Application of SVC on Stabilizing Torsional Oscillations and Improving Transient Stability

A. F. Abdou, A. Abu-Siada, and H. R. Pota

Abstract-- **This paper investigates the use of static var compensator (SVC) to stabilize multi-mode torsional oscillations of sub-synchronous resonance (SSR) of a large turbine generator set and to improve the system transient stability. In this context, the study is performed on a detailed nonlinear model for system-1 of the second IEEE benchmark for computer simulation of sub-synchronous resonance using EMTDC/PSCAD. The voltage at the machine terminals along with the generator shaft speed are used to control the number of SVC capacitors which are switched on or off and to generate a proper firing angle for the SVC thyristors to control the reactive power exchange between the AC system and the SVC. Results show that the proposed controller is very effective in damping all SSR modes of the system under study. The proposed controller is efficient, simple, cost effective and easy to implement.**

Index Terms—**Sub-synchronous Resonance (SSR), SVC, Stability.**

I. INTRODUCTION

DUE to the significant increase in power demand, transmission line operators are required to increase transmission line power transfer capability. In this context, they have two options; the first one is to build an additional parallel transmission line which is not a cost effective option especially for long transmission lines. The second option is to use a series-capacitor transmission lines which is a very cost effective option when compared with the former one. However, series-capacitor transmission lines are not without problems. If a resonant frequency of the transmission system is complementary to any one of the torsional oscillating frequencies of the turbine generator mass-spring system, the sub-synchronous resonance (SSR) will develop. The electric resonance of the transmission system and the torsional oscillations of the mass-spring system of the turbine generator set will be mutually excited causing serious shaft oscillations and other damages to the system [1]. The first two shaft failures caused by SSR occurred at Mohave power station in 1970 and 1971 respectively [2-4]. Since then, an extensive effort has been made to increase torsional mode damping and many countermeasures have been suggested in the literature to damp the SSR. Some suggested solutions include the use of superconducting magnetic energy storage (SMES) unit [5-7], shunt reactor controller [8, 9], thyristor-controlled dynamic resistance braking [3, 10], excitation control of synchronous generator [11, 12], gate controlled series capacitors [13, 14], and static synchronous compensator (STATCOM) [15].

Due to the sustainable increase in electric power demand, power systems are becoming larger and more interconnected. As a consequence, transient stability problem has become more serious. If the stability is lost, network collapse may occur with significant financial losses and severe damages to the power grid that could lead to overall blackout [16, 17]. Many solutions have been suggested in the literature to improve the system transient stability. Some suggested solutions include the use of SMES unit [5, 18-20], thyristor-controlled series compensation (TCSC) [21-23], fault current limiter and thyristor controlled braking resistor [24].

Flexible AC transmission systems (FACTS) based on power electronic converters such as STATCOM is being used extensively in power systems because of its ability to provide flexible reactive power flow control [25]. This paper investigates the use of static var compensator (SVC) to enhance the transient stability and to damp the SSR of a steam turbine-generator connected to a large interconnected AC grid via a series-capacitor compensated transmission line.

II. SVC MODELING AND CONTROL

The SVC is basically representing a shunt connected static var generator/absorber whose output is adjusted to exchange capacitive or inductive current with the power system to maintain or to control specific parameters of the electrical power system, typically bus voltage. It is used extensively to provide fast reactive power and voltage regulation support. The firing angle control of the thyristor enables the SVC to have almost instantaneous response.

There are two types of the SVC namely, fixed capacitor-thyristor controlled reactor (FC-TCR) and thyristor switched capacitor-thyristor controlled reactor (TSC-TCR). The later type is used in this paper because it is more flexible than FC-TCR and it uses lower reactor rating. Fig. 1shows a schematic diagram for a typical TSC-TCR SVC that consists of two thyrisors switched capacitors (TSC) and one thyristor controlled reactor (TCR).

