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Modeling and Simulation of Three Phase D-SVC for Load Compensation

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ABSTRACT

The transmission of electric power has to take place in the most efficient way in addition to providing flexibility in the process. Flexible A.C. Transmission System (FACTS) promotes the use of static controllers to enhance the controllability and increase the power transfer capability. Providing reactive shunt compensation with shunt-connected capacitors and reactors is a well-established technique to get a better voltage profile in a power system. Shunt Capacitors are inexpensive but lack dynamic capabilities, thus some form of dynamically controlled reactive power compensation becomes essential. In this paper, three phase Distribution Static Var Compensator (D-SVC) has been developed and studied under different conditions. Open loop mode and closed loop mode of operation of D-SVC is simulated and studied. The work presented here is very much useful for distribution system, for effective reactive power management and better Voltage control.

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1. INTRODUCTION

Modern power system is complex and it is essential to fulfill the demand with better power quality. Reactive power compensation is defined as the management of reactive power to improve the performance of ac system. The concept of reactive power compensation embraces a wide and diverse field of both system and customer problems, especially related with power quality issues, since most of the power quality issues can be solved with the adequate control of reactive power. In general the problem of VAR compensation is viewed by load compensation and voltage support. Providing reactive shunt compensation with shunt-connected capacitors and reactors is a well-established technique to get a better voltage profile in a power system. The basic form of reactive power compensation required, to compensate reactive power loads, is the fixed shunt capacitors being well distributed across the network and located preferably closed to the loads. This would ensure reasonable voltage profile during steady state condition. However, this may not be adequate to ensure stability under overload or contingency conditions. Shunt capacitors are inexpensive but lack dynamic capabilities, thus some form of dynamically controlled reactive power compensation becomes essential. Instead of mechanical switching (using circuit breakers) of these devices, we can use thyristor valves, thereby increasing the control capability radically [1]-[4].

1.1. Distribution Static Var Compensators (D-SVC)

The Static Var Compensators (SVC) has been widely used by utilities since mid-1970s. SVC is based on conventional capacitors and inductors combined with fast semiconductor switches without turn off capability (i.e. SCR thyristor). The purpose, topologies and control principle of D-SVC is similar to SVC, but used for distribution line. They mimic the working principles of a variable shunt susceptance and use fast thyristor controllers with settling times of only a few fundamental frequency periods. From the operational point of view, the D-SVC adjusts its value automatically in response to changes in the operating conditions of the network. By suitably controlling its equivalent reactance, it is possible to regulate the voltage magnitude, thus enhancing significantly the performance of the power system [5],[6].

This paper is structured in such a way that section 1 gives the introduction and importance of reactive power compensation. Operating principle of Distribution Static Var Compensators (D-SVC) is discussed in section 2. Modeling and simulation of three phase six pulse star and delta connected D-SVC are carried out for open loop operation in section 3. The closed loop operation for delta connected D-SVC is discussed in section 4. Finally, section 5 gives the conclusion of the proposed work.

2. D-SVC OPERATING PRINCIPLE

Figure 1 shows the schematic diagram of the most basic Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR) arrangement of the D-SVC. It is equivalent to a variable susceptance.

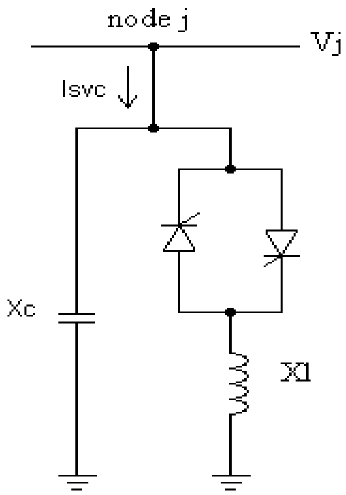

Figure 1. Schematic representation of an FC-TCR arrangement of D-SVC

An ideal variable shunt compensator is assumed to contain no resistive components, i.e. $G_{SVC} = 0$. Accordingly, it draws no active power from the network. On the other hand, its reactive power is a function of nodal voltage magnitude at the connection point, say node j and the D-SVC equivalent susceptance, B_{SVC}. Thus the active power (P_j) and reactive power (Q_j) in SVC are given by equations (1) and (2):

$$P_j = 0 \tag{1}$$

$$Q_j = -|V_j|^2 B_{SVC} \tag{2}$$

The main advantage of D-SVCs over simple mechanically-switched compensation schemes is their near-instantaneous response to changes in the system voltage. They are, in general, cheaper, higher-capacity, faster and more reliable than dynamic compensation schemes such as synchronous condensers [7]-[9].

