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POWER QUALITY IMPROVEMENT BY SIX-LEG DSTATCOM IN THREE-PHASE FOUR-WIRE DISTRIBUTION SYSTEM

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ABSTRACT

This paper proposes a six leg voltage source inverter (VSI) based distributed static synchronous compensator (DSTATCOM) to compensate voltage swells under linear and nonlinear loads in a three-phase four-wire (3P4W) distribution system. The proposed scheme with associated control strategy has the capability to mitigate voltage swells under linear and nonlinear loads and makes the load voltage as balanced sinusoidal. The performance of the proposed scheme has been verified using MATLAB/ Simulink platform and detailed results are presented.

KEYWORDS

Voltage swell, DSTATCOM, VSI, SRF, linear, nonlinear

1. INTRODUCTION

Recent work on worldwide power distribution shows a substantial growing number of sensitive loads such as hospital equipment, industry automations, semiconductor device manufacturer. The most common characteristics of these loads in modern industry and commercial applications are their ability to produce voltage sags and swells. According to an EPRI report, the economic losses due to poor power quality are $400b, a year in the U.S alone [1-2]. According to IEEE standard a voltage swell is defined as an increase in root mean square voltage from 110% to 180% of the normal voltage at the power frequency for the duration from 0.5 cycles of 1 minute. A voltage swell can occur due to a fault switching off a large load and switching to a large capacitor bank [3-4]. Voltage Swells are characterized by their magnitude and duration [5]. There, are many different solutions have been proposed to eliminate voltage swells [6], conventionally the passive filters are used for power quality issues. But nowadays power electronics based on a new kind of emerging custom power devices such as Dynamic voltage restorer, Distributed static compensator and unified power quality conditioner have been more popular because they offer the advantages of flexibility and high performance to improve the controllability of power distribution network) [7].The DSTATCOM is one of the solid state shunt connected CPD, which is one of the victorious solution to enhance different significant aspects of power quality) [8-11].Performance of DSTATCOM depends upon the control algorithm used for reference current calculation and firing pulse generation strategy. Most common and popularly used control strategies for 3p4w DSTATCOM are an instantaneous active power theory, symmetrical component theory, improved instantaneous active and reactive current component theory [12], p-q and p-q-r theory [13], hysteresis current controller technique [14], d-q reference frame or synchronous reference frame theory [15], etc.

In this work, synchronous reference frame theory is used for the control of VSI based DSTATCOM. A new configuration of DSTATCOM is proposed for a three-phase four-wire power distribution system, which is based on six-leg VSI. The DSTATCOM is modulated and simulated using time-domain MATLAB\Simulink platform to mitigate voltage swell under linear and nonlinear load. Comparative analysis of the voltage swell compensator under linear and nonlinear loads in between without compensator and with compensator is presented.

2. DESCRIPTION OF DSTATCOM CONFIGURATION

Figure 1 shows a schematic diagram of a shunt connected power electronic based DSTATCOM with balance resistive-capacitive (R-C) and diode-rectifier load connected to a three-phase four-wire distribution network having a source resistance and inductance. The DSTATCOM produces suitable compensating currents (i_{Ca}, i_{Cb}, i_{Cc}) and injected to each phase of the system to eliminate voltage swells. To filter high-frequency components of compensating currents, an interfacing inductance L_f is used at the AC side of the voltage source inverter based DSTATCOM.

3. MATHEMATICAL MODELING OF VSI-BASED DSTATCOM

This part shows the mathematical modeling of the supply system, shunt connected DSTATCOM and nonlinear load.

