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Design and Simulation of STATCOM to Improve Power Quality

Md. Nazrul Islam[1], Md. Arifur Kabir[1], and Yashiro Kazushige[2]

[1]Research & Technical Service,
Bangladesh National Power Grid, Bangladesh

[2]JICA Experts, Japan

ABSTRACT: The performance of power systems decreases with the size, the loading and the complexity of the networks. This is related to problems with load flow, power oscillations and voltage quality. Such problems are even deepened by the changing situations resulting from deregulation of the electrical power markets, where contractual power flows do no more follow the initial design criteria of the existing network configuration. Additional problems can arise in case of large system interconnections, especially when the connecting AC links are weak. FACTS devices, however, provide the necessary features to avoid technical problems in the power systems and they increase the transmission efficiency. This paper presents a study on the design of a shunt connected FACTS device (STATCOM) and investigates the application of this device to control voltage dynamics and to damp out the oscillation in electric power system. STATCOM is one of the key shunt controllers in flexible alternating current transmission system (FACTS) to control the transmission line voltage and can be used to enhance the load ability of transmission line and extend the voltage stability margin. In this paper, the proposed shunt controller based on the voltage source converter topology as it is conventionally realized by VSC that can generate controllable current directly at its output terminal. The performance and behavior of this shunt controller is tested in 3-machine 9-bus system as well as the performance is compared in the test system with and without STATCOM at three cases in MATLAB/Simulink. Simulation results prove that the modeled shunt controller is capable to improve the Power quality significantly.

KEYWORDS: FACTS, STATCOM, VSC, CSC, PLL, PWM, PID.

1 INTRODUCTION

The traditional steady state stability studies and Transient stability studies take into account the active power flow P and power angle ∂ and generally assume constant receiving and sending end bus voltage. The reactive power flow Q and voltage fall during heavy current flow is neglected. This approach could not explain the several black-outs in USA, Europe, Japan etc. during the last quarter of the twentieth century. The blackouts were due to voltage collapse. During voltage collapse, the bus voltage starts falling and as a result power transfer P through the transmission line starts reducing resulting in ultimate voltage collapse and loss of system stability of entire network. That's why voltage stability studies have received more attention and have acquired a vital place in power system Studies. Voltage collapse phenomena take place where reactive power management is inadequate.

The application of power electronics in the electric power transmission plays an important role to make the system more reliable, controllable and efficient [1]. Due to deregulation, environmental legislations and cost of construction, it is becoming increasingly difficult to build new transmission lines. Thus it is essential to fully utilize the capacities of the existing transmission system. The flexible AC Transmission system (FACTS) has become a popular solution to our large/over extended power transmission & distribution system. FACTS devices are proving to be very effective in using the full transmission capacity while increasing power system stability, transmission efficiency and maintaining power quality and reliability of Power system. These devices are mainly based on either voltage source converter (VSC) or Current Source Converter (CSC) and have fast response time. As an important member of FACTS devices family, STATCOM has been at the centre of attention

Corresponding Author: Md. Nazrul Islam (nazrul.pgcb@yahoo.com)

and the subject of active research for many years. STATCOM is a shunt connected device that is used to provide reactive power compensation to a transmission line. This controller can either absorb or inject reactive power whose capacitive or inductive current can be controlled independent of the AC line voltage. Thus, STATCOM can enhance the transmission line load ability by extending the MW margin and improves the oscillation of voltage transients through efficient regulation of the transmission line voltage at the point of connection [1]-[3].

This paper deals with the modeling of a SPWM based STATCOM with a PID controller implemented on a 3- machine 9-bus test system. The device is connected to a load bus with a converter transformer. The modeling of shunt controller and testing is simulated in the MATLAB/Simulink environment. The controller is represented as block diagram that presents practical electronic model of shunt controller. PID controller is used to control the current injection at the connection point by varying the desired parameters, one is Modulation index (AM) and another is power angle (∂). Mainly there are four loop tuning methods for a PID controller; those are manual tuning, Ziegler-Nichols, software Tools and Cohencoon method. Firstly, Ziegler-Nichols method is chosen for loop tuning and then manual tuning is applied to the PID controller by trial and error method to take its performance at optimum level. In fact, there are four different control strategies for a STATCOM controller, direct control, decoupling control, cross control and matrix control. The direct control method is used here to control the output of shunt connected FACTS device.