3. MODELLING OF THREE PHASE SIX PULSE STAR AND DELTA CONNECTED D-SVC (OPEN LOOP)

The aim of the D-SVC in this application is to provide voltage regulation at the point of connection, following load variations. Initially the D-SVC is operated in open loop mode. When the load is increased and the voltage at the load point experiences voltage sag. The D-SVC controller operation changes in order to restore the voltage back to the target value [10]-[12].

The D-SVC parameters have been determined according to the compensation requirements for the case when the second load is connected. Based on the reactive power ($Q_{SVC} \approx 5.5$kVAr) required by Load 2, the D-SVC is sized with enough capacity to supply at least this reactive power in order to drive the voltage V_{bus} back to the reference. The design details of source and loads are given in Table 1 and Table 2 respectively.

Table 1. Design details of Source

Design details of Source	
Voltage	415V
Frequency	50Hz
Source resistance	0.01Ω
Source reactance	0.01H

Table 2. Design details of Loads

Design details of Loads	Load-1	Load-2
Voltage	415V	415V
Reactive power	4 kVAr	5.43kVAr
Real Power	5.5kW	0 kW

The values for the capacitance and the TCR inductance are then calculated based on this setting. The capacitive reactance is given by

$$X_C = (V_{bus})^2/Q_{SVC} = (415)^2 / 9.5 * 10^3 = 18.129\,\Omega \tag{3}$$

Let

$$X_L = X_C /2 \tag{4}$$

$$\Rightarrow C = 1.756 * 10^{-4}\ \text{F} \tag{5}$$

$$\Rightarrow L = 0.02885\text{H} \tag{6}$$

Once the capacitance and the inductance have been sized, it is necessary to determine the initial operating condition of the D-SVC. The selection of initial firing angle 'α' should be such that under this operating condition the D-SVC does not exchange any power with the AC system. It can be determined from the firing angle - reactive power characteristic of the SVC, which is a function of inductive and capacitive reactance. Firstly, it is necessary to obtain the effective reactance X_{SVC} as a function of firing angle α as below:

$$X_{TCR} = \Pi X_L / (\sigma - \sin\sigma) \tag{7}$$

$$\sigma = 2\,(\Pi - \alpha) \tag{8}$$

where σ is the conduction angle of the thyristor.

At $\alpha = 90°$, the TCR conducts fully and the equivalent reactance $X_{TCR} = X_L$. At $\alpha = 180°$, the TCR is blocked and its equivalent reactance becomes infinite. The total effective reactance of the D-SVC, including the TCR and capacitive reactance, is determined by the parallel combination of both components, as given in equations (9) and (10).

$$X_{SVC} = X_C X_{TCR} / (X_C + X_{TCR}) \tag{9}$$

$$X_{SVC} = \Pi\, X_C X_L / (X_C[\,2(\Pi - \alpha) + \sin 2\,\alpha] - \Pi\, X_L) \tag{10}$$

But,

$$Q_{SVC} = (V_{bus})^2 / X_{SVC} \tag{11}$$

3.1. Simulink Model of Three Phase Six Pulse Star Connected D-SVC

Figure 2 presents the simulink model of a three phase star connected D-SVC (FC- TCR configuration), that provides the voltage control at load side by in open loop operation. Since FC-TCR is shunt connected device, for fixed capacitive reactive var, the current through the inductor is varied by changing the thyristor gating angle $90<\alpha<180$. By using ideal switch at required time intervals loads are connected and FC-TCR arrangements are connected to improve the voltage sag or swell. The Real power demand is kept constant and the reactive power is varied by the three phase balanced load. For open loop control gate pulse for six thyristors in star are given by pulse generator.

