Stability enhancement of hydroelectric multi-machines Power system using hybrid PSS-FACTS devices

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Abstract— This paper investigates comparison of SVC and STACOM performance for the transient stability improvement of a two area hydroelectric multi machines power system. The improvement of transient stability of a two- area multi- machine power system, using SVC (Static VAR Compensator) STATCOM (Static Synchronous Compensator) which is an effective FACTS (Flexible AC Transmission System) device capable of controlling the active and reactive power flows in a transmission line by controlling appropriately parameters. Simulations are carried out under Matlab/Simulink environment for the two- area multi- machine power system model with SVC & STATCOM to analyze the effects of SVC & STATCOM on transient stability performance of the system under two types of contingency (3-phase-to-ground fault and sudden load changes). The performance of SVC and STATCOM is compared from each other. In comparative result, STACOM gives the better result than SVC. So for the improvement of transient stability STATCOM is better than SVC. The simulation results showed the effectiveness and robustness of the proposed STATCOM and SVC on transient stability improvement of the system.

Keywords – *Hydroelectric power system, multi-machines, Power system Stabilizer, FACTS, Stability enhancement.*

I. INTRODUCTION

Now a day's power transmission and distribution systems are facing the increasing demands for more power, better quality and higher reliability at lower cost, as well as low environmental effect. Under these conditions, transmission networks are called up on to operate at high transmission levels, one of the major causes of voltage instability is the reactive power limit of the system. Improving the system's reactive power handling capacity via Flexible AC transmission System (FACTS) devices is a remedy for prevention of voltage instability and hence voltage collapse. The implementation of reactive power compensation devices in modern power systems is growing up for dynamic characteristic improvement. Reactive power compensation has a great influence on the dynamic performance of the voltage stability and helps to maintain a flat voltage profile, increases transmission efficiency and also reluctant to temporarily overvoltages that arise from different faulty conditions that may damage power system equipments [1].

There are many other factors that increase the risk of voltage stability problems in power systems such as the growing use of induction motors and the use of HVDC links that are connected to weak ac systems [2], [3]. Transient stability refers to the capability of a system to maintain synchronous operation in the event of large disturbances such as multi- phase short- circuit faults or switching of lines [4]. The resulting system response involves large excursions of generator rotor angles and is influenced by the nonlinear power angle relationship. Stability depends upon both the initial operating conditions of the system and the severity of the disturbance. Recent development of power electronics introduces the use of flexible ac transmission system (FACTS) controllers in power systems. FACTS controllers are capable of controlling the network condition in a very fast manner and this feature of FACTS can be exploited to improve the voltage stability, and steady state and transient stabilities of a complex power system [5], [6]. This allows increased utilization of existing network closer to its thermal loading capacity, and thus avoiding the need to construct new transmission lines. Static VAR Compensator (SVC) is a first generation FACTS device that can control voltage at the required bus thereby improving the voltage profile of the system. The primary task of an SVC is to maintain the voltage at a particular bus by means of reactive power compensation (obtained by varying the firing angle of the thyristors) [7]. SVCs have been used for high performance steady state and transient voltage control compared with classical shunt compensation. SVCs are also used to dampen power swings, improve transient stability, and reduce system losses by optimizing reactive power control [8], [9]. The STATCOM is an electronic generator of dynamic reactive power, which is connected in shunt and is designed to provide smooth, continuous voltage regulation, to prevent voltage collapse, to improve transmission stability and to dampen power oscillations. This article investigates the damping enhancing capability of a STATCOM. The STATCOM was proposed by several researchers to compensate the reactive current from or to the power system. This function is identical to the synchronous condenser with rotating mass, but its response time is extremely faster than of the synchronous condenser. This rapidity is very effective to increase transient stability, to enhance voltage support, and to damp low frequency oscillation for the transmission system.

