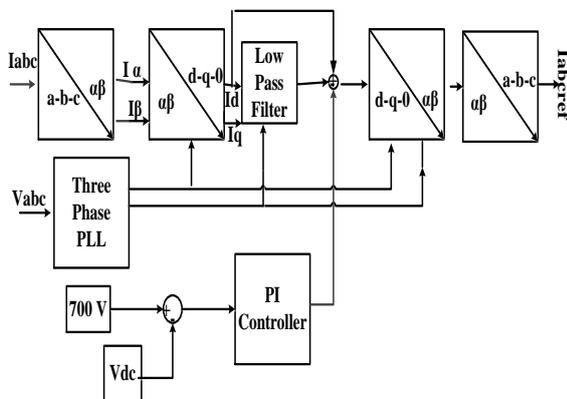
### 4 Synchronous Reference Frame Theory

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  $V_{sa}$ ,  $V_{sb}$ , and  $V_{sc}$  and load current  $I_{la}$ ,  $I_{lb}$ , and  $I_{lc}$  are the input of the controller. These signals are coming from the distribution system in which the controller is connected. Firstly, the three-phase stationary signal is

**Table 2** Comparison of DSTATCOM topologies in various sector.

| Topologies  | No. of switches | Voltage rating | Capacitor required | Transformer required | DC-link voltage [ $V_m/N$ ] | Capacitor current rating | Switching states | Types of load       | Application  |
|---|-----------------|----------------|--------------------|----------------------|-----------------------------|--------------------------|------------------|---------------------|--|
| Four leg voltage source converter                               | 8M              | $V_{dc}$       | 1                  | 0                    | 3.4                         | Low                      | 16               | 3-Phase/<br>1-Phase | Data communication automation industry, Military equipment         |
| Three leg voltage source converter with T-connected transformer | 6M              | $V_{dc}$       | 1                  | 1                    | 1.6                         | Low                      | 8                | 3-Phase/<br>1-Phase | UPS, asynchronous speed drives (ASD), VFD, Wireless power transfer |
| Three H-bridge  | 12M             | $V_{dc}$       | 1                  | 0                    | 3.7                         | High                     | 8                | 3-Phase/<br>1-Phase | Distributed generated system, Motor drives, Household inverter     |

Note:  $V_m$  = Peak value of supply voltage,  $V_{dc}$  = DC bus voltage,  $M$  = No. of Secondary, and  $N$  = No. of turns.



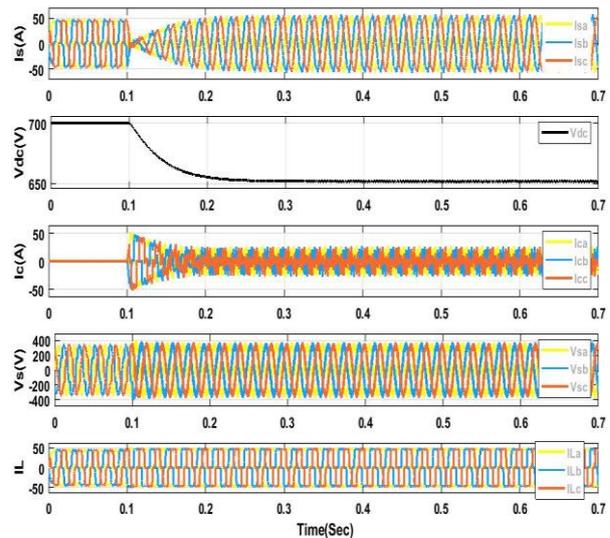
**Fig. 5** Three H-bridge based DSTATCOM.

converted into a corresponding synchronously rotating d-q-o reference signal by Clarke transformation, and then a low pass filter is used for extracting ripples. The voltage component of a positive sequence is used for obtaining the synchronizing angle [1]. These signals are processed by three-phase PLL for the production of sine and cosine signals. Now the amount which is subtracted from DC bus reference voltage ( $V_{dc}^*$ ) and the voltage of DC capacitor ( $V_{dc}$ ) of DSTATCOM is given to a PI controller. The output of PI controller is reviewed while the drop ingredient of current ( $I_{loss}$ ) and is summed to the DC ingredient of load current ( $I_{Ld}$ ) to produce ( $i_d^*$ ). 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 the sinusoidal pulse width modulation technique followed by synchronous reference frame theory [8].