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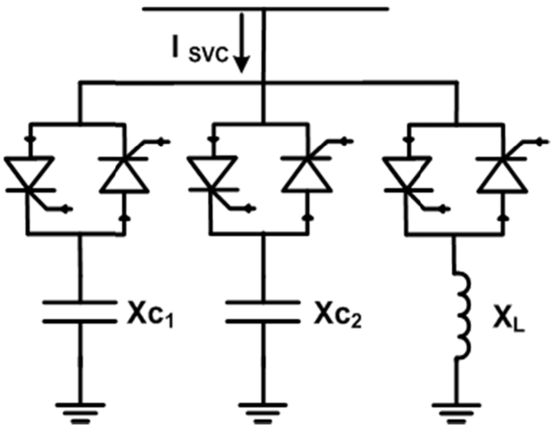

Fig. 1 TSC-TCR SVC structure.

In this paper, the SVC is used to suppress all SSR oscillation modes and to improve the power system transient stability of a large turbine generator set connected to a large interconnected network via series capacitor compensated transmission line. To achieve this, the control scheme shown in Fig. 2 is proposed where the voltage deviation at the machine terminals ΔV_1 and the generator shaft speed deviation $\Delta\omega_{gen}$ are used as input signals to the proposed controller.

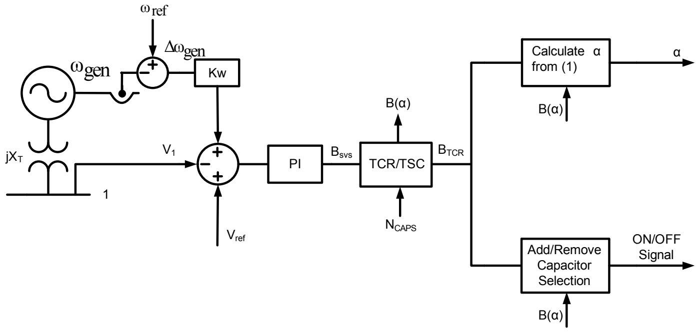

Fig. 2 Proposed control system scheme.

The controller provides three outputs: a capacitor bank switching signal that determines the number of capacitor banks needed to be on, thyristor firing angle α that is required to control the TCR and the TCR susceptance $B(\alpha)$. As shown in Fig. 2, the voltage and the speed deviations are used as input signals to the PI controller that is used to generate a SVC susceptance reference value B_{svc} . The B_{svc} is used as an input to a non-linear susceptance characteristic for the TCR / TSC along with the number of TSC that in use N_{CAPS} to generate the TCR susceptance $B(\alpha)$ and the non-linear TCR suceptance B_{TCR}, these two output are used to create the on/off signal and the thyristor firing angle α. The susceptance of the TCR as a nonlinear function of the firing angle is calculated from (1) [26]:

$$B(\alpha) = \frac{1}{X_L}\left(1-\alpha-\frac{\sin(\pi\alpha)}{\pi}\right) \qquad (1)$$

where $B(\alpha)$ is the susceptance of the TCR fired at an angle α.

The total effective SVC reactance (X_{SVC}) as a function of the TCR firing angle, is the parallel combination of the inductive and capacitive branches and can be calculated as [27]:

$$X_{SVC}(\alpha) = \frac{\pi X_C X_L}{X_C[2(\pi-\alpha)+\sin(2\alpha)]-\pi X_L} \qquad (2)$$

where X_L and X_C are respectively the total inductive reactance and capacitive reactance.

The PI controller parameters are selected by using the robust optimization method Nelder and Mead [28, 29]. In this optimization method the parameters can be obtained with significantly reduced computational time and effort in comparison with traditional techniques. The Nelder and Mead algorithm adjusts the PI parameters (K_I, K_P) based on how well it minimizes the cumulative objective function (OF). In this paper, the objective function is represented as an integral-squared-error (ISE) that is widely used in steady-state and dynamic optimization problems.

$$OF = ISE = \int_{t_0}^{t_f}\left(\Delta V_1 + \Delta\omega_{gen} * K_\omega\right)^2 dt \qquad (3)$$

where K_w is the speed control gain value.