II. MATHEMATICAL MODEL OF THE STUDIED POWER SYSTEM

In an n-machine power system, the full dynamics of a

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synchronous generator is described by the following equations in $d_i - q_i$ co-ordinate [10]

$$\begin{bmatrix} Vdi \\ Vqi \end{bmatrix} = - \begin{bmatrix} ri & 0 \\ 0 & ri \end{bmatrix} \begin{bmatrix} Idi \\ Iqi \end{bmatrix} + (1+w_i) \begin{bmatrix} -\psi di \\ \psi qi \end{bmatrix},$$

$$\begin{bmatrix} -\psi di \\ \psi qi \end{bmatrix} = \begin{bmatrix} -E''di \\ E''qi \end{bmatrix} - \begin{bmatrix} 0 & x''qi \\ x''di & 0 \end{bmatrix} \begin{bmatrix} Idi \\ Iqi \end{bmatrix}$$

$$\begin{bmatrix} \dot{E}'qi \\ \dot{E}''qi \\ \dot{E}''di \end{bmatrix} = \begin{bmatrix} -\frac{1}{T'doi} & 0 & 0 \\ \frac{T'doi - T''doi}{T'doi\, T''doi} & \frac{-1}{T''doi} & 0 \\ 0 & 0 & -\frac{1}{T'q0i} \end{bmatrix} \begin{bmatrix} E'qi \\ E''qi \\ E''di \end{bmatrix} +$$

$$\begin{bmatrix} \frac{1}{T'doi} & 0 & -\frac{xdi - x'di}{T'doi} \\ \frac{1}{T'doi} & 0 & -\frac{T''d0i\,(xdi - x'di) + T'd0i\,(x'di - x''di)}{T''doi\, T'doi} \\ 0 & \frac{xqi - x''qi}{T''q0i} & 0 \end{bmatrix} \times \begin{bmatrix} Eqi \\ Iqi \\ Idi \end{bmatrix}$$

$$\begin{bmatrix} \dot{\delta} i \\ \dot{i} \end{bmatrix} = - \begin{bmatrix} 0 & 0 \\ 0 & -\frac{Di}{2Hi} \end{bmatrix} \begin{bmatrix} \delta i \\ i \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1i}{2Hi} \end{bmatrix} (T_{Mi} - T_{ei})$$

$$T_{ei} = \psi_{di} I_{qi} - \psi_{qi} I_{id} \quad (1)$$

Dynamic model of the generator above is completed with the addition of that of governors and AVRs as follows

$$T_{mi} = GOV_i(s)\ ⍰_i,\ E_{qei} = Avr_i(s)\left(V_{0i} - \sqrt{V_{di}^2 + V_{qi}^2}\right) \quad (2)$$

i=1,2,..........,n

where $Gov_i(s)$ and Avri(s) are the transfer function of the governors and AVRs, respectively. The model for the power network is static and expressed in a common x–y coordinate [10]

$$I_G = Y_G V_G \quad (3)$$

where Y_G is the network admittance matrix with only n generator nodes left and

$$I_G = [I_{gx1}\ I_{gy1}\ I_{gx2}\ I_{gy2} \dots I_{gxn}\ I_{gyn}]^T$$

$$V_G = [V_{gx1}\ V_{gy1}\ V_{gx2}\ V_{gy2} \dots V_{gxn}\ V_{gyn}]^T$$

The transformation between $d_i - q_i$ and x–y co-ordinates is

$$I_{Gdq} = TI_G;\ V_{Gdq} = TV_G \quad (4)$$

where

$$I_{Gdq} = [I_{d1}\ I_{q1}\ I_{d2}\ I_{q2} \dots I_{dn}\ I_{qn}]^T$$

$$V_{Gdq} = [V_{d1}\ V_{q1}\ V_{d2}\ V_{q2} \dots V_{dn}\ V_{qn}]^T$$

$$T = \mathrm{diag}(T_i) \quad T_i = \begin{bmatrix} \cos\delta_i & \sin\delta_i \\ \sin\delta_i & -\cos\delta_i \end{bmatrix}$$

III. DESCRIPTION AND MODELLING OF CONTROLLERS

A. The SVC

Fig. 1 shows a schematic diagram of a static var compensator. The compensator normally includes a thyristorcontrolled reactor (TCR), thyristor-switched capacitors (TSCs) and harmonic filters. It might also include mechanically switched shunt capacitors (MSCs), and then the term static var *system* is used. The harmonic filters (for the TCR-produced harmonics) are capacitive at fundamental frequency. The TCR is typically larger than the TSC blocks so that continuous control is realized. Other possibilities are fixed capacitors (FCs), and thyristor switched reactors (TSRs). Usually a dedicated transformer is used, with the compensator equipment at medium voltage. The transmission side voltage is controlled, and the Mvar ratings are referred to the transmission side.