2 Basic Configuration and Principle of Operation

Basically, shunt connected FACTS device can be realized by either a VSC or a CSC [4]. But the VSC topology is preferred because CSC topology is more complex than VSC in both power and control circuits. In CSC such as GTO (Gate Turn Off Thyristor) is used, a diode has to be placed in series with each of the switches. This almost doubles the conduction losses compared with the case of VSC. The DC link energy storage element in CSC topology is inductor where as that in VSC topology is a capacitor. Thus, the efficiency of a CSC is expected to be lower than that of a VSC [6]-[9]. The modeled STATCOM using VSC topology is being used in the test system to supply reactive power to increase the transmittable power and to make it more compatible with the prevailing load demand. Thus, the shunt connected FACTS device should be able to minimize the line over voltage under light load condition and maintain voltage levels under heavy load condition. Two VSC technologies can be used for the VSC. One of them, VSC is constructed with IGBT/GTO-based SPWM inverters. This type of inverter uses sinusoidal Pulse-Width Modulation (SPWM) technique to synthesize a sinusoidal waveform from a DC voltage source with a typical chopping frequency of a few kilohertz. Harmonic voltages are cancelled by connecting filters at the AC side of the VSC. This type of VSC uses a DC link voltage Vdc. Output voltage is varied by changing the modulation index of the SPWM modulator. Thus modulation index has to be varied for controlling the reactive power injection to the transmission line. In another type VSC is constructed with GTO-based square-wave inverters and special interconnection transformers. Typically four three-level inverters are used to build a 48-step voltage waveform. Special interconnection transformers are used to neutralize harmonics contained in the square waves generated by individual inverters. In this type of VSC, the fundamental component of output voltage is proportional to the voltage Vdc. Therefore Vdc has to be varied for controlling the reactive power.

The shunt controller is like a current source, which draws from or injects current into the system at the point of connection. The shunt controller may be variable impedance, variable source or a combination of these [10]. Variable shunt impedance connected to the line voltage causes a variable current flow and hence represents injection of current into the line. As long as the injected current is in phase quadrature with the line voltage, the shunt controller only supplies or consumes reactive power. When system voltage is low, the STATCOM generates reactive power (STATCOM capacitive). When system voltage is high, it absorbs reactive power (STATCOM inductive). The variation of reactive power is performed by means of a VSC connected on the secondary side of a coupling transformer. The VSC uses forced-commutated power electronic devices (GTOs, IGBTs or IGCTs) to synthesize a voltage V2 from a DC voltage source. Any other phase relationship will involve handling of real power as well [11]. So, the shunt controller is therefore a good way to control the voltage at and around the point of connection through injection of reactive current (leading or lagging) alone or a combination of active and reactive current for a more effective voltage control and damping of voltage dynamics [12]. The real power (P) and reactive power (Q) are given by:

$$P = \frac{E.V}{X} Sin\partial \tag{1}$$

$$Q = \frac{E^2}{X} - \frac{E.V}{X} Cos\partial \tag{2}$$

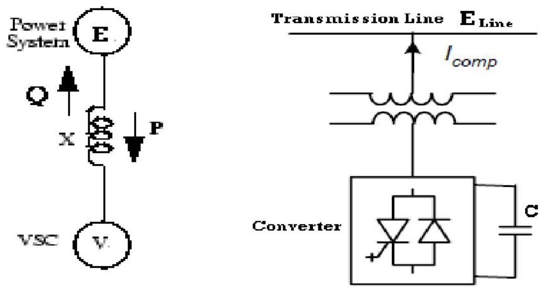

Fig. 1. Static Synchronous Compensator

E is the line voltage of transmission line. V is the generated voltage of VSC. X is the equivalent reactance of interconnection transformer and filters and δ is the phase angle of E with respect to V. In steady state operation, the voltage V generated by the VSC is in phase with E (δ=0), so that only reactive power is flowing (P=0). If V is lower than E, Q is flowing from E to V (STATCOM is absorbing reactive power). On the reverse, if V is higher than E, Q is flowing from V to E (STATCOM is generating reactive power). Since we are using here a VSC based on SPWM inverters hence modulation index is varied for controlling the reactive power injection to the transmission line. A capacitor is connected on the DC side of the VSC acts as a DC voltage source. In steady state the voltage V has to be phase shifted slightly behind E in order to compensate for transformer and VSC losses and to keep the capacitor charged.