## 5 Results and Discussion

### 5.1 Three-Phase Four-Wire Four-Leg Voltage Source Converter

Fig.6 represents the Performance of Four leg Voltage source converter based DSTATCOM. From top to



**Fig. 6** Three H-bridge based DSTATCOM.

bottom the waveform represents the  $I_s$ ,  $V_{dc}$ ,  $I_c$ ,  $V_s$ , and  $I_L$ . It has been seen that from zero to 0.1sec the performance of DSTATCOM is uncompensated. It is achieved by connecting a three-phase breaker for on and off.  $I_s$  is sinusoidal after 0.2sec. There is a transient period of 0.1 sec to 0.2 sec. After 0.2sec the transient period ends and the steady-state of the system is reached. Thus we have seen that in the steady-state  $I_s$  is sinusoidal, it means that DSTATCOM works and the effect of the non-linear load is not seen. Regulation of DC bus voltage ( $V_{dc}$ ) is constant throughout in the steady-state period of 0.2 to 0.7sec.  $V_s$  seems to be constant throughout of magnitude 415V in the period from 0.2 to 0.7sec. From the waveform of  $I_s$  and  $V_s$  it is seen that both are in phase. The waveform of  $I_L$  is distorted due to the effect of the non-linear load. Hence from the above performance of the four-leg voltage source converter it is able to mitigate the effect of the non-linear load from the source current and source voltage, and also it is able to balance the phase.

Figs. 7-9 represent the THD of all three phases of source current. According to IEEE-519, THD of source-side current is below 5%. From these figures, it is seen that THD of  $I_{sa}$ ,  $I_{sb}$ , and  $I_{sc}$  is 4.52%, 4.70%, and

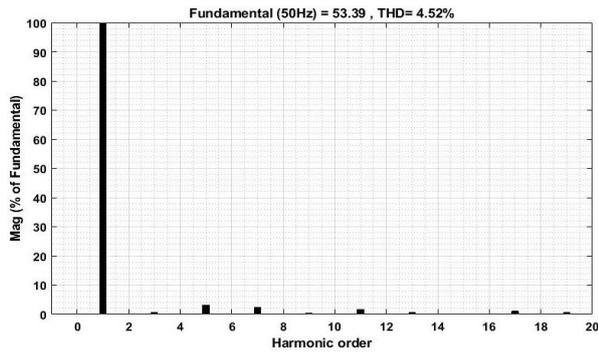


Fig. 7 THD of  $I_{sa}$ .

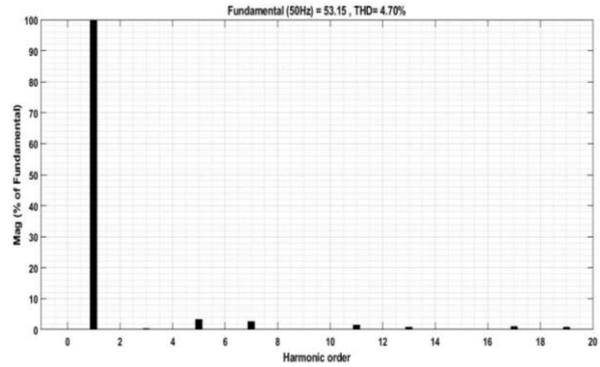


Fig. 8 THD of  $I_{sb}$ .

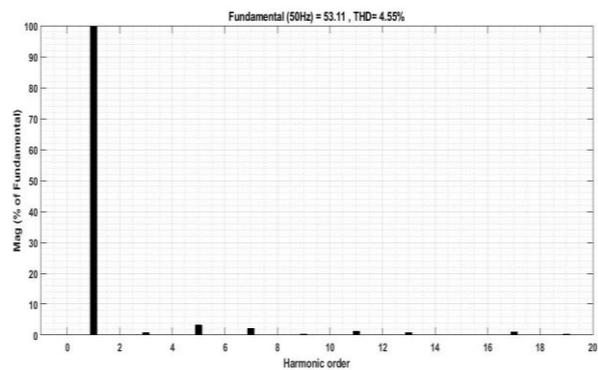


Fig. 9 THD of  $I_{sc}$ .