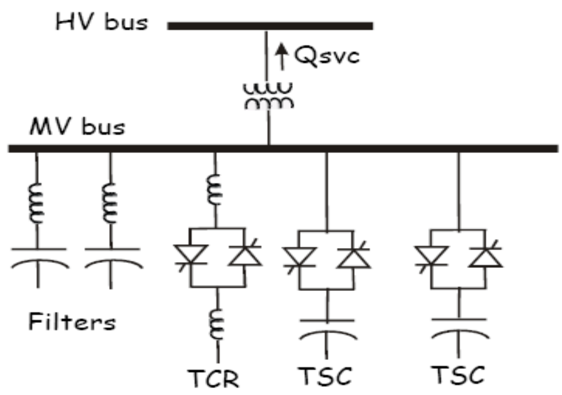

Fig. 1 Schematic diagram of an SVC

The rating of an SVC can be optimized to meet the required demand. The rating can be symmetric or asymmetric with respect to inductive and capacitive reactive power. As an example, the rating can be 200 Mvar inductive and 200 Mvar capacitive, or 100 Mvar inductive and 200 Mvar capacitive.Therefore, when FACTS devices are installed in the n-machine power system, only Eq. (3) needs to be modified to take account of the influence of FACTS control on the dynamics of the power system. If these FACTS devices are SVCs which do not have energy storage units, the network equation of the power system will have the same form to that of Eq. (3), which can be obtained by deleting the nodes where these FACTS devices are installed.

A.1. The SVC V- I characteristics

The SVC can be operated in two different modes:

- In voltage regulation mode (the voltage is regulated within limits as explained below)
- In var control mode (the SVC susceptance is kept constant)

When the SVC is operated in voltage regulation mode, it implements the following V-I characteristic.

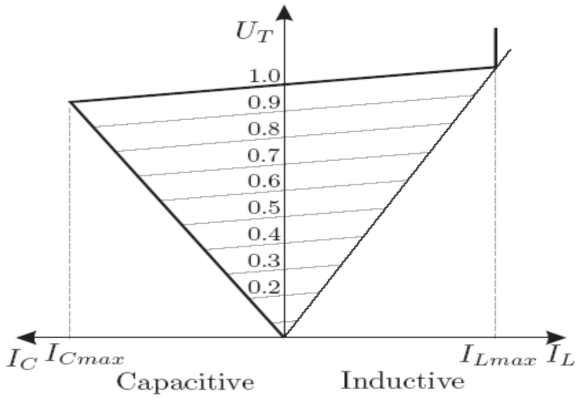

Fig. 2 The V- *I* characteristic of the SVC.

As long as the SVC susceptance B stays within the maximum and minimum susceptance values imposed by the total reactive power of capacitor banks (Bc_{max}) and reactor banks (Bl_{max}), the voltage is regulated at the reference voltage Vref. However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and the V-I characteristic has the slope indicated in the figure 2.

B. The STATCOM

Static synchronous compensators (STATCOMs), which are part of the FACTS device family, consist primarily of a three-phase PWM rectifier/inverter that can be shunt-connected to any system in order to dynamically compensate the reactive power requirement of the system. Similar to a three-phase PWM rectifier/inverter, a STATCOM is a voltage-source converter which converts dc power into ac power of variable amplitude and phase angle. By varying the amplitude and phase angle of the three-phase ac currents at its ac side, a STATCOM can supply a variable and precise amount of reactive power to the ac power system to which it is connected. This feature can be used to ensure that the voltage across the ac power system connected to the STATCOM is maintained at the nominal value or to ensure that the power factor of a large industrial application is maintained at unity.