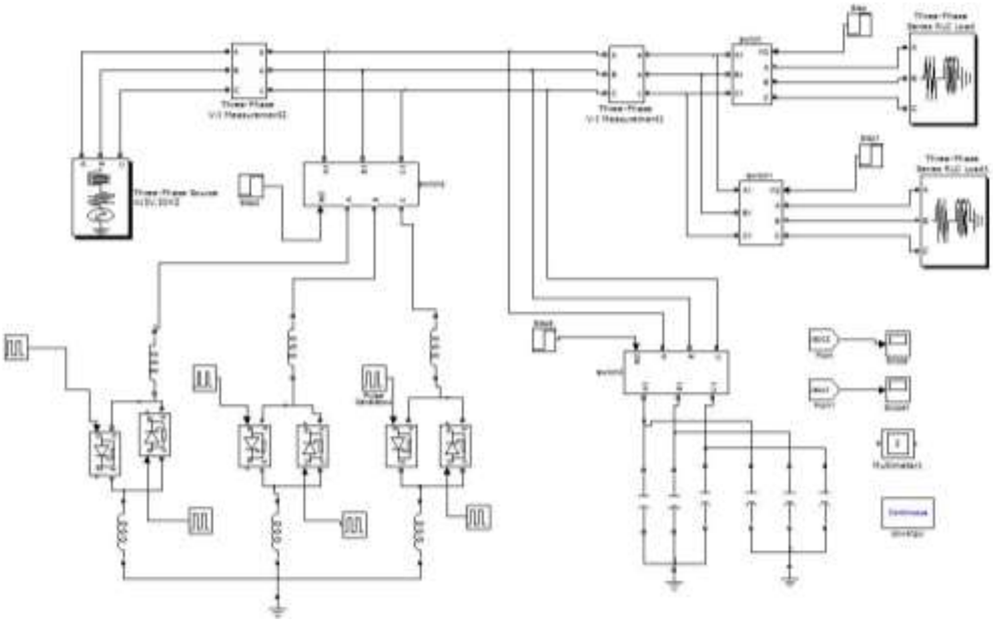

Figure 2. Three phase star connected D-SVC

3.1.1. Test Cases and Simulation Results with D-SVC (Star connected)

The simulation studies carried out are as follows: In the first case, D-SVC is operated in open-loop mode. The voltage V_{rms} at the load point is close to 0.96p.u. At time t = 0.04s, Load1 with inductive reactive power 4 kVAr is switched on. Under this condition, the voltage at the load point drops to 0.93 p.u. At 0.1 sec, Load2 with inductive reactive power 5.43 kVAr is switched on. The terminal bus voltage further sags to 0.84 p.u. At 0.16 sec, FC-TCR is switched on with firing angle 150 degree, now the voltage profile increased to 0.94 p.u. as shown in Figure 3.

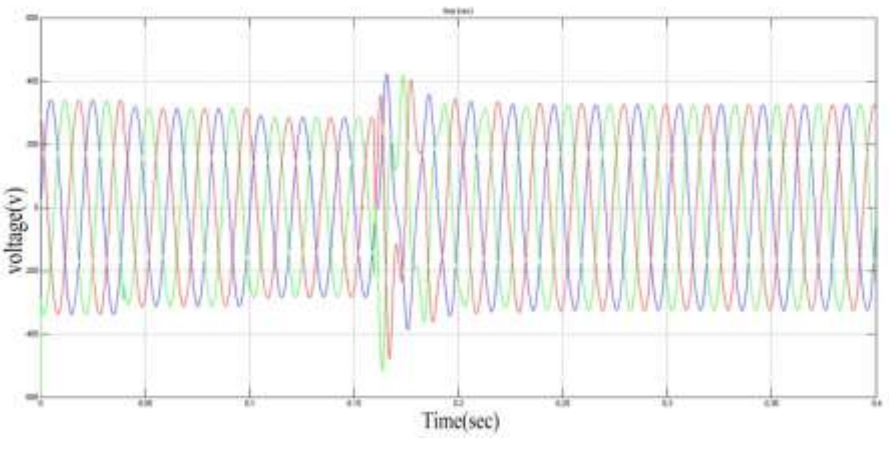

Figure 3. Voltage waveform for six pulse star connected D-SVC

By analysing the single phase waveform, harmonic distortion after the FC-TCR swicthing operation is studied,the harmonic order and magnitude (percentage of fundamental) is plotted. From Figure 4, it can be seen that the harmonic content for star connected FC-TCR is higher from the FFT analysis (THD = 17.01%).