3 MODELING OF SHUNT CONVERTER

Figure shows a construction of STATCOM utilizing one interconnection transformer and three GTO/Diode based double arm H-bridges. Each H-bridge is connected to the each phase of the secondary of interconnection transformer. Transformer primary is connected to the transmission line. Conventionally, shunt controllers are constructed of three phase converters or inverters. But it is possible to replace the three phase converter with three single phase converter. The three phase converter constructed with three single phase converter produces less switching ripples than the conventional three phase converter [16]. So, three phase converter constructed with three single phase converters is used. T1, T2 and T3 represent the transformer coils of phase A, B and C respectively that form a three phase transformer secondary connected to shunt converter. A capacitor (C) which acts as a voltage source is used. The original circuit diagram of each GTO/Diode bridge (B1,B2 and B3) is shown in figure . Each H-bridge consists of four GTO and four diodes where the GTO and diode are connected in anti-parallel. So, four different control pulses are required to control each of bridges. Therefore to apply firing pulses to three different bridges properly, total twelve different pulses are required for controlling the shunt converter.

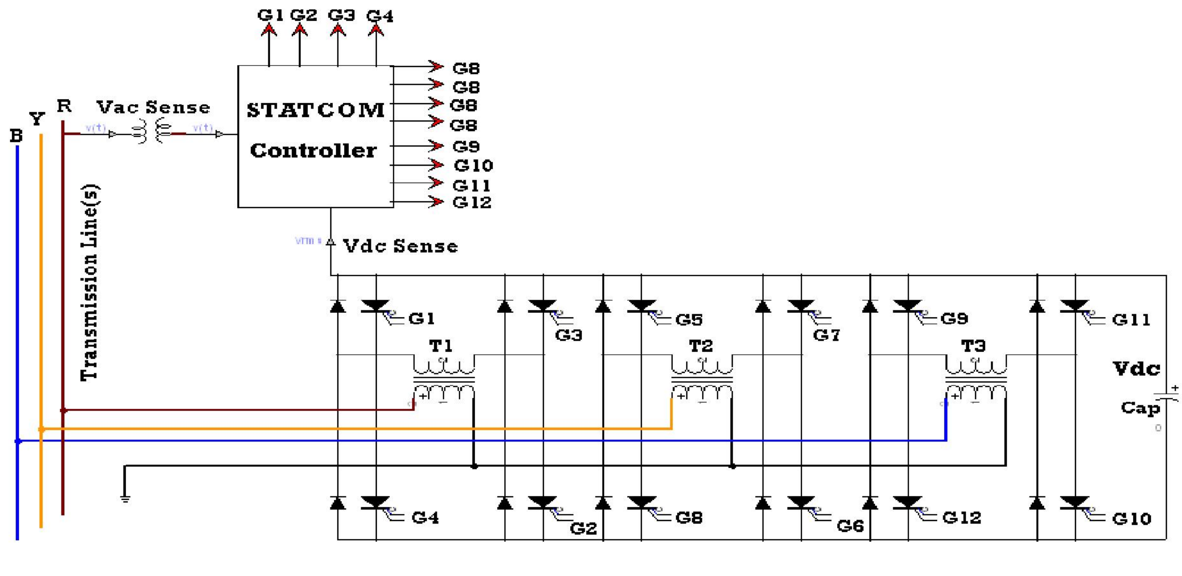

Fig. 2. Modeled Shunt Connected FACTS Device

4 CONTROL STRATEGY

STATCOM can be controlled in voltage control mode and Var control mode. The control used in this simulation is AC voltage control mode. Mainly, the control is divided into two parts. One is for angle order and another is for the order of modulation index. The shunt converter is operated in such a way as to demand this DC terminal power from the line keeping the voltage across the storage capacitor Vdc constant. So, according to equation-1, the angle is ordered in such a way that the net real power absorbed from the line by this shunt FACTS device is equal to the losses of the converters and the transformer only. The remaining capacity of this shunt converter can be used to exchange reactive power with the line so to provide VAR compensation at the connection point. The reactive power according to equation-2 is electronically provided by the shunt converter and the active power is transmitted to the DC terminals. The shunt converter reactive current is automatically regulated to maintain the transmission line voltage at the point of connection to a reference value.