STATCOMs are commonly used to maintain a constant voltage across ac transmission lines. Similar to a shunt capacitor substation, a STATCOM increases the power transfer capacity of an ac transmission line when added. However, STATCOMs have a number of advantages over shunt-capacitor substations, most notably:

- Tighter control of the voltage compensation across the ac transmission line
- Increased line stability during transients (i.e., during sudden changes in the load at the receiver end of the ac transmission line), due to the superior quickness of the STATCOM response.

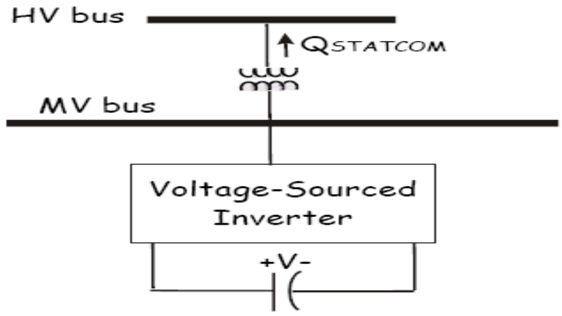

Fig.3 Block diagram of a typical STATCOM.

For the modeling of STATCOMs, the influence of the dynamics of the DC capacitors in the STATCOMs will be considered and included in the total dynamic model of the power system. Therefore, the format of the network equation of Eq. (3) will be changed. In the n-machine power system, if a STATCOM is installed at node i, we have $I_{si}=(V_{0i}-V_i)/jX_{SDTi,}$where X_{SDTi} is the reactance of the step-down transforme of the STATCOM. The mathematical model of the STATCOM is [10,11]

$$I_{si}= I_{six}+j\, I_{siy}$$

$$V_{0i}=\frac{3mi}{4}V_{DCi}(\cos\psi_i+j\sin\psi_i) \tag{9}$$

$$\frac{dV_{DCi}}{dt}=\frac{I_{DCi}}{C_{DCi}}=\frac{3m_i}{4C_{DCi}}(I_{six}\cos\psi_i+I_{siy}\sin\psi_i)$$

Hence we have

$$I_{si}=\frac{Vi}{jX_{SDTi}}+\frac{3mi}{4X_{SDTi}}V_{DCi} \tag{10}$$

B.1. STATCOM V- I characteristics

The STATCOM can be operated in two different modes:

- In voltage regulation mode (the voltage is regulated within limits as explained below).
- In var control mode (the STATCOM reactive power output is kept constant).

When the STATCOM is operated in voltage regulation mode, it implements the following V-I characteristic. As long as the reactive current stays within the minimum and minimum current values (-Imax, Imax) imposed by the converter rating, the voltage is regulated at the reference voltage Vref. However, a voltage droop is normally used (usually between 1% and 4% at maximum reactive power output), and the V-I characteristic has the slope indicated in the figure 2. the STATCOM can provide full capacitive- reactive power at any system voltage even as low as 0. 15pu. The characteristic of a STATCOM reveals strength of this technology: that it is capable of yielding the full output of capacitive generation almost independently of the system voltage output at lower voltages). This capability (constant-current is particularly useful for situations in which the STATCOM is needed to support the system voltage during and after faults where voltage collapse would otherwise be a limiting factor [12, 13].

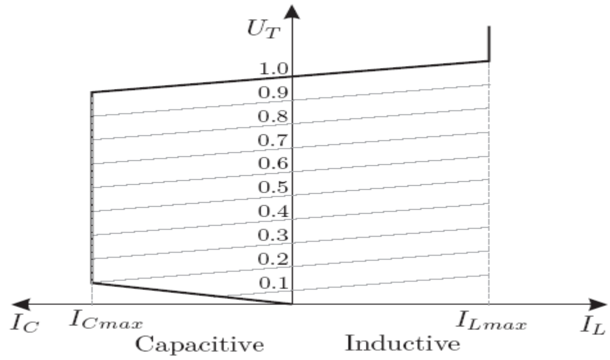

Fig. 4 The V- *I* characteristic of the STATCOM.