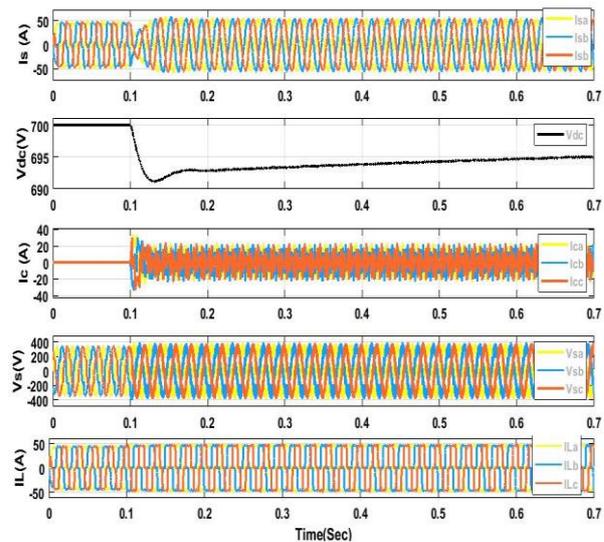


Fig. 10 Performance of three-pole voltage source converter with T-connected transformer based DSTATCOM.

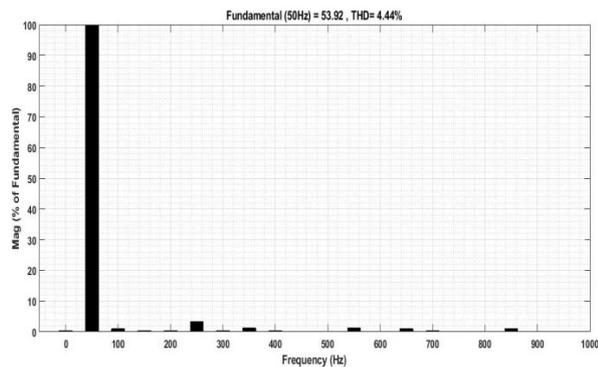


Fig. 11 THD of  $I_{sa}$ .

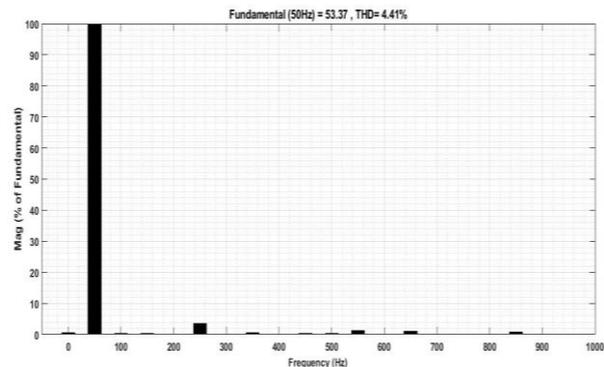


Fig. 12 THD of  $I_{sb}$ .

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 represents the performance of the three-pole voltage source converter with T-connected transformer-based DSTATCOM in the uncompensated, transient and steady-state mode. Three legs consisting of 6 switches

of IGBT/diode and T-connected transformer are also used in this topology of the DSTATCOM waveform of  $I_s$ ,  $V_{dc}$ ,  $I_c$ ,  $V_s$  and  $I_L$  can be seen from Fig. 10. It is seen that  $I_s$  is non-sinusoidal in zero to 0.1sec, transient in the interval of 0.1 to 0.2sec, and after 0.2sec sinusoidal which indicates that operation of DSTATCOM is successfully and it neglects the effect of non-linear load. The voltage of the DC bus capacitor ( $V_{dc}$ ) is regulated after 0.2sec. It is seen that  $V_{dc}$  is almost constant and its

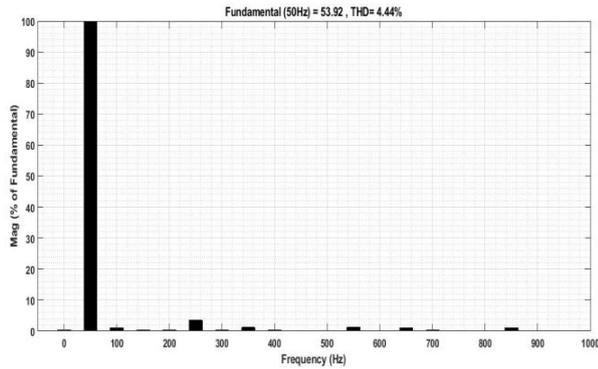


Fig. 13 THD of  $I_{sc}$ .