3.1 MATHEMATICAL MODELING OF SUPPLY SYSTEM

The supply system modeling can be represented in terms of volt-ampere equations as:

$$V_{Sa} = i_{Sa}R_{Sa} + V_{La} + V_{ta} \tag{1}$$

Where $V_{La} = L_{Sa}\left(\frac{di_{Sa}}{dt}\right)$ then the equation (1) can be rewritten as

$$V_{Sa} = i_{Sa}R_{Sa} + L_{Sa}\left(\frac{di_{Sa}}{dt}\right) + V_{ta} \tag{2}$$

$$V_{Sb} = i_{Sb}R_{Sb} + L_{Sb}\left(\frac{di_{Sb}}{dt}\right) + V_{tb} \tag{3}$$

$$V_{Sc} = i_{Sc}R_{Sc} + L_{Sc}\left(\frac{di_{Sc}}{dt}\right) + V_{tc} \tag{4}$$

Where, V_{Sa}, V_{Sb} and V_{Sc} are the three-phase supply voltages, i_{Sa}, i_{Sb} and i_{Sc} are the three-phase supply currents, V_{ta}, V_{tb} and V_{tc} are the three-phase terminal voltages at the point of common coupling (PCC), R_S and L_S are the supply resistance and inductance of the supply respectively. Equation (2) (3) and (4) can be rewritten in the form of state space derivative as:

$$\frac{di_{Sa}}{dt} = \left(V_{Sa} - V_{ta} - i_{Sa}R_{Sa}\right) \Big/ L_{Sa} \tag{5}$$

$$\frac{di_{Sb}}{dt} = \left(V_{Sb} - V_{tb} - i_{Sb}R_{Sb}\right) \Big/ L_{Sb} \qquad (6)$$

$$\frac{di_{Sc}}{dt} = \left(V_{Sc} - V_{tc} - i_{Sc}R_{Sc}\right) \Big/ L_{Sc} \qquad (7)$$

3.2 MODELING OF VSI-BASED DSTATCOM

$$V_{ta} = i_{Ca}R_{c} + L_{c}\left(\frac{di_{Ca}}{dt}\right) + v_{Ca} \qquad (8)$$

$$V_{tb} = i_{Cb}R_{c} + L_{c}\left(\frac{di_{Cb}}{dt}\right) + v_{Cb} \qquad (9)$$

$$V_{tc} = i_{Cc}R_{c} + L_{c}\left(\frac{di_{Cc}}{dt}\right) + v_{Cc} \qquad (10)$$

$$V_{Nc} = -i_{Nc}R_{C} - L_{C}\left(\frac{di_{Nc}}{dt}\right) \qquad (11)$$

Where, i_{Ca}, i_{Cb} and i_{Cc} are the three-phase DSTATCOM currents, v_{Ca}, v_{Cb} and v_{Cc} ate the three-phase DSTATCOM AC voltages, V_{Nc} is the DSTATCOM neutral voltage, R_C and L_C are DSTATCOM resistance and inductance respectively. The first order differential equations for the derivatives of DSTATCOM currents can be represented in the form of state space equations:

$$\frac{di_{Ca}}{dt} = \left(V_{ta} - v_{Ca} - i_{Ca}R_{c}\right) \Big/ L_{c} \qquad (12)$$

$$\frac{di_{Cb}}{dt} = \left(V_{tb} - v_{Cb} - i_{Cb}R_{c}\right) \Big/ L_{c} \qquad (13)$$

$$\frac{di_{Cc}}{dt} = \left(V_{tc} - v_{Cc} - i_{Cc}R_{c}\right) \Big/ L_{c} \qquad (14)$$

3.3 MODELING OF NONLINEAR LOAD

The three-phase diode-rectifier with capacitive-resistive (R-C) load is considered as nonlinear load. The basic equations for the three-phase non-linear loads are represented as:

$$V_{Sa} = V_{La} + i_{La}R_{sa} + L_{Sa}\left(\frac{di_{La}}{dt}\right) \qquad (15)$$

$$V_{Sb} = V_{Lb} + i_{Lb}R_{sb} + L_{Sb}\left(\frac{di_{La}}{dt}\right) \qquad (16)$$

$$V_{Sc} = V_{Lc} + i_{Lc}R_{sc} + L_{Sc}\left(\frac{di_{Lc}}{dt}\right) \qquad (17)$$