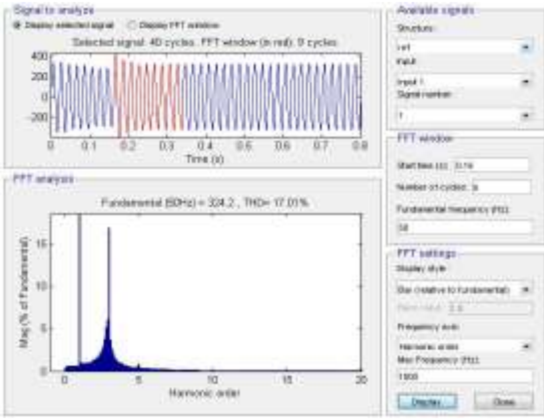

Figure 4. FFT analysis for star connected D-SVC

3.2. Simulink Model of Three Phase Six Pulse Delta Connected D-SVC

In Figure 5 three phase six pulse delta connected FC-TCR with firing angle 150 degree simulation is given. Six thyristors are connected, among that two thyristors are connected anti parallel with per phase. The gate pulse from pulse generator is 180 phase shift of each other. Since it is three phase, thyristors sets differ by 120 phase shift. Voltage measurement block provides the three phase sinusoidal waveform as output. The voltage sags by addition of reactive loads and compensation is done by three phase FC-TCR.

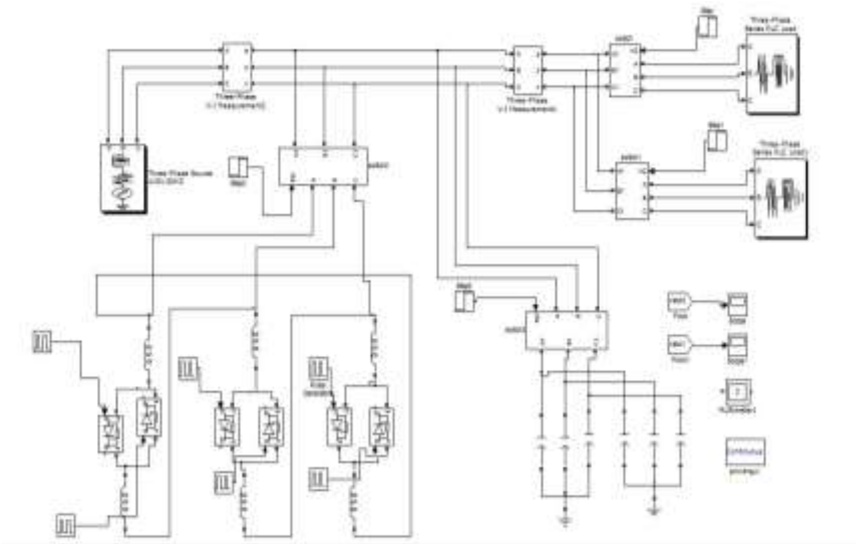

Figure 5. Three phase Delta connected D-SVC

3.2.1. Test Cases and Simulation Results with D-SVC (Delta connected)

Similar to previous case, D-SVC is operated in open-loop mode. The voltage V_{rms} at the load point is close to 0.96p.u. At time t = 0.04s, Load1 with inductive reactive power 4 kVAr is switched on. Under this condition, the voltage at the load point drops to 0.93 p.u. At 0.1 sec, Load2 with inductive reactive power 5.43 kVAr is switched on. The terminal bus voltage further sags to 0.84 p.u. At 0.16 sec., FC-TCR is switched on with firing angle 150 degree, now the voltage profile increased to 0.96 p.u., as shown in Figure 6.

