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MODELING AND SIMULATION OF 14 BUS SYSTEM WITH D-STATCOM FOR POWERQUALITY IMPROVEMENT

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ABSTRACT

This paper deals with modeling and simulation of fourteen bus system employing D-STATCOM for power quality improvement. The improvement in voltage stability with D-STATCOM is presented. A 11 level inverter based D-STATCOM is proposed to reduce the harmonics in the output. Voltages at varies buses with and without D-STATCOM are present ed. The simulation results will be compared with the analytical results.

KEY WORDS: Distribution static synchronous compensator (D-STATCOM), Power Quality (PQ), Flexible AC Transmission System (FACTS), Voltage sag mitigation, Real and Reactive power

The rapid development of the high-power electronics industry has made Flexible AC Transmission System (FACTS) devices viable and attractive for utility applications. Flexible AC Transmission Systems (FACTS), besides the underlying concept of independent control of active and reactive power flows, are an efficient solution to the reactive power control problem and voltage in transmission and distribution systems, offering an attractive alternative for achieving such objectives. Electric power quality (EPQ) problems mainly include unbalance voltage and current, flicker, harmonics, voltage sag, dip, performance and its compensation does not depend on the common coupling voltage. Therefore, STATCOM is very effective during the power system disturbances. Moreover, much research confirms several advantages of STATCOM.

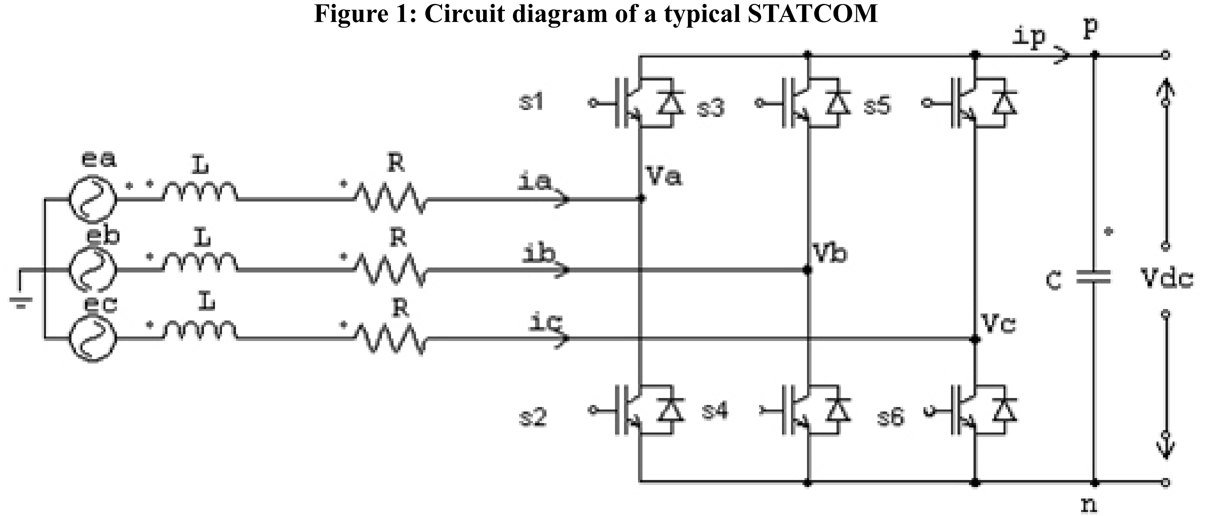
The present paper deals with the mathematical modeling of multilevel STATCOM, where, an equivalent value of dc sources (in general, capacitors) over one cycle period is computed using principle of energy equivalence. The mathematical model is developed using this equivalent capacitor value for analysis and control system design purpose. (Shukla et al., 2007; 2008)

MODELING OF STATCOM

Circuit Model

The voltage source converter based STATCOM is the dominant topology in practice.