To make the parameters selection robust, for any set of trial parameters, several system runs as shown in Fig. 3 are conducted. An $OF(K_I, K_P)$ is determined for the entire aggregate of runs, in which each run in the aggregate corresponds to one operating condition of the network.

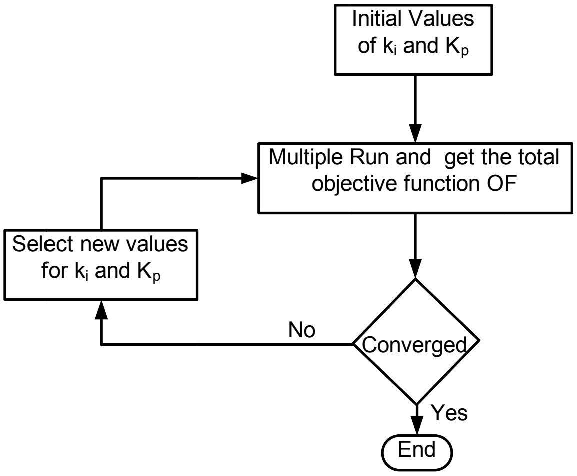

Fig. 3 Schematic diagram for selecting PI parameters.

III. DAMPING OF SSR

The first system of IEEE second benchmark model for SSR studies [30], is used in this paper as a test system. A single generator (600 MVA) is connected to an infinite bus through two parallel lines, one of which is series compensated as shown in Fig. 4. The detailed model of the IEEE second benchmark model can be found in [31] and the system parameters are given in the appendix. The shaft system of the turbine generator set consists of four masses; high-pressure turbine (HP), low-pressure turbine (LP), generator rotor (Gen) and the exciter (Ex). The SVC is connected at the machine terminal bus (bus-1) to provide adequate damping for the turbine generator set. To carry out the investigations, a non-linear model of the system shown in Fig. 4 is developed to incorporate the interaction between the electric network and the torsionally oscillating shaft system of the turbine-generator set. The system has been simulated with all non-linearities such as exciter ceiling voltage and the PI parameters (K_P, K_I) limits are included.

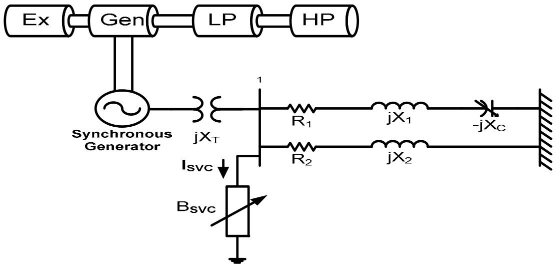

Fig. 4 The IEEE Second Benchmark Model including SVC.

To demonstrate the effectiveness of the SVC proposed controller in damping SSR of the system under study, the EMTDC/PSCAD program is used to examine the system dynamic performance for a transmission line compensation degree (X_C/X_L) = 0.55, machine active power output P_0 =1 pu and machine terminal voltage V_t = 1 pu.

Fig. 5, Fig. 6, and Fig. 7 show the dynamic response of the studied system without and with the SVC at the operating conditions mentioned above. Both figures show the generator shaft speed ω_g, torsional torque induced in the high-pressure, low-pressure turbines shaft (T_{HP-LP}) and the low-pressure turbine, generator shaft (T_{LP-Gen}). Without SVC and due to the lack of system damping, the system at 55% compensation degree of the transmission line is unstable as is evident by the high torsional forces induced in the generator mechanical shaft sections and the significant increment in the shaft speed. The shaft mechanical torque reaches to a crest value of 2 pu which is 300% of the nominal value. If this issue is not attended, it will lead to severe damages in the mechanical shaft.