C. The Power System Stabilizer (PSS)

Power system stabilizers (PSS) have been extensively used as supplementary excitation controllers to damp out the low frequency oscillations and enhance the overall system stability. Fixed structure stabilizers have practical applications and generally provide acceptable dynamic performance. There have been arguments that these controllers, being tuned for one nominal operating condition, provide suboptimal performance when there are variations in the system load. There are two main approaches to stabilize a power system over a wide range of operating conditions, namely robust control.

The block diagram for the designed conventional PSS is Shown in Fig. 5

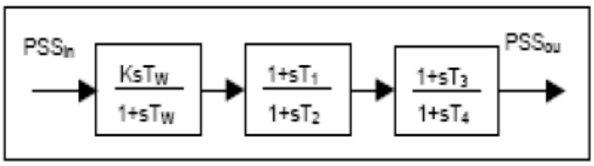

Fig. 5. Conventional Power System Stabilizer

IV. The power system description

The double machine three bus systems qualitatively important characteristics of the behaviour of machine system, it is extremely useful to describe the general concepts of power systems stability and is relatively simple to study [14]. Shown in Fig.5 is thus used to show the effect of STATCOM in improving system transient stability [15]. For the purpose of studying the transient phenomena, the proposed MATLAB/ SIMULINK control scheme in computer software designed specifically for the solution of power system electromagnetic transients. Double machine three bus model of a power system for evaluating the proposed design method is considered. Using this model, we consider A 1000 MVA hydraulic generation plant (M1) connected to a load centre through a long 400 kV, 700 km transmission line. The load center is modelled by a 5000 MW resistive load. The load is fed by the remote 1000 MVA plant and a local generation of 5000 MVA (plant M2). To maintain system stability after contingencies, the transmission line is shunt compensated at its center by a 200 Mvar Static synchronous compensators (STATCOM) in the first time and then with a 200 Mvar static var compensator (SVC) in the goal to compare between the two FACTS devices .The two machines are equipped with a hydraulic turbine and governor (HTG), excitation system, and power system stabilizer (PSS). Single line diagram of the model is shown in Fig.6.

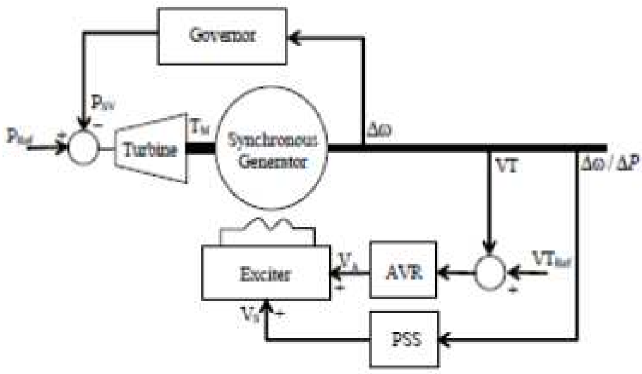

Fig. 5. Generation unit diagram.

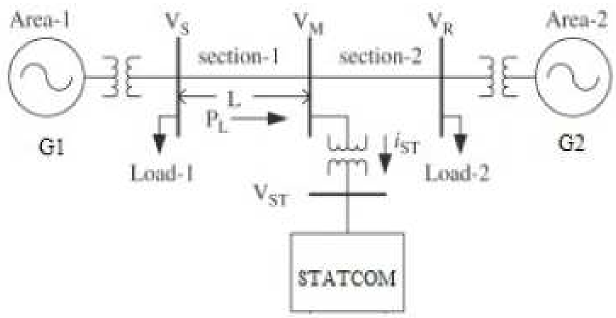

Fig. 6. Single line diagram of two generating station with STACOM.