The line voltage and Dc link voltage across capacitor are measured to calculate the amount of reactive power to regulate the line voltage and consequently the modulation index is varied in such a way as to calculate reactive power can be injected at the point of connection and thus the shunt FACTS device acts as a voltage regulator. The SPWM firing pulses to the GTOs are obtained by comparing the PWM carrier signal and the reference sine wave. The amplitude of reference sine wave is 1 Volt and frequency is 50 Hz which is similar to system operating frequency. The carrier frequency is set at 1.5 KHz which is 30 times the system operating frequency. The phase lock loop (PLL) plays an important role in synchronizing the switching to the system voltage and lock to the phase at fundamental frequency. The converter is consisted of 12 GTO with additional components. The controller controls the firing pulses from G1 to G12 which are sinusoidal pulse width modulated signals. The following figure shows the block diagram of control strategy to generate only one pulse width modulated signal and 11 signals can be generated similarly.

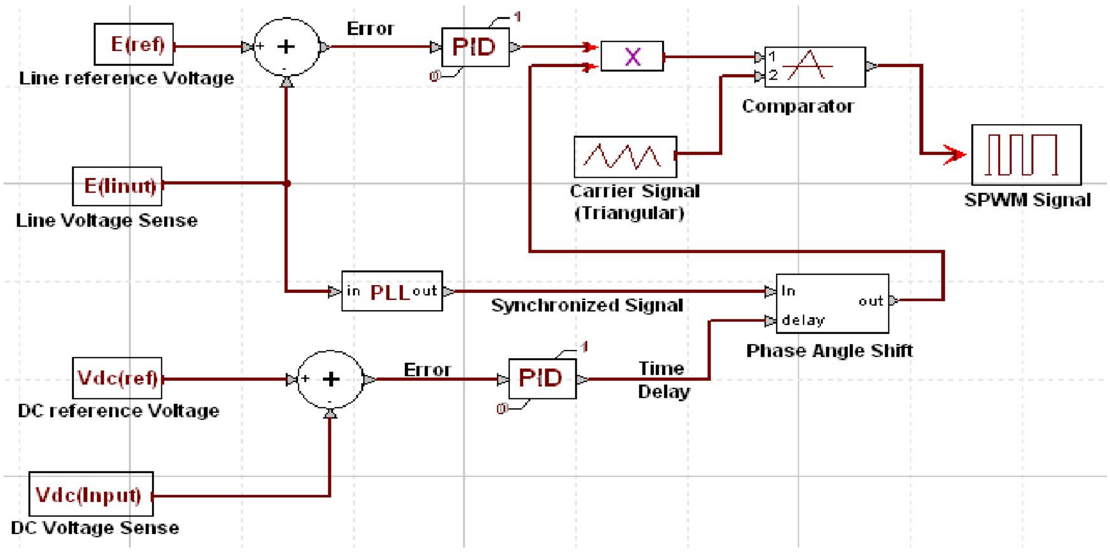

Fig. 3. Block Diagram of STATCOM Controller

5 SIMULATION SETUP AND RESULTS

Figure 4 shows the 3 machine 9 bus test system for simulation. The test system includes machines, transmission lines and loads at different buses. The modelled FACTS device (STATCOM, 300 MVA) is installed at Bus-9. Two types of large loads (Load-1 & Load-2) are also connected at bus-9. Power is flowing to Bus-9 by TL1 and TL2.

Case 1: At starting, Load-1(50 MW & 30 MVAR) and Load-2 (100 MW & 50 MVAR) is not connected to the Bus-9. A fault takes place at t=0.3 second at TL1 and instantaneously Bk-1 and BK -2 is tipped to isolate the transmission line TL1 from the system. At the same time (t=0.3s) Load-1 is connected to the system and Load-2 is connected at t=0.7 second. The start time of simulation at t=0 s and the end time is t=1 second. Waveforms Scales are zoomed so that the voltage oscillations can be seen clearly.