Where V_{La}, V_{Lb} and V_{Lc} are load voltages across load capacitors. The state space equations for three phase nonlinear load can be written as:

$$\left(\frac{di_{La}}{dt}\right) = \left(V_{Sa} - V_{La} - i_{La} R_{sa}\right) \Big/ L_{Sa} \tag{18}$$

$$\left(\frac{di_{Lb}}{dt}\right) = \left(V_{Sb} - V_{Lb} - i_{Lb} R_{sb}\right) \Big/ L_{Sb} \tag{19}$$

$$\left(\frac{di_{Lc}}{dt}\right) = \left(V_{Sc} - V_{Lc} - i_{Lc} R_{sc}\right) \Big/ L_{Sc} \tag{20}$$

4. DSTATCOM CONTROL STRATEGY

Control strategy plays the most important role in any CPDs. The performance of a DSTATCOM system solely depends upon its control technique for generation of reference signals.

4.1 SYNCHRONOUS REFERENCE FRAME (SRF) THEORY

This control scheme is based on the transformation of load currents (i_{La}, i_{Lb}, i_{Lc}) from a-b-c frame to the synchronously rotating reference frame to extract the direct, quadraure and zero-sequence components. A block diagram of the control topology is shown in Figure 2.

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_{Lo} \end{bmatrix} = (2/3) \begin{bmatrix} \cos\theta & -\sin\theta & 0.5 \\ \cos\left(\theta - 120^0\right) & -\sin\left(\theta - 120^0\right) & 0.5 \\ \cos\left(\theta + 120^0\right) & -\sin\left(\theta + 120^0\right) & 0.5 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{21}$$

$$i_{sd}^{*} = \overline{i_{Ld}} + i_{Cd} \tag{22}$$

$$i_{sq}^{*} = K_q \overline{i_{Lq}} + u i_{Cq} \tag{23}$$

Where, $\overline{i_{Ld}}$ and $\overline{i_{Lq}}$ are the average values of the d- axis and q-axis components of the load currents.

$$\begin{bmatrix} \overline{i_{Ld}} \\ \overline{i_{Lq}} \end{bmatrix} = G(s) \begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} \tag{24}$$

Where $G(s)$ is the transfer function and logical variable, $u = 0$ if the power factor is to be regulated and $u = 1$ if bus voltage is to be regulated. Kq=1 in the latter case.

$$K_q = Q_L^* \Big/ \overline{Q_L} \tag{25}$$

The reference for the source current is the d-q frame and first converted to the α-β frame and then to the a-b-c frame using following formulation.

$$\begin{bmatrix} i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix} = \left\{ \begin{matrix} \cos(\omega t) & \sin(\omega t) \\ -\sin(\omega t) & \cos(\omega t) \end{matrix} \right\} \begin{bmatrix} i_{sd}^* \\ i_{sq}^* \end{bmatrix} \tag{26}$$

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \sqrt{\left(2/3\right)} \left\{ \begin{matrix} 1 & 0 \\ -1/2 & -\sqrt{3}/2 \\ -1/2 & \sqrt{3}/2 \end{matrix} \right\} \begin{bmatrix} i_{sa}^* \\ i_{sb}^* \end{bmatrix} \tag{27}$$

Hence

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \sqrt{\left(2/3\right)} \left\{ \begin{matrix} \cos(\omega t) & \sin(\omega t) \\ \cos\left(\omega t - \left(2\Pi/3\right)\right) & \sin\left(\omega t - \left(2\Pi/3\right)\right) \\ \cos\left(\omega t + \left(2\Pi/3\right)\right) & \sin\left(\omega t + \left(2\Pi/3\right)\right) \end{matrix} \right\} \begin{bmatrix} i_{sd}^* \\ i_{sq}^* \end{bmatrix} \tag{28}$$

The reference for the source current vectors ($i_{sa}^*, i_{sb}^*, i_{sc}^*$) are compared and the desired compensator currents ($i_{Ca}^*, i_{Cb}^*, i_{Cc}^*$) are obtained as the difference between the load and the source currents.