Figure 1: Circuit diagram of a typical STATCOM



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Where

i_a, i_b, i_c	line currents
V_a, V_b, V_c	converter phase voltages
e_a, e_b, e_c	AC source phase voltages
Vdc=Vpn	DC side voltage
I_p	DC side current
L	inductance of the line reactor;
R	resistance of the line reactor;
C	DC side capacitor,

Mathematical Model

Based on the equivalent circuit of STATCOM shown in Figure 2.1 we can derive the mathematic model of STATCOM as fallow, (Mitra and Venayagamoorthy, 2008)

From power electronics principles we get

$$i_p = \begin{bmatrix} D_{ap} - D_{bp} \\ D_{bp} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix}^T \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \tag{1}$$

Where

D_{kp} are switching functions and K= a,b,c

$$i_{ab} = \frac{1}{3}(i_a - i_b),\ i_{bc} = \frac{1}{3}(i_b - i_c),\ i_{ca} = \frac{1}{3}(i_c - i_a)$$

and

$$\begin{bmatrix} V_a - V_b \\ V_b - V_c \\ V_c - V_a \end{bmatrix} = \begin{bmatrix} D_{ap} - D_{bp} \\ D_{pb} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix} Vpn \tag{2}$$

From circuit principles we get

$$Ri_a + L\frac{di_a}{dt} = e_a - V_a \tag{3}$$

$$Ri_b + L\frac{di_b}{dt} = e_b - V_b \tag{4}$$

$$Ri_c + L\frac{di_c}{dt} = e_c - V_c \tag{5}$$

and

$$L\frac{di_{ab}}{dt} = \frac{1}{3}L\left(\frac{di_a}{dt} - \frac{di_b}{dt}\right) \tag{6}$$

this equation can be expanded as below

$$L\frac{di_{ab}}{dt} = \frac{1}{3}[(e_a - V_a) - (e_b - V_b)] - i_{ab}R$$

$$= \frac{1}{3}[(e_a - e_b) - (V_a - V_b)] - i_{ab}R \tag{7}$$

similarly we can get

$$L\frac{di_{bc}}{dt} = \frac{1}{3}[(e_b - e_c) - (V_b - V_c)] - i_{bc}R \tag{8}$$

$$L\frac{di_{ca}}{dt} = \frac{1}{3}[(e_c - e_a) - (V_c - V_a)] - i_{ca}R \tag{9}$$

Writing the above three equations together we have

$$\frac{d}{dt}\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \frac{1}{3L}\begin{bmatrix} e_a - e_b \\ e_b - e_c \\ e_c - e_a \end{bmatrix} - \frac{1}{3L}\begin{bmatrix} V_a - V_b \\ V_b - V_c \\ V_c - V_a \end{bmatrix} - \frac{R}{L}\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \tag{10}$$

By applying equation (2) to equation (10)

$$\frac{d}{dt}\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \frac{1}{3L}\begin{bmatrix} e_a - e_b \\ e_b - e_c \\ e_c - e_a \end{bmatrix} - \frac{1}{3L}\begin{bmatrix} D_{ap} - D_{bp} \\ D_{pb} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix} Vpn - \frac{R}{L}\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \tag{11}$$

and

$$C\frac{dVpn}{dt} = i_p = \begin{bmatrix} D_{ap} - D_{bp} \\ D_{bp} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix}^T \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix}. \tag{12}$$

It is common practical in power system application to transform 3 phase AC dynamics into orthogonal components in a rotating reference frame. Here components are referred to as the real and reactive components, those that lead to useful work and those that do not respectively. From the power system theory we get the real and reactive currents relative to a rotating reference frame with angular frequency ω as

$$\begin{bmatrix} i_d \\ i_q \\ 0 \end{bmatrix} = P\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{13}$$

and

$$P = \frac{2}{3}\begin{bmatrix} \cos(\omega t) & \cos(\omega t - \frac{2}{3}\pi) & \cos(\omega t + \frac{2}{3}\pi) \\ -\sin(\omega t) & -\sin(\omega t - \frac{2}{3}\pi) & -\sin(\omega t + \frac{2}{3}\pi) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \tag{14}$$

where

id active current component,

iq reactive current component,

then we have

$$\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} i_a - i_b \\ i_b - i_c \\ i_c - i_a \end{bmatrix} = \frac{1}{3}(\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} i_b \\ i_c \\ i_a \end{bmatrix}) = \overline{T}^{-1}\begin{bmatrix} i_d \\ i_q \\ 0 \end{bmatrix} \tag{15}$$