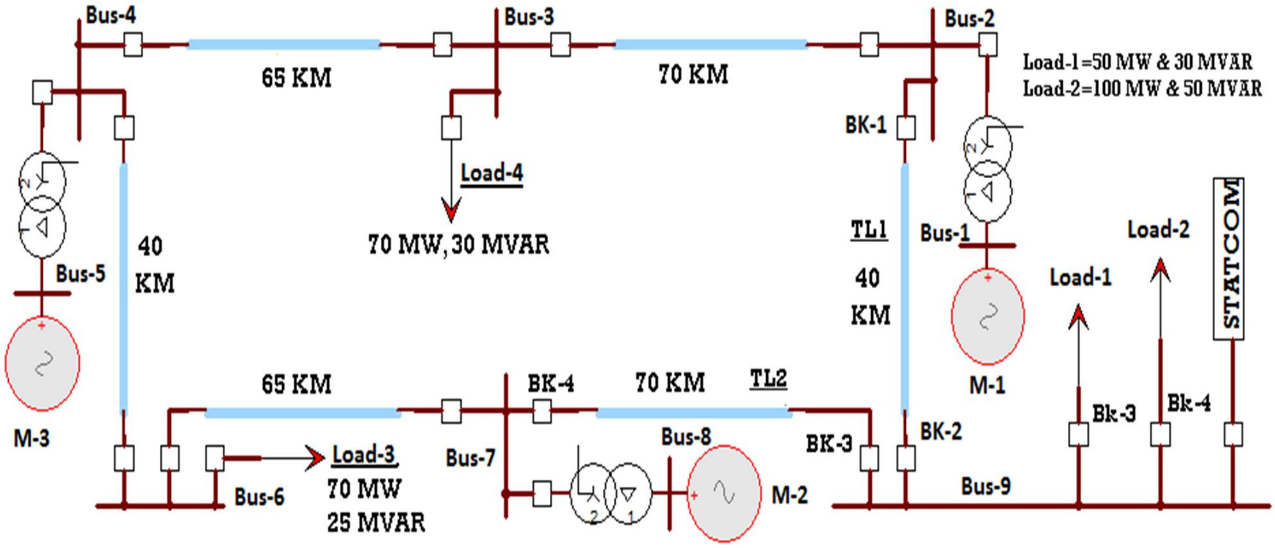

Fig. 4. STATCOM connected to the 3 machine 9 bus test System

Figure 5 shows the voltages of Bus-9 in per unit (p.u) when STATCOM is not in use. The solid line represents the voltage in p.u when modelled STATCOM is connected to the bus. As it is installed at Bus-9 the voltage is controlled at that bus successfully. Figure 6 shows the injected reactive power to the Bus-9 to control the voltage and real power drawn by the STATCOM to keep the DC link voltage (Vdc) across the capacitor constant because the DC voltage tends to change during operation. In steady state the voltage V has to be phase shifted slightly behind E in order to compensate for transformer and VSC losses and to keep the capacitor charged. The DC link voltage (Vdc) across the capacitor is shown in Figure 7. The modulation index is required to change due to generate or absorb the required amount of reactive power. To maintain the transmission line voltage at Bus-9 the modulation index is controlled by PID controller which is shown in Figure 7.