$$\left. \begin{matrix} i_{Ca}^* = i_{La} - i_{sa}^* \\ i_{Cb}^* = i_{Lb} - i_{sb}^* \\ i_{Cc}^* = i_{Lc} - i_{sc}^* \end{matrix} \right\} \tag{29}$$

5. SIMULATION OF DSTATCOM

Figure 1 shows the proposed configuration of the test system used to carry out the transient modeling and simulation of the DSTATCOM with associated control strategy. This DSTATCOM model is simulated with the SRF control technique with simulation period 0.3 s. The electrical power system parameters are summarized in Table 1**.**

6. SIMULATION RESULTS AND DISCUSSION

In this section, the simulation results of SRF control based three-phase four-wire DSTATCOM supplying two loads are presented. Load1 is considered as fixed resistive load (R-load) and load2 is considered as variable linear and nonlinear load. The variable linear load is taken as three-phase resistive-capacitive (R-C) whereas nonlinear load is realized by three-phase diode-rectifier with R-C load. Breaker 1 is used to control the period of operation of VSI-based DSTATCOM and breaker 2 is used to control the connection of variable load to the distribution network. Initially, both the loads are connected to the network, but after a certain period of time load2 are switched off by opening the breaker2. Due to sudden removal of heavy load, voltage swell occurs in the source voltage.

6.1 VOLTAGE SWELLS MITIGATION BY SRF CONTROL BASED DSTATCOM UNDER LINEAR LOAD

Due to switching off a three-phase linear load by opening breaker2, a three-phase balanced voltage swell occurs in the source terminal of the distribution network from 0.01 to 0.25s. Then the voltage signal recovers to its normal value. During three-phase balanced voltage swell, the voltage magnitude of all the three phases may reach a level of 205% as shown in Figure 3 (a). For balanced voltage swell of 65%, the source voltage signal before compensation, the compensation current, the load voltage after voltage swell compensation are depicted in Figure 3(a) to (c). As figure shows, the proposed SRF control based voltage swell compensator restore the voltage on the load side by injecting proper compensating current in each phase so that the load voltage remains at the desired level. The performance of SRF control based uncompensated and compensated load voltages under linear load are shown in Figure 4. As the figure shows when the compensator is connected, the voltage at the load terminal reaches rapidly to the normal levels 140V. This can be resolved by injecting the appropriate amount of current to the distribution network under voltage swell conditions.

6.2 VOLTAGE SWELLS MITIGATION BY SRF METHOD UNDER NONLINEAR LOAD

Figure 5 (a) to (c) depicts the simulation results of SRF control based DSTATCOM with nonlinear load. In this case the three-phase source voltage magnitude raised to 30% of the normal level for the duration of 0.24 s. Then voltage recovers to its normal level. As it can be observed from the simulation results, the SRF control based DSTATCOM is able to generate the desired current components for three-phases rapidly and helps to maintain load voltage sinusoidal at the normal value. Figure 6 depicts the load voltages under nonlinear load conditions with and without voltage swell compensator. As the graph shows when SRF control based voltage swell compensator is added to the distribution system, it produces required amount of compensation current in each phase rapidly, so that the load voltage remains at the acceptable level.

Figure 7 shows the compensating load voltage under linear and nonlinear load conditions with SRF based voltage swell compensator. From the Figure it is observed that, SRF based DSTATCOM compensate voltage swell of magnitude 65% and 30% under linear as well as nonlinear load condition and brings back the voltage to its normal level.

7. CONCLUSION

In this work, SRF control based DSTATCOM installed in three-phase four wire distribution systems has been presented. Simulation results illustrated the capability of the voltage swell compensator and its control scheme to compensate voltage event such as voltage swell under linear and nonlinear load conditions.