where

$$\overline{T}^{-1} = \frac{1}{\sqrt{3}}\begin{bmatrix} -\sin(\omega t - \frac{1}{3}\pi) & \cos(\omega t - \frac{1}{3}\pi) & 1 \\ \sin(\omega t) & -\cos(\omega t) & 1 \\ -\sin(\omega t + \frac{1}{3}\pi) & \cos(\omega t + \frac{1}{3}\pi) & 1 \end{bmatrix} \tag{16}$$

if we set Tas the first two 2×3 subspace of matrix T, we can get

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = T\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \tag{17}$$

Similarly we can get

$$\begin{bmatrix} e_d \\ e_q \end{bmatrix} = T\begin{bmatrix} e_{ab} \\ e_{bc} \\ e_{ca} \end{bmatrix} \tag{18}$$

$$\begin{bmatrix} D_d \\ D_q \end{bmatrix} = T\begin{bmatrix} D_{ab} \\ D_{bc} \\ D_{ca} \end{bmatrix} \tag{19}$$

Applying equation (17) to the left part of equation (11)

$$\frac{d}{dt}\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \frac{1}{3L}\begin{bmatrix} e_a - e_b \\ e_b - e_c \\ e_c - e_a \end{bmatrix} - \frac{1}{3L}\begin{bmatrix} D_{ap} - D_{bp} \\ D_{pb} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix} Vpn - \frac{R}{L}\begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} \tag{20}$$

Applying equations (18) and (19) to equation (11)

$$\frac{dT^{-1}}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + T^{-1}\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} = \frac{1}{3L}T^{-1}\begin{bmatrix} e_d \\ e_q \end{bmatrix} - \frac{1}{3L}T^{-1}\begin{bmatrix} D_d \\ D_q \end{bmatrix} \cdot V_{pn} - \frac{R}{L}T^{-1}\begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{21}$$

From power system principles we get

ed = V_m

eq = 0 and

$$T\frac{dT^{-1}}{dt} = \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \tag{22}$$

multiply T to both side of equation (21) and applying equation (22), we obtain

$$\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega & -\frac{Dd}{3L} \\ -\omega & -\frac{R}{L} & -\frac{Dq}{3L} \end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ Vdc \end{bmatrix} + \begin{bmatrix} \frac{1}{3L} \\ 0 \\ 0 \end{bmatrix} V_m \tag{23}$$

By applying equations (17) and (19) to equation (12) we have

$$\frac{dVdc}{dt} = \frac{1}{C}i_p = \frac{1}{C}\begin{bmatrix} D_{ap} - D_{bp} \\ D_{bp} - D_{cp} \\ D_{cp} - D_{ap} \end{bmatrix}^T \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} = \begin{bmatrix} D_d \\ D_q \end{bmatrix}^T T^{-T}T^{-1}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{3}{2C}\begin{bmatrix} D_d \\ D_q \end{bmatrix}^T \begin{bmatrix} i_d \\ i_q \end{bmatrix}.$$

Which leads to

$$\frac{dVdc}{dt} = \frac{dVpn}{dt} = \frac{1}{C}i_p = \frac{3}{2C}\begin{bmatrix} D_d \\ D_q \end{bmatrix}^T \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{24}$$

Rearranging equations (23) and (24) we get

$$\frac{di_d}{dt} = \frac{-R}{L}i_d + i_q\omega - \frac{Vdc}{3L}D_d + \frac{1}{3L}V_m \tag{25}$$

$$\frac{di_q}{dt} = -i_d\omega - \frac{R}{L}i_q - \frac{Vdc}{3L}D_q \tag{26}$$

$$\frac{dVdc}{dt} = \frac{3}{2C}i_d D_d + \frac{3}{2C}i_q D_q \tag{27}$$

Finally we find that we can represent the "outer loop" dynamics of STATCOM, the dynamics resulting from any arbitrary switching function , by representing the above equation in its the standard state space form (Xiao-ping et al., 2006).