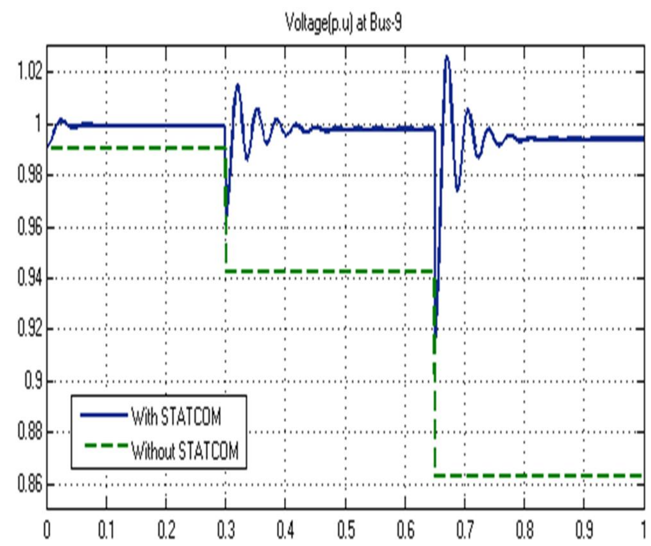

Fig. 5. Transmission line voltage at bus-9

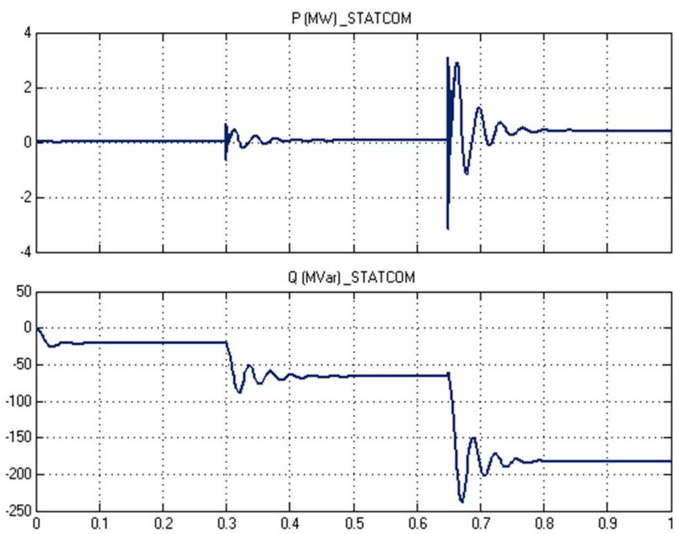

Fig. 6. STATCOM Real Power (Drawn) & Reactive Power(Supplied)

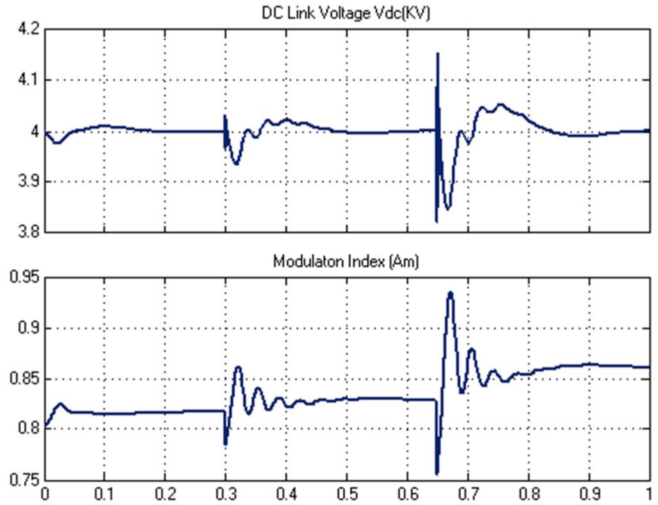

Fig. 7. DC Link Voltage & Control of Modulation Index

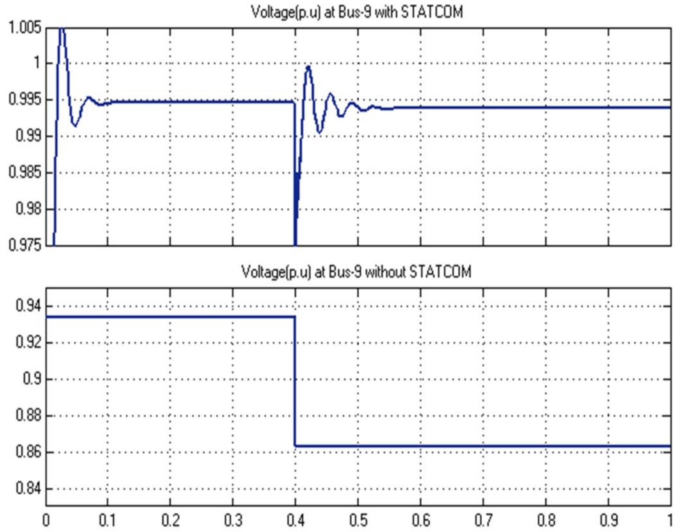

Fig. 8. Transmission line voltage at bus-9

Case 2: At starting (t=0.0 s), Load-1 and Load-2 is connected to the Bus-9 and drawing huge power. But for any reason (either manual or protection) transmission line TL1 is disconnected from the system at t=0.4 second. Simulation starts at t=0 second and ends at t=1 second. Waveforms Scales are zoomed so that the voltage oscillations can be seen clearly. Figure 8 shows the voltages of Bus-9 in per unit (p.u) when STATCOM is not in use. The solid line represents the voltage in p.u when modeled STATCOM is connected to the bus. As it is installed at Bus-9 the voltage is controlled at that bus successfully. Figure 9 shows the injected reactive power to the Bus-9 to control the voltage and real power drawn by the STATCOM to keep the DC link voltage (Vdc) across the capacitor constant because the DC voltage tends to change during operation. In steady state the voltage V has to be phase shifted slightly behind E in order to compensate for transformer and VSC losses and to keep the capacitor charged. The DC link voltage (Vdc) across the capacitor is shown in Figure 10. The modulation index is required to change due to generate or absorb the required amount of reactive power. To maintain the transmission line voltage at Bus-9 the modulation index is controlled by PID controller which is shown in Figure 10.