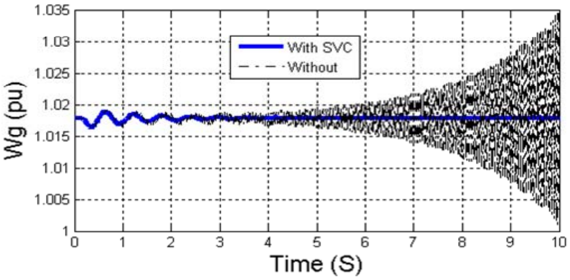

Fig. 5 Generator shaft speed with and without the SVC

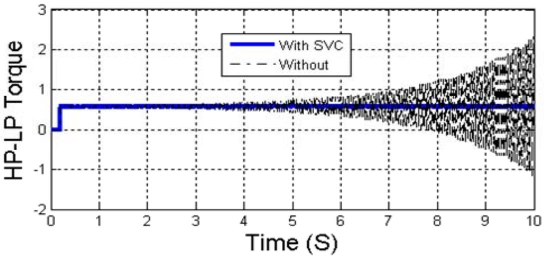

Fig. 6 Hp to Lp Torque with and without the SVC.

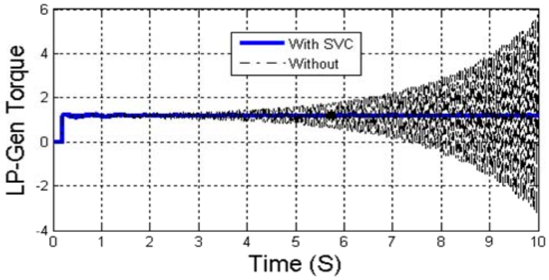

Fig. 7 Lp to Gen Torque with and without the SVC.

When the SVC is connected at the generator bus, the damping of the synchronous generator is greatly enhanced and the stability margin can be extended as can be shown in Fig. 5, Fig. 6, and Fig. 7.

It can also be shown that using a SVC will reduce the high torsional forces on the turbine-generator shaft sections to almost normal steady state values and the settling time decreases substantially. It will also reduce the generator shaft speed oscillations and maintain it at the nominal value.

IV. TRANSIENT STABILITY

The single machine infinite bus (SMIB) system qualitatively exhibits important characteristics of the behaviour of a multi-machine system; it is extremely useful to describe the general concepts of power systems stability and is relatively simple to study. The same system shown in Fig. 4 is thus used to show the effect of SVC in improving system transient stability.

A three phase short-circuit fault is simulated at the middle of the second line. The fault is initiated at t=2 s and is assumed to be cleared at t=2.1 s. The same operating conditions mentioned in the previous section along with 55% compensation degree were maintained during this study. During the short circuit fault the transmitted electrical power decreases significantly while mechanical input power to the generator remains constant; as a result, the generator performance exhibits significant oscillations as clearly shown in the case without SVC (Fig. 9 to Fig. 11). The shaft speed increment is more than the previous case shown in Fig. 5 even after clearing the fault. When the fault is cleared at 2.1 s, the shaft speed and machine power angle are continuously oscillating and the system is not able to retain stability due to the lack of damping. As a result of the short circuit fault, 60% voltage sag is introduced at the machine's terminal and the voltage is not recovered after the fault clearance due to the lack of reactive power support. The torque on the mechanical shaft will increase to a level that will cause severe damages to the shaft as can be seen in Fig. 11.

When the SVC is connected to the generator terminals, reactive power controller adapts the value of the inverter firing angle according to system requirements. The impact of reactive power modulation using SVC on system performance can be seen in Fig. 9 through Fig. 11. Connecting the SVC to the generator terminals will maintain the rotor speed and the machine angle at their nominal values even during the fault as shown in Fig. 8 and Fig. 10 respectively. The voltage sag at the generator terminals is not significantly improved by connecting the SVC. However, the SVC suppresses all voltage oscillations after fault clearance. The shaft torsional forces will be reduced to almost the normal steady state condition.