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \\ Vdc \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & \omega & -\frac{D_d}{3L} \\ -\omega & -\frac{R}{L} & -\frac{D_q}{3L} \\ \frac{3}{2C}D_d & \frac{3}{2C}D_q & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{3L} \\ 0 \\ 0 \end{bmatrix} V_m \tag{28}$$

This completes the nonswitching dynamic model of STATCOM as equation (28). From the model we can see the states of the STATCOM dynamic loop are i_d, i_q and V_{dc}. V_m can be considered as a system constant parameter. The control variables are D_d, D_q. Note that this is a bilinear system and in our application, full state feedback control of STATCOM, represents a nonlinear system.

PRINCIPLE OF OPERATION

The STATCOM consists of a voltage source converter connected in shunt with the system. For the distribution level STATCOM pulse width modulation is typically used to reduce the harmonic output of the converter. Depending on the application, the D-STATCOM may be operated to achieve the following objectives:

1. voltage regulation at a particular ac bus
2. rapid power factor correction of a particular load
3. power factor correction and load balancing and/or harmonic compensation of a particular load.

Basically, the STATCOM system is comprised of three main parts: a VSC, a set of coupling reactors or a step-up transformer, and a controller. In a very-high-voltage system, the leakage inductances of the step-up power transformers can function as coupling reactors. The main purpose of the coupling inductors is to filter out the current harmonic components that are generated mainly by the pulsating output voltage of the power converters. The STATCOM is connected to the power networks at a PCC, where the voltage-quality problem is a concern. All required voltages and currents are measured and are fed into the controller to be compared with the commands. The controller then performs feedback control and outputs a set of switching signals to drive the main semiconductor switches of the power converter accordingly. The single line diagram of the STATCOM system is illustrated in Figure 1. In general, the VSC is represented by an ideal voltage source associated with internal loss connected to the AC power via coupling reactors.

In principle, the exchange of real power and reactive power between the STATCOM and the power system can be controlled by adjusting the amplitude and phase of the converter output voltage. In the case of an ideal lossless power converter, the output voltage of the converter is controlled to be in phase with that of the power system. In this case, there is no real power circulated in the STATCOM; therefore, a real power source is not needed. To operate the STATCOM in capacitive mode or var generation, +Q, the magnitude of the converter output voltage is controlled to be greater than the voltage at the PCC. In contrast, the magnitude of the output voltage of the converter is controlled to be less than that of the power system at the PCC on order to absorb reactive power or to operate the STATCOM in inductive mode, -Q. However, in practice, the converter is associated with internal losses caused by non-ideal power semiconductor devices and passive components. As a result, without any proper controls, the capacitor voltage will be discharged to compensate these losses, and will continuously decrease in magnitude. To regulate the capacitor voltage, a small phase shift d is introduced between the converter voltage and the power system voltage. A small lag of the converter voltage with respect to the voltage at the PCC causes real power to flow from the power system to the STATCOM, while the real power is transferred from the STATCOM to the power system by controlling the converter voltage so that it leads the voltage at the PCC. Figure 2 illustrates phasor diagrams of the voltage at the PCC, converter output current and voltage in all four quadrants of the PQ plane (Carpita and Teconi, 1991; Hendrimasdi, 2009)

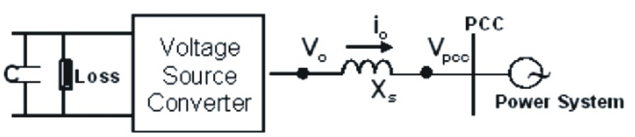


Figure 2.a: Single line diagram of D-STATCOM

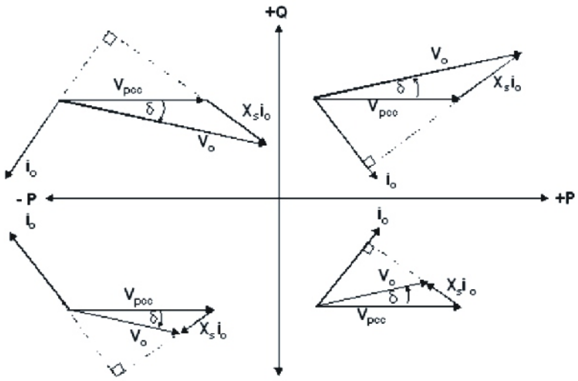


Figure 2.b: Phasor diagram for power exchanges

The above literature does not deal with modeling and simulation of 14 bus system using simulink. This work presents modeling and simulation of thirty bus system employing a D-STATCOM.