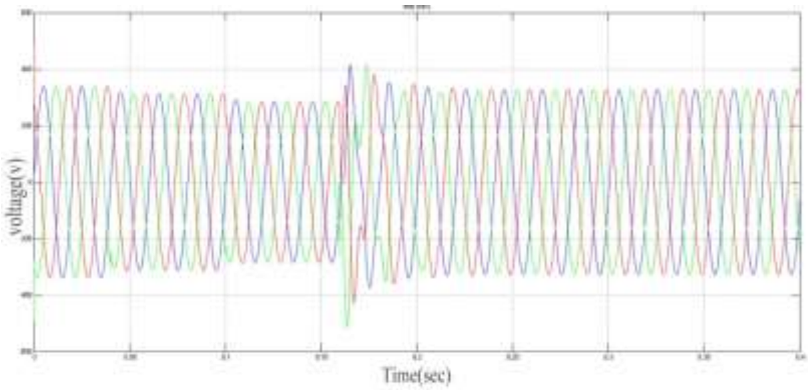

Figure 6. Voltage waveform for three phase delta connected D-SVC

By analysing the single phase waveform, harmonic distortion after the FC-TCR swicthing operation is studied,the harmonic order and magnitude (percentage of fundamental) is plotted. From Figure 7, it can be seen from the FFT analysis that the THD content for delta connected FC-TCR is 3.32%. From FFT analysis of star and delta connected FC-TCR arrangement, the total harmonic distortion for delta configuration is much lower, hence simulation study of closed loop operation is carried out for delta connected FC-TCR.

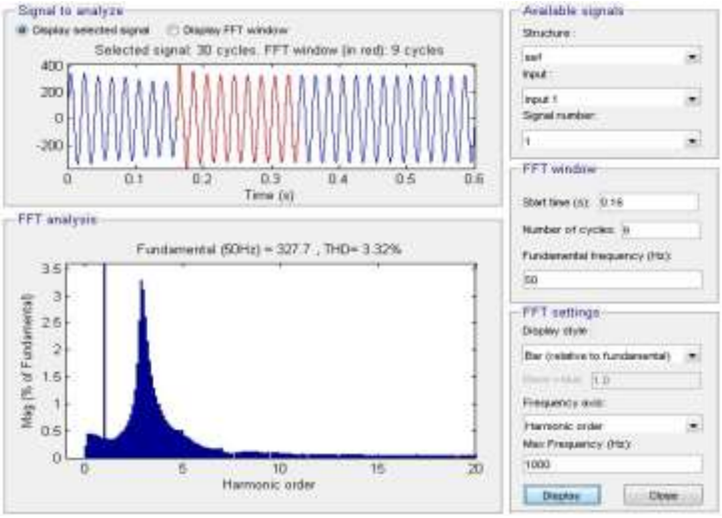

Figure 7. FFT analysis for delta connected D-SVC

Hence the main advantages of delta connected FC-TCR over star connected FC-TCR are:

a. Triplen Harmonics are less in delta connection.
b. Transient time period is less in delta connection.

4. MODELLING AND SIMULATION THREE PHASE SIX PULSE D-SVC DELTA CONNECTED (CLOSED LOOP OPERATION)

Similar to open loop operation FC-TCR is connected in shunt arrangement with fixed capacitor banks. In close loop operation gating pulse for thyristors are calculated by firing pulse generator circuit by comparing the reference voltage with the voltage sag on loading. The voltage difference that is the error is fed to PI controller to provide the delay signal to pulse generator circuit on adding optimum firing angle. The block diagram of the control scheme is shown in Figure 8.

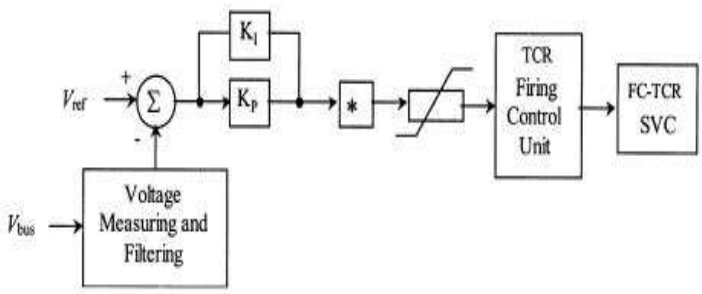

Figure 8. Closed loop block diagram – D-SVC

4.1. Closed loop Simulink Model of three phase six pulse delta connected D-SVC

The simulation circuit for D-SVC developed in Matlab-simulink using the topology described in previous section is shown in Figure 9. The associated firing pulse generation and the TCR closed loop scheme are shown in Figure 10 and Figure 11 respectively. The aim of the D-SVC in this application is to provide voltage regulation following load variations. Initially, the D-SVC is operated in open-loop mode where the power exchange between the D-SVC and the ac system is zero. When the load is increased and the voltage at the load point experiences voltage sag. When the load is increased, the D-SVC controller operation changes to closed-loop mode in order to adjust its effective impedance X_{svc} so that it injects capacitive current into the system to restore the voltage to the original value.