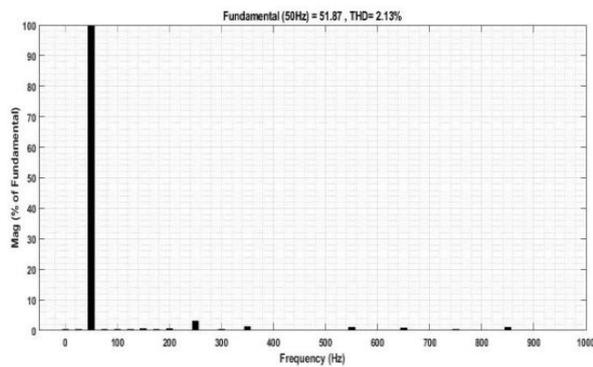


Fig. 15 THD of  $I_{sa}$ .

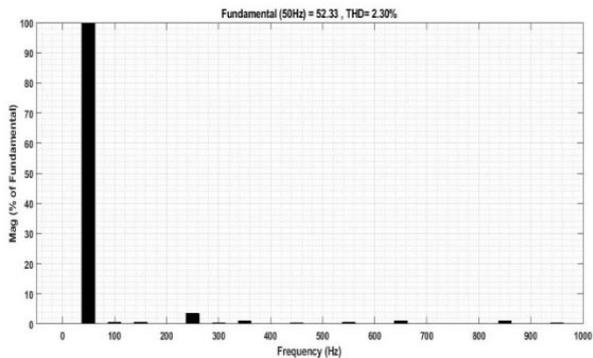


Fig. 17 THD of  $I_{sc}$ .

magnitude approaches 700V after transient time. The source voltage is  $V_s$  constant after 0.2sec. The phase of  $I_s$  and  $V_s$  is constant.  $I_L$  is deteriorated due to non-linear load.

Figs. 11-13 represent the Total harmonic distortion of all three phases of source current  $I_s$ . THD of  $I_{sa}$ ,  $I_{sb}$ , and  $I_{sc}$  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

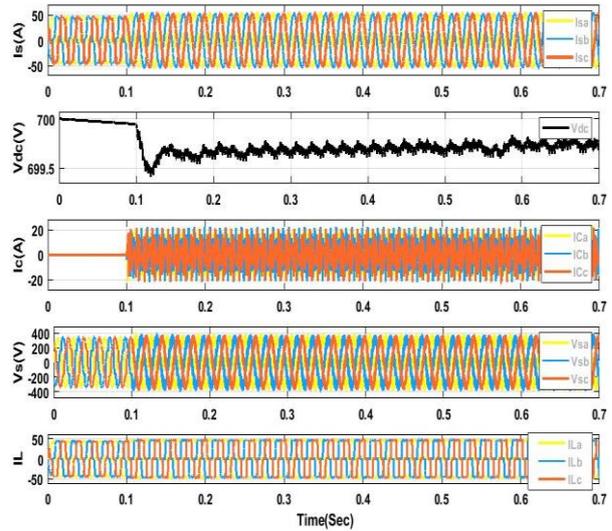


Fig. 14 Performance of three H- bridge based DSTATCOM.

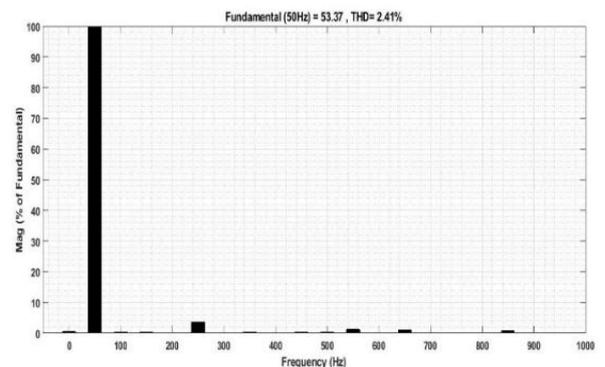


Fig. 16 THD of  $I_{sb}$ .

voltage source converter. Zigzag transformer can be used as a T- connected transformer. Transformer plays an important role in providing neutral current path and compensates them. From the above analysis and performance of DSTATCOM it is seen that three-pole voltage source converter with a T-connected transformer is able to eliminate the harmonics from the source current, reactive power compensation and balance the phases. The T-connected transformer is designed for integrating the DSTATCOM by its secondary winding. The transformer also reduces the rating of the switch as we can see from the figure that there is no increment of THD even it uses less number of the switches.