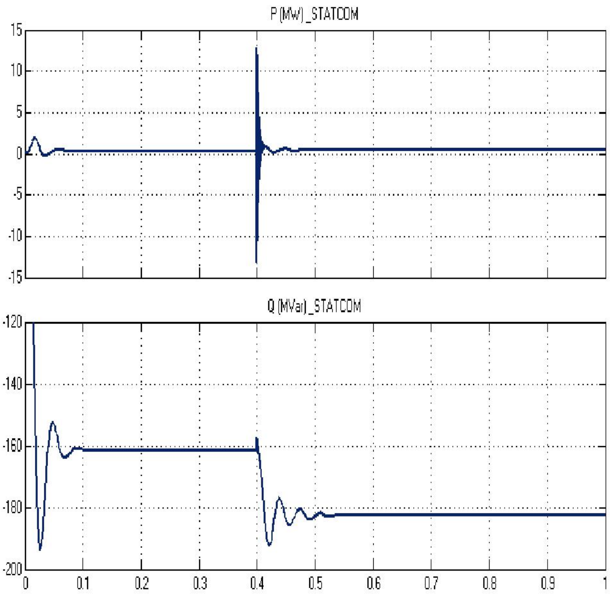

Fig. 9. STATCOM Real Power (Drawn) & Reactive Power (Supplied)