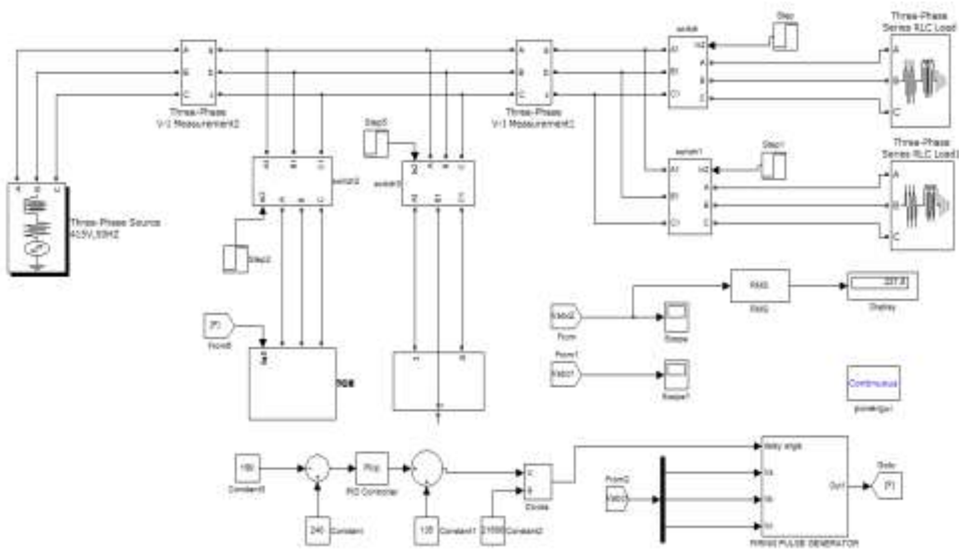

Figure 9. Matlab Simulink model for three phase six pulse delta connected closed loop operation

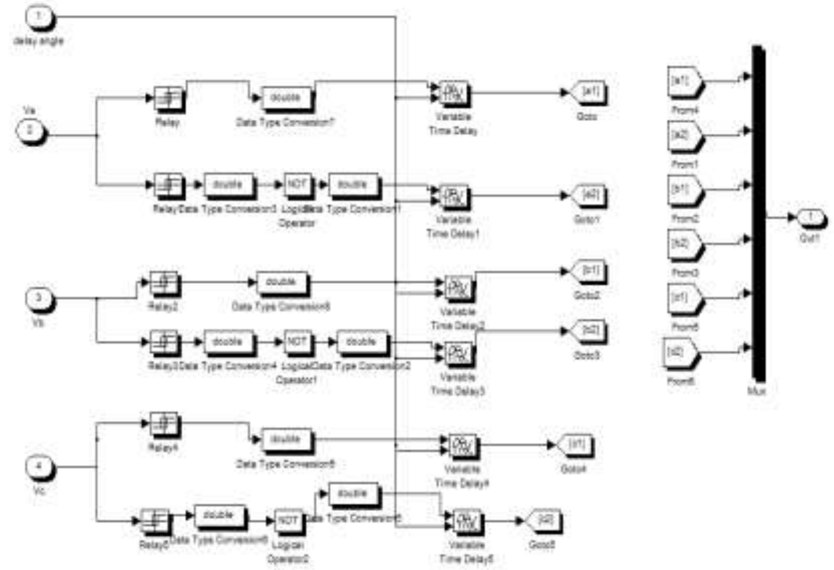

Figure 10. Firing pulse generator

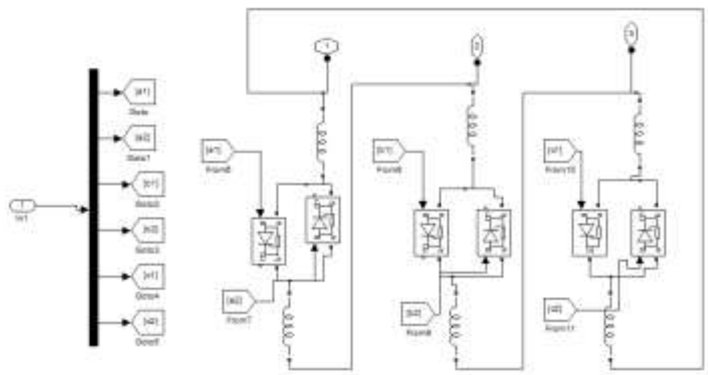

Figure 11. TCR configuration for closed loop operation

To generate gating pulse pattern for six thyristor automatically,a delay angle and three phase voltage is used.Voltage signal is converted into relay signal and it is varied by time delay to produce required firing pulse.The anti parralel thyristor firing pulse is obtained by 180 degree phase shift. These pulse are given to TCR configuration.