SIMULATION RESULTS

The 14 bus system is considered for simulation studies. The circuit model of 14 bus system without D-STATCOM is shown in Fig. 3a. Each line is represented by series impedance model. The shunt capacitance of the line is neglected. The Load voltage and Real & reactive power at busses 2,11 are shown in Figs.3b, 3c, 3d and 3e respectively.

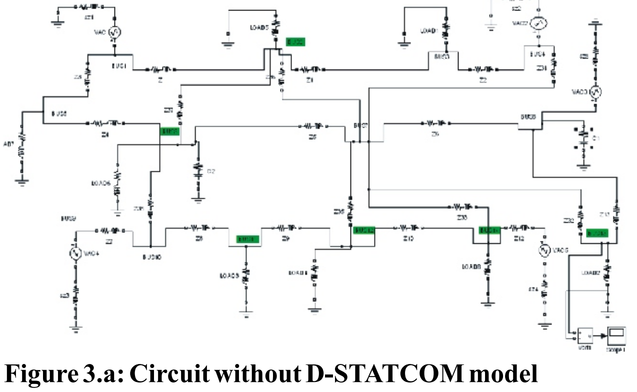
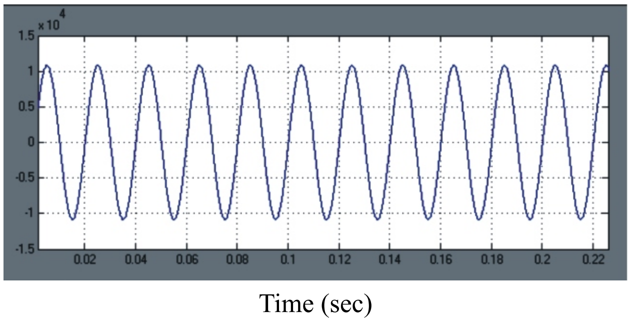
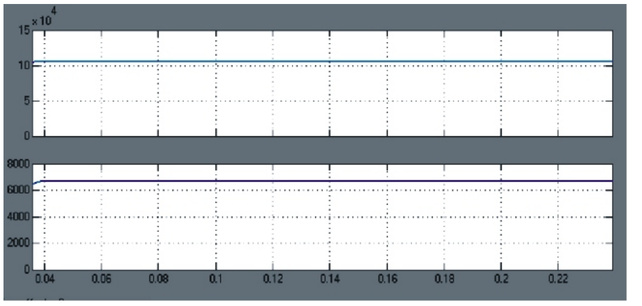


Figure 3.a: Circuit without D-STATCOM model



Time (sec)

Figure 3.b: LOAD VOLTAGE in bus 2



Time (sec)

Figure 3c.: Real and Reactive power in bus 2

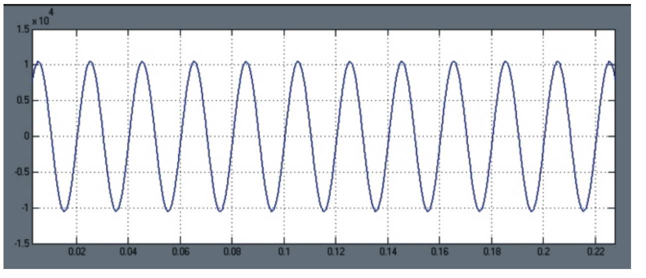


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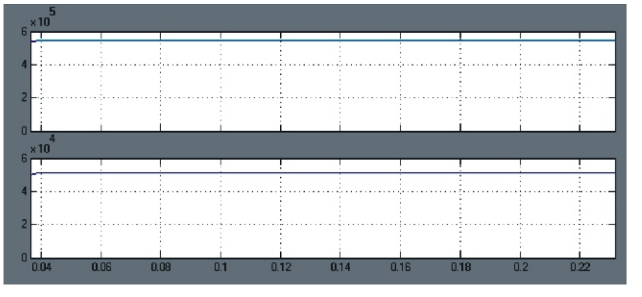
Figure 3.d: load voltage in bus 11