V. Simulation results and discussion

The dynamic performance of the STATCOM along with the proposed control strategy is demonstrated and discussed in this section. Moreover, the performance of the STATCOM is compared with that of the conventional SVC and of the system equipped only with (AVR-PSS-GOVERNOR) regulator during fault operating condition and sudden load changes. The MATLAB/ SIMULINK software program is used for system modelling and simulation.

A-Three phase to ground fault

A Fault Breaker block is connected at bus Vs. to observe the impact of the regulator on system stability (PSS and GOVERNOR) in a first time then of the (PSS-GOVERNOR) and SVC coordination in second time then the impact of the (PSS-GOVERNOR) and STATCOM in third time. We apply a 3-phase-to-ground fault during [5 to 5.2] seconds and observe the impact of the two FACTS devices for stabilizing the network during a severe contingency.

The system response to a three phase to ground fault is depicted in Figs. 7- 8-9. It is worth nothing that in this type of fault, the system equipped with PSS-GOVERNOR alone has lost its stability after the fault and its behaviour is like a system with an open loop. The SVC doesn't respond instantaneously compared with the STATCOM which responds quickly and injects higher amount of reactive power that ensures better transient performance of the ac voltage at the 400 kV bus as seen in Fig. 7.This can be attributed to the fact that the SVC provides reactive power proportional to the square of its terminal voltage fig.8, therefore severe voltage drops on its terminals limit its reactive power injection capability.

B- Sudden load changes

In a first part and to test and compare the impact of static compensators on our system we did create a default (three conductors shorting to earth), in fact the regulation of voltage and maximum power that a line can transport are two of its most important features, the voltage of a line should remain fairly constant as the active power consumed by the load varies. Ordinarily, the change in voltage from zero to full load should not exceed 5% of the rated voltage, although sometimes you tolerate a regulation up to 10%. In order to test the robustness and response of the static compensators to the load changes, we performed the following tests to (PSS and GOVERNOR) and to the static compensators (SVC and STATCOM). the test consists in fixing the load to 3000MW, at t = 10s there been an abrupt increase in the load up to 4500 MW.

The system response to the sudden load changes is depicted in Figures (10-11 and 12). in this type of fault, the STATCOM responds quickly too and injects higher amount of reactive power that ensures better transient performance of the ac voltage at the 400 kV, the system equipped with only (PSS-GOVERNOR) has always a behaviour of a system with an open loop.

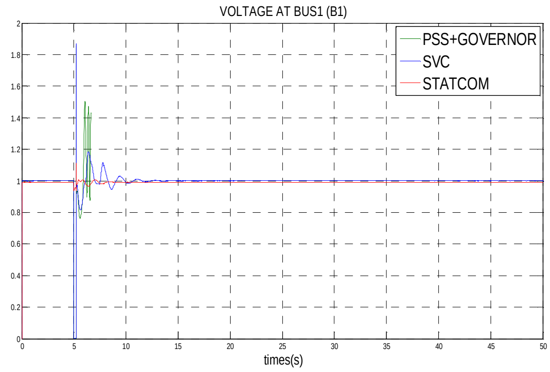

Fig.7. VOLTAGE AT BUS B1 with PSS-GOVERNOR, SVC and STATCOM during three phases to ground fault

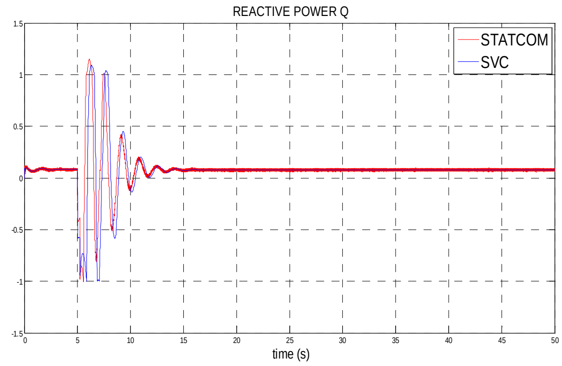

Fig.8 Reactive power injected by STATCOM and SVC during three phases to ground fault