4.1.1. Simulation Results with Delta connected D-SVC (Closed loop)

The simulation studies carried out are as follows: In the first case, D-SVC is operated in open-loop mode. The voltage V_{rms} at the load point is close to 0.96p.u. At time t = 0.04s, Load1 with inductive reactive power 4 kVAr is switched on. Under this condition, the voltage at the load point drops to 0.93 p.u. At 0.1 sec, Load2 with inductive reactive power 5.43 kVAr is switched on. The terminal bus voltage further sags to 0.84 p.u. At 0.16 sec, FC-TCR is switched on with firing angle 150 degree, now the voltage profile increased to 0.92 p.u., as shown in Figure 12. It is seen that the waveform to attain steady state is higher when compared to open loop fixed capacitor with thyristor controlled reactor configuration. At 0.16 sec FC-TCR is switched on, the transient period exist upto 0.25sec to attain steady state condition. This type of closed loop configuration reduces the time response and provides automatic voltage regulation for fluctuation in load.

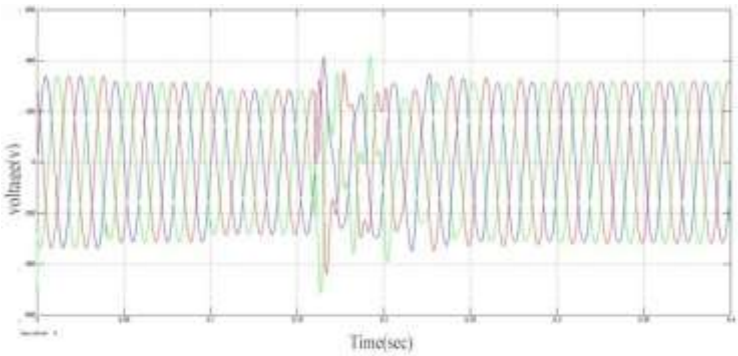

Figure 12. Voltage waveform for closed loop delta connected D-SVC

On comparing the harmonic spectrum analysis with open loop operation, the closed loop harmonic content is slightly high. For open loop delta connected FC-TCR the value for THD is 3.32%, whereas in case of closed loop operation THD is 5.35%, as shown in Figure 13.

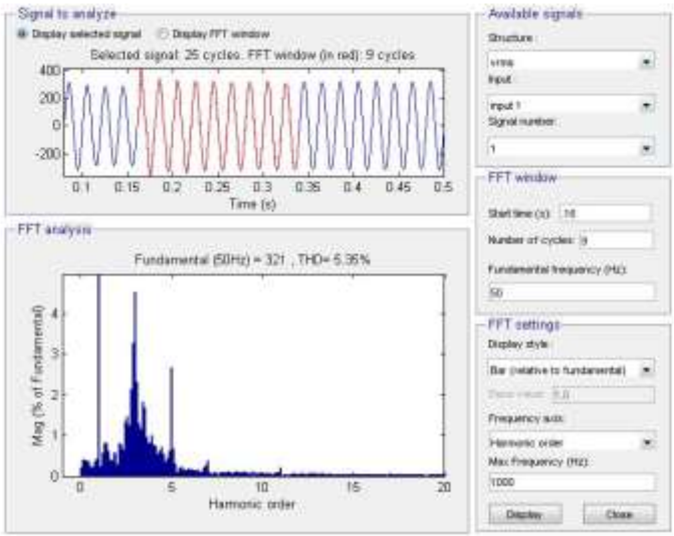

Figure 13. FFT analysis for closed loop delta connected D-SVC

5. CONCLUSION

This paper has discussed the FC-TCR model arrangement of three phase Static Var Compensator (D-SVC). The model is applied to the study of power quality and its voltage regulation capabilities. This characteristic makes it ideally suitable for low-voltage custom power applications. The control scheme was tested under a wide range of operating conditions, and it was observed that D-SVC could provide the fast acting voltage support necessary to prevent the possibility of voltage reduction and voltage collapse at the bus to which it is connected.

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