Time (sec)

Figure 3.e: Real and Reactive power in bus 11

The 14 bus system with D-STATCOM is shown in Fig. 4a. The D-STATCOM is added to the bus 12 to improve power quality. The reactive power of the loads connected to the nearby buses is studied. The Load voltage and real & reactive powers in the buses 2, and 11 are shown in Figs. 4b, 4c, 4d and 4e respectively. The summary of the reactive power in various buses is given in Table 1. It can be seen that the reactive power increases in the buses near the D-STATCOM. The increase in reactive power is due to increase in the voltage of the nearby buses.

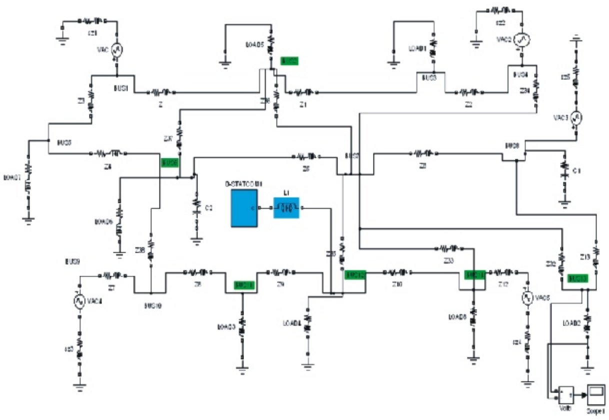
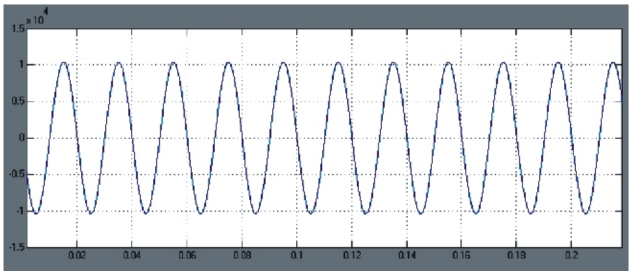
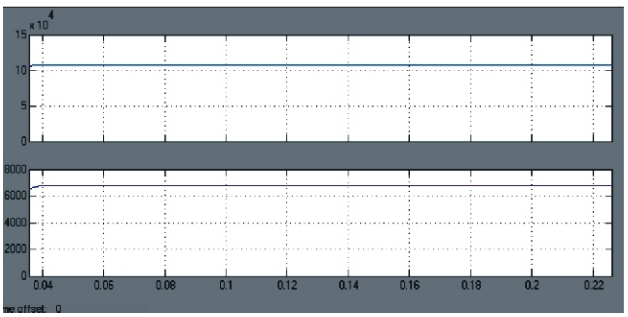


Figure 4.a: Circuit model with STATCOM



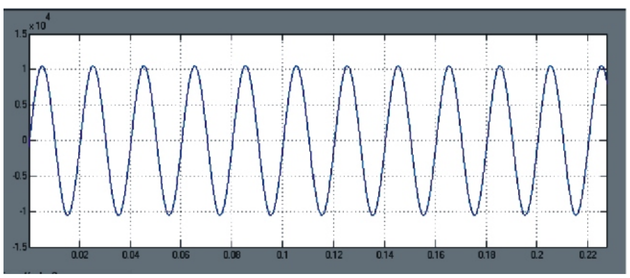
Time (sec)

Figure 4.b: LOAD VOLTAGE in bus 2



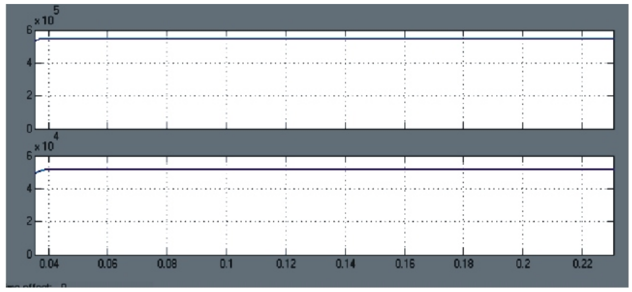
Time (sec)