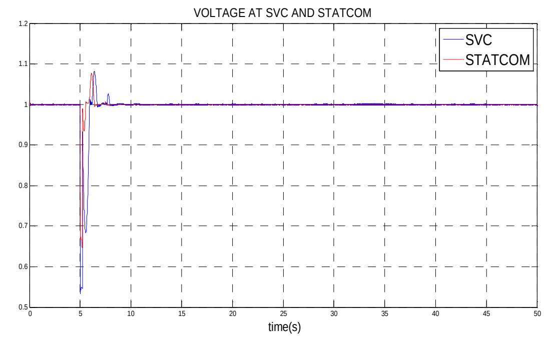

Fig. 9 terminal voltage of STATCOM and SVC during three phases to ground fault

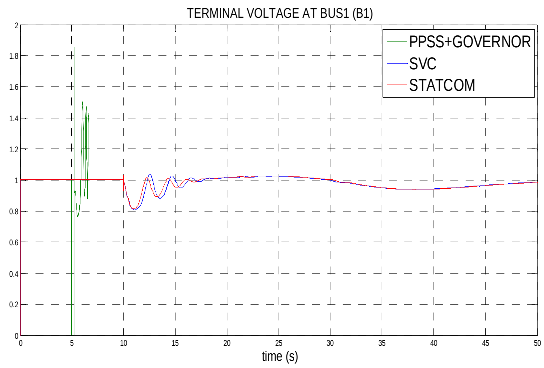

Fig.10. VOLTAGE AT BUS B1 with PSS-GOVERNOR, SVC and STATCOM during load changes.

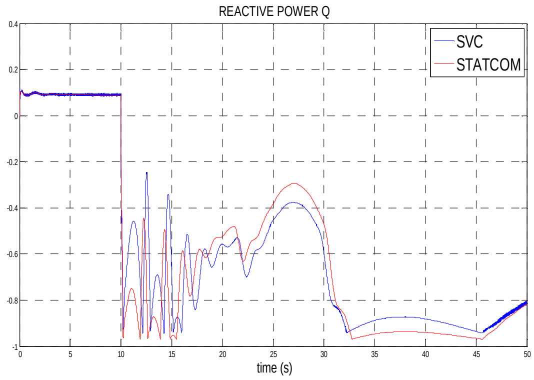

Fig.11 Reactive power injected by STATCOM and SVC during load changes.

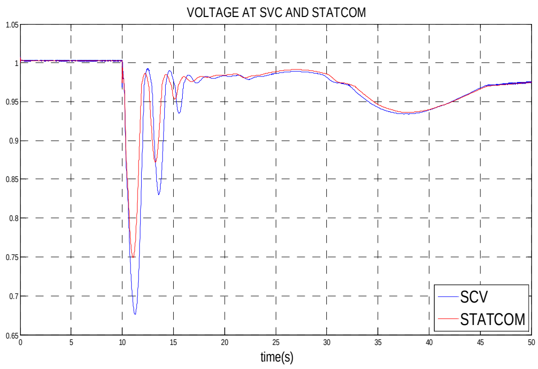

Fig.12 terminal voltage of STATCOM and SVC during load change

VI. Conclusion

The dynamic performance of a PI- type controlled STATCOM is investigated for various contingencies compared with that of conventional SVC. To this extend, a proposed PI- type controller is designed to provide high dynamic performance during system interruptions. The better transient response of the STATCOM against that of the SVC is clearly evident especially in cases of sudden load changes, the key difference between the SVC and the STATCOM can be observed. The reactive power generated by the SVC is lower than the reactive power generated by the STATCOM is. We can then see that the maximum capacitive power generated by a SVC is proportional to the square of the system voltage (constant susceptance) while the maximum capacitive power generated by a STATCOM decreases linearly with voltage decrease (constant current). This ability to provide more capacitive power during a fault is one important advantage of the STATCOM over the SVC. In addition, the STATCOM will normally exhibit a faster response than the SVC because with the voltage-sourced converter, the STATCOM has no delay associated with the thyristor firing (in the order of 4 ms for the SVC).

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