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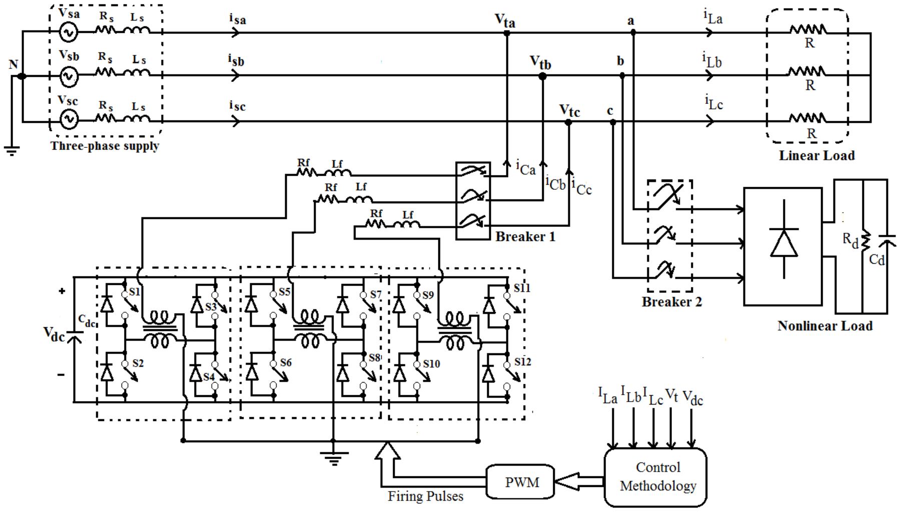