The effect of improving system damping and improving overall performance using SVC is very obvious as can be seen in the simulation results.

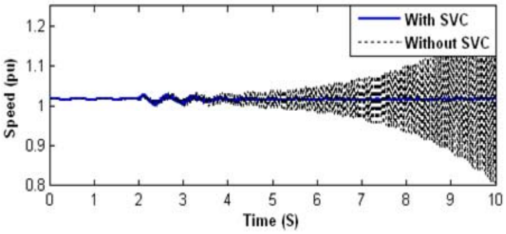

Fig. 8 The machine Speed.

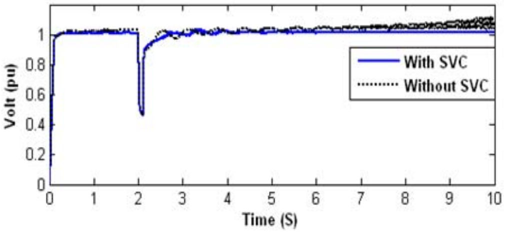

Fig. 9 The volt at bus 1

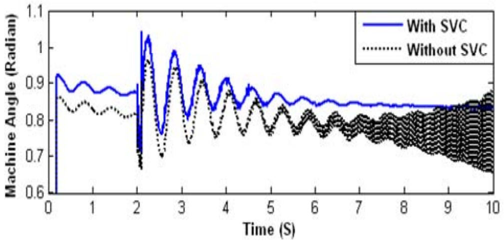

Fig. 10 The machine angle.

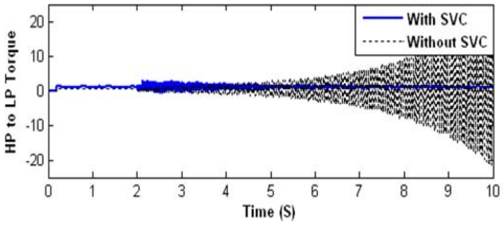

Fig. 11 The High-pressure to low-pressure turbine (T_{HP-LP})

V. CONCLUSIONS

The dynamic response for the IEEE second bench mark model for SSR studies system without and with the SVC using the proposed controller is examined. Results show that the additional degree of freedom provided by the SVC under the proposed controller significantly improves the system overall performance. The proposed control algorithm can effectively render reactive power support to damp system torsional oscillations and to enhance system transient stability during a three phase short circuit fault. This controller is very simple in its structure and would require very little hardware to implement. The optimization method used to tune the PI parameters is reliable, fast and assure robust parameters selection.

APPENDIX

A. Generator Data

Rating = 600 MVA V_{LL} =22 kV R_a =0.0045 p.u.
X_l = 0.14 p.u. X_d = 1.65 p.u. X_q = 1.59 p.u.
X'_d = 0.25 p.u. X''_d = 0. 20 p.u. X''_q = 0.46 p.u.
X''_q = 0. 20 p.u. T'_{do} = 4.5 s T''_{do} = 0.040 s
T'_{qo} = 0.55 s T''_{qo} = 0.09 s

B. Torsional System Data

Mass	Inertia Ibm-ft^2	Damping Ibf-ft-sec/rad	Spring Constant in Ibf-ft /rad
Exc	1383	4.3	
			4.39 x 10^6
Gen	176204	547.9	
			97.97 x 10^6
LP	310729	966.2	
			50.12 x 10^6
HP	49912	155.2	

C. SVC

Transformer rating=200MVA No of capacitor stage=2

TCR Rating=100 MVAR Total TSC Rating=167 MVAR

K_P=0.26 K_I=0.20

D. Transmission Line Parameters

R1=18.5 Ω R2=16.75 Ω

L1=0.5305 H L2=0.49006 H

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