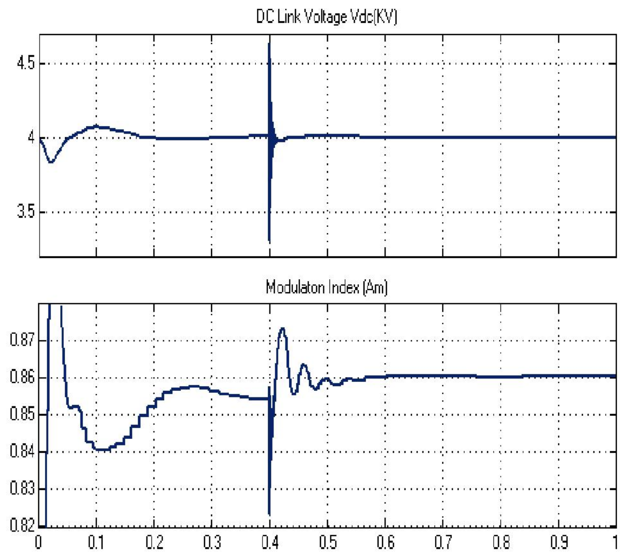

Fig. 10. DC Link Voltage & Control of Modulation Index

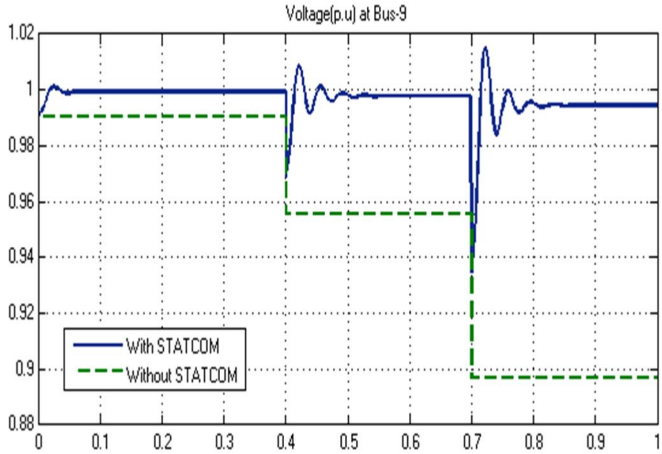

Fig. 11. Transmission line voltage at bus-9

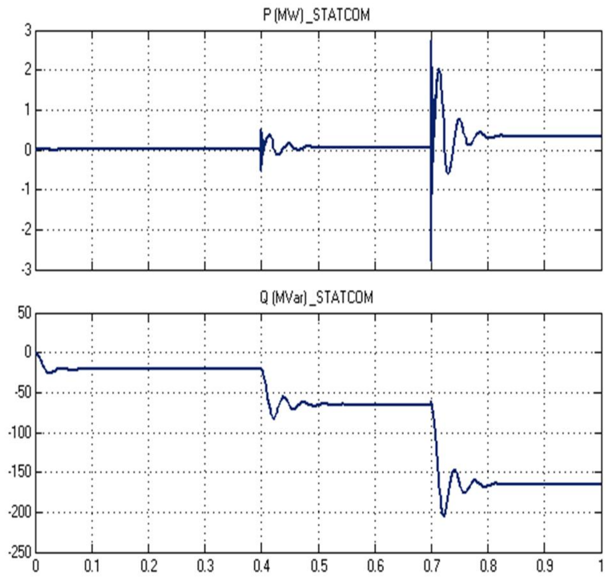

Fig. 12. STATCOM Real Power (Drawn) & Reactive Power (Supplied)

Case 3: At starting, Load-1 and Load-2 is not connected to the Bus-9. A fault takes place at t=0.4 second at TL1 and instantaneously Bk-3 and BK -4 is tipped to isolate the transmission line TL2 from the system. At the same time (t=0.4s) Load-1 is connected to the system and Load-2 is connected at t=0.7 second. Simulation starts at t=0 second and ends at t=1 second. Waveforms Scales are zoomed so that the voltage oscillations can be seen clearly.Figure 11 shows the voltages of Bus-9 in per unit (p.u) when STATCOM is not in use. The solid line represents the voltage in p.u when modelled STATCOM is connected to the bus. As it is installed at Bus-9 the voltage is controlled at that bus successfully. Figure 12 shows the injected reactive power to the Bus-9 to control the voltage and real power drawn by the STATCOM to keep the DC link voltage (Vdc) across the capacitor constant because the DC voltage tends to change during operation. In steady state the voltage V has to be phase shifted slightly behind E in order to compensate for transformer and VSC losses and to keep the capacitor charged. The DC link voltage (Vdc) across the capacitor is shown in Figure 13. The modulation index is required to change due to generate or absorb the required amount of reactive power. To maintain the transmission line voltage at Bus-9 the modulation index is controlled by PID controller which is shown in Figure 13.

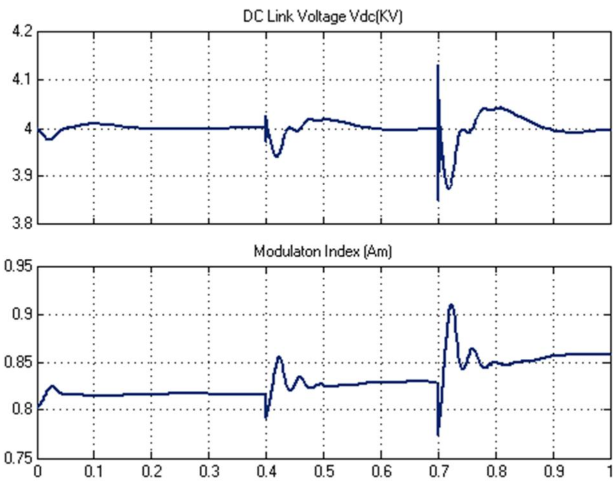

Fig. 13. DC Link Voltage & Control of Modulation Index

6 CONCLUSION

In simulation, worst events are considered to examine the performance of modeled shunt connected FACTS device. The simulation results show that the modeled STATCOM is capable enough to control the transmission line voltage dynamics as well as the same shunt controller can be used in VAR control mode. Vdc is regulated by controlling proper phase shift and transmission voltage is regulated by varying the modulation index. Two single input and single output (SISO) closed loop systems are used. The response of controller is very fast due to apply direct control method. The simulation results also prove that the shunt device with proposed switching scheme functions successfully as the real time voltage controller and it improves the dynamic stability with a wide range of control the reactive power. The magnitude of voltage oscillation in simulation and other figures are zoomed along y axis to observe the oscillation clearly but actually the oscillations are very low. Three single phase converters are used rather than three phase converter to reduce switching ripples. A part of Dhaka ring of Bangladesh National Grid is modeled as transmission line in this paper.

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