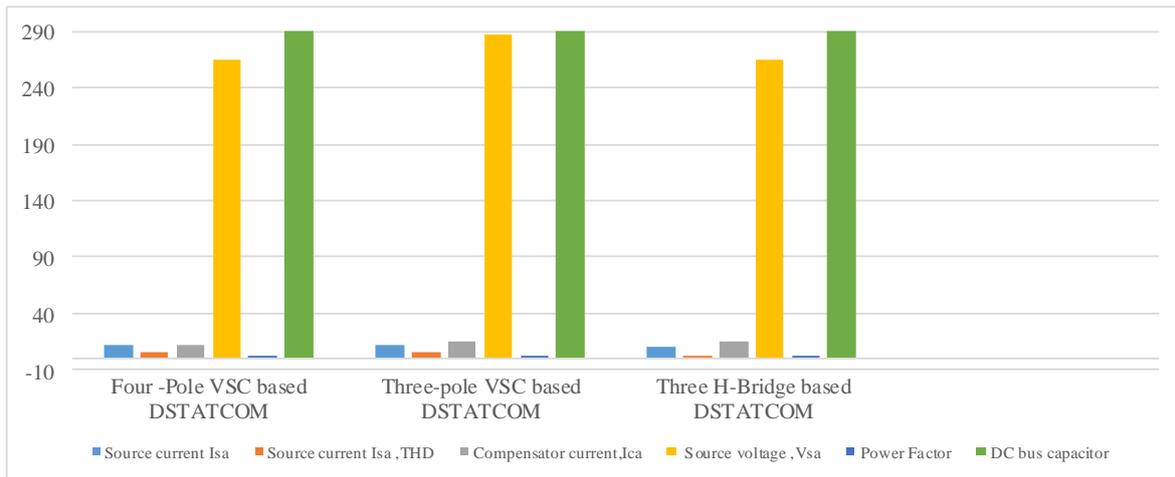
### 5.3 Three H-Bridge based DSTATCOM

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

The voltage of DC-link capacitor  $V_{dc}$  connected at the

**Table 3** Result analysis of different topologies of DSTATCOM.

| S. No. | Topologies                         | Source current (RMS) $I_s$ [A] |          |          | Source current (THD) [%] |          |          | Compensator current (RMS) $I_c$ [A] |          |          | Source voltage $V_s$ [V] |          |          | Power factor | DC capacitor voltage [V] |
|--------|------------------------------------|--------------------------------|----------|----------|--------------------------|----------|----------|-------------------------------------|----------|----------|--------------------------|----------|----------|--------------|--------------------------|
|        |                                    | $I_{sa}$                       | $I_{sb}$ | $I_{sc}$ | $I_{sa}$                 | $I_{sb}$ | $I_{sc}$ | $I_{ca}$                            | $I_{cb}$ | $I_{cc}$ | $V_{sa}$                 | $V_{sb}$ | $V_{sc}$ |              |                          |
| 1      | Four-pole                          | 10.8                           | 53.52    | 45.24    | 4.52                     | 4.70     | 4.55     | 11.02                               | 7.48     | 3.537    | 58                       | 266.2    | 324.2    | 0.953        | 660                      |
| 2      | Three-pole T-connected transformer | 36.87                          | 20.04    | 56.91    | 4.44                     | 4.41     | 4.44     | 40.52                               | 25.54    | 14.98    | 15.34                    | 287.9    | 272.6    | .956         | 695                      |
| 3      | Three H-bridge                     | 11.66                          | 40.49    | 52.15    | 2.13                     | 2.30     | 2.41     | 14.13                               | 8.211    | 5.914    | 48.22                    | 266.2    | 314.4    | .897         | 699                      |



**Fig. 18** Chartable form of different topologies of DSTATCOM.

DC side of the inverter is regulated after 0.2sec. It is seen that  $V_{dc}$  is almost constant and its magnitude is 700V after transient time. The source voltage is  $V_s$  constant after 0.2sec. The phase of  $I_s$  and  $V_s$  is the same which indicates that Three H-bridge based DSTATCOM is able to eliminate the harmonics from source current and makes it sinusoidal, balances the phases and reactive power compensation. Figs. 15-17 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 the grid side.

Table 3 depicts comparative arrangements of different parameter of DSTATCOM topologies and Fig. 18 indicates its chartable representation.

**7 Conclusion**

Three different topologies of DSTATCOM are proposed for mitigation of power quality problems like load balancing, harmonic elimination, and reactive power compensation.

From the 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 the error to the DC-link capacitor which helps to eliminate harmonics and balance the voltage of the bus bar.

4. Switch in the Three H-bridge helps to minimize the loss of inverter by the DC-link capacitor.
5. Regulation of DC bus capacitor in the case of Three H-bridge is fast and almost 700 V throughout the time interval.
6. The overall performance of Three H-bridge based DSTATCOM is the best among all the three topologies.

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