Figure 4.c: Real and Reactive power in bus 2



Time (sec)

Figure 4.d: Load voltage in bus 11



Time (sec)

Figure 4.e: Real and Reactive power in bus 11

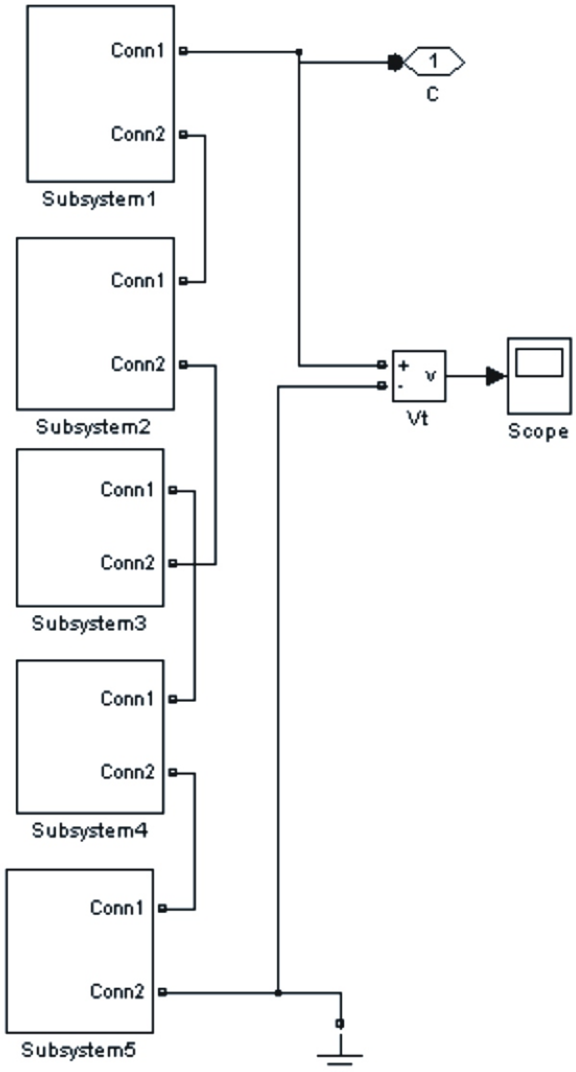


Figure 5: Level Inverter

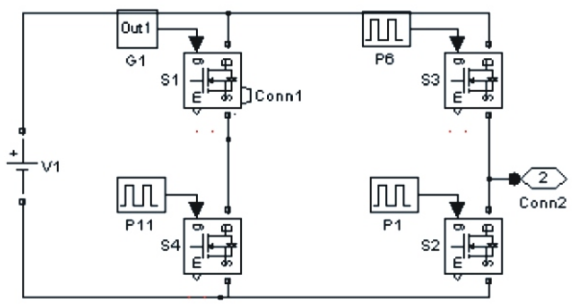


Figure 6: Single H-bridge inverter

Table 1:The summary of the reactive power in various buses

Bus no	Q (MVAR) without STATCOM	Q (MVAR) with STATCOM	VOLTAGE (KV) without TATCOM	VOLTAG (KV) with STATCOM
2	0.066	0.0676	7314	7349
6	1.27	1.29	6652	6672
11	0.0513	0.052	7411	7441
12	0.01	0.011	7417	7454
13	0.029	0.030	7658	7805
14	0.058	0.059	7345	7392

CONCLUSION

14 bus system is modeled and simulated using MATLAB SIMULINK and the results are presented. The simulation results of 14 bus system with and without D-STATCOM are presented. Voltage stability is improved by using D-STATCOM. This system has reduced reliability and improved power quality. The simulation results are in line with the predictions. This concept can be extended to 64 bus system. The scope of present work is the modeling and simulation of 14 bus system.

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