Figure 1. Schematic diagram of VSI-based DSTATCOM

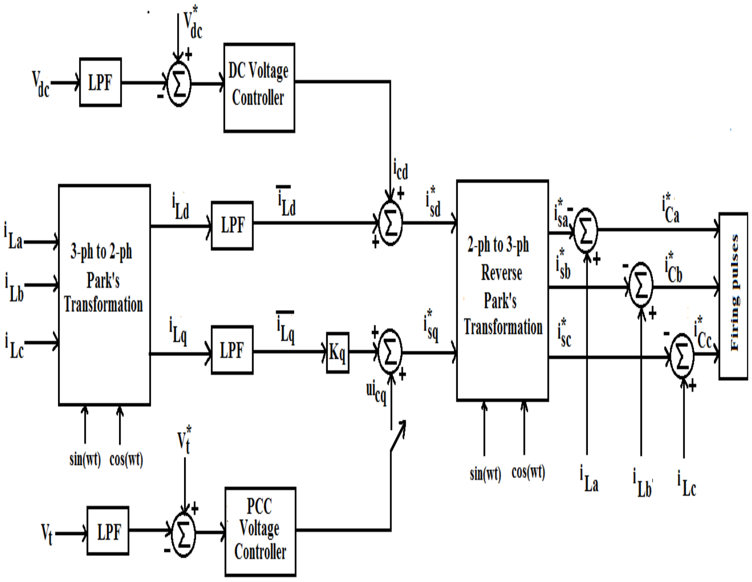

Figure 2. Block diagram of SRF controller

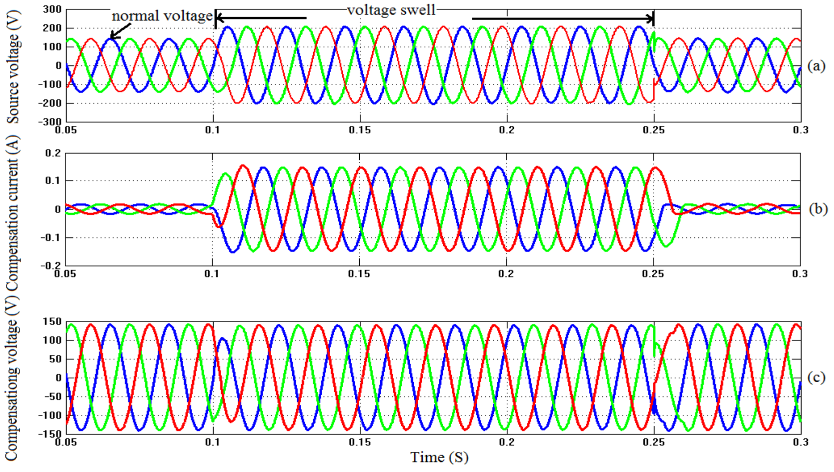

Figure 3. Voltage swells under linear load with SRF controller

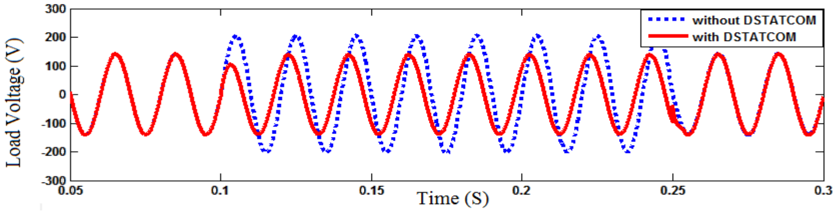

Figure 4. Load voltage with and without DSTATCOM by SRF controller

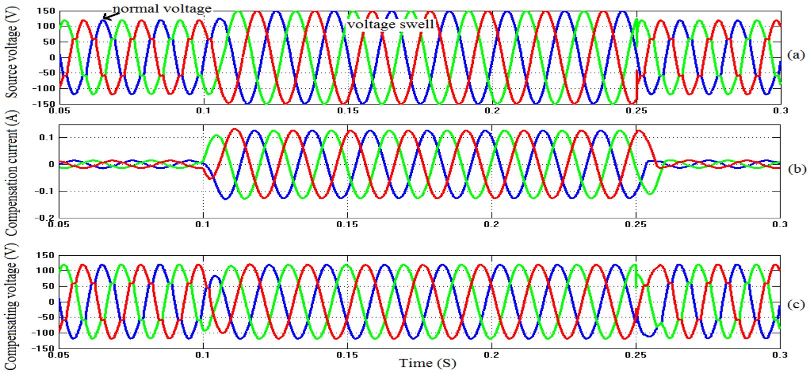

Figure 5. Voltage swells under nonlinear load with SRF theory

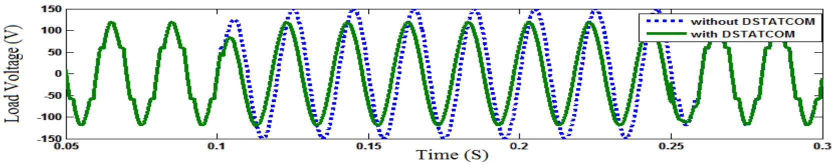

Figure 6. Load voltage with and without DSTATCOM by SRF controller

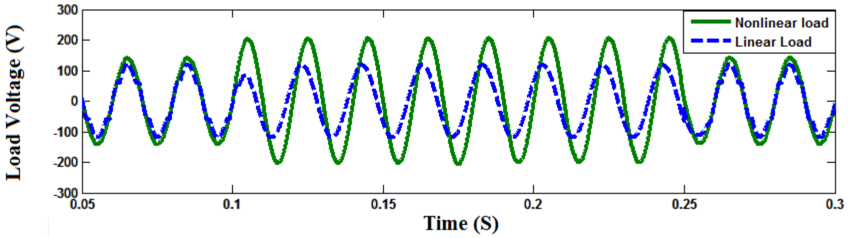

Figure. 7 Compensation of load voltage under linear and nonlinear load

TABLE 1. Network parameters used in the simulink

Parameter	Value
Source voltage	Vs = 415 V, 50Hz
Line impedance	Z_s = 1.57+j15.70 Ω
Linear load	Active power= 20W, Reactive power =40 VAR
Nonlinear load	R_d = 400 Ω, L_d = 50 mH
Filter parameter	L_f = 7.0 μF
DC side voltage and capacitance	V_{dc} = 7000 V, C_{dc} = 2000 μF
Proportional and PI controller	Kpi = 0.6, kp2 = -0.2, ki = -40

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