

Effect of Supplementary STATCOM Stabilizer Tuned Based on Simulated Annealing on Dynamic Stability Improvement in Electric Power System

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Abstract: In this study, the performance of supplementary stabilizer for static synchronous compensator (STATCOM) tuned based on simulated annealing in order to improvement of dynamic stability is studied. Since STATCOM is usually used for damping Low Frequency Oscillations (LFO), a supplementary stabilizer is incorporated with STATCOM to reach the mentioned purpose. Simulated Annealing (SA) as a heuristic optimization technique is used for tuning the parameters of the STATCOM supplementary stabilizer. The IEEE 14 bus test system is considered for achieving simulation results. In order to show the ability of SA-based STATCOM to damp LFO, the system responses in case with and without STATCOM are compared. Also two different operation conditions i.e. normal and heavy have been considered for better examination of SA-based STATCOM performance. Several nonlinear time-domain simulation tests visibly show the ability of STATCOM in damping of power system oscillations and consequently stability enhancement.

Key words: Damping of power system oscillations, dynamic stability enhancement, flexible ac transmission systems, multi machine electric power system, simulated annealing, static synchronous compensator

INTRODUCTION

The rapid development of the high-power electronics industry has made Flexible AC Transmission System (FACTS) devices viable and attractive for utility applications. FACTS devices have been shown to be effective in controlling parameters of power system and also in damping power system oscillations. In recent years, new types of FACTS devices have been investigated that may be used to increase power system operation flexibility and controllability, to enhance system stability and to achieve better utilization of existing power systems (Hingorani and Gyugyi, 2000). The Static Synchronous Compensator (STATCOM) is one of the most important FACTS devices and it is based on the principle that a voltage-source inverter generates a controllable AC voltage source behind a transformer-leakage reactance so that the voltage difference across the reactance produces active and reactive power exchange between the STATCOM and the transmission network. It can be used for dynamic compensation of power systems to provide voltage support (Slepchenkov *et al.*, 2011; Li *et al.*, 2007; Singh *et al.*, 2004; Lahaçani *et al.*, 2010; Valderrábano and Ramirez, 2010). Also STATCOM can be used for transient stability improvement by damping of low frequency power system oscillations (Chatterjee and

Ghosh, 2011; Padiyar and Prabhu, 2006; Furini *et al.*, 2011; Hemmati *et al.*, 2011).

In this study, the ability of supplementary stabilizer joint with STATCOM is investigated for dynamic stability improvement via damping of low frequency oscillations. An auxiliary stabilizer based on STATCOM is used to increase power system damping torque. Simulated Annealing (SA) is considered for tuning the parameters of the proposed STATCOM supplementary stabilizer. A multi machine power system installed is chosen as case study. Different load conditions are incorporated to show effectiveness of STATCOM. Simulation results show the validity of STATCOM in LFO damping and stability enhancement at large electric power systems.

System under study: In this study IEEE 14 bus test system is considered to evaluate the proposed method. The system data are completely given in IEEE standards. Figure 1 shows the considered system with a STATCOM installed in bus 14. Detail of the system data have been given in (University of Washington). To evaluate the effectiveness and robustness of the proposed method over a wide range of loading conditions, two different cases as nominal and heavy loading are considered. Where, in the heavy condition, the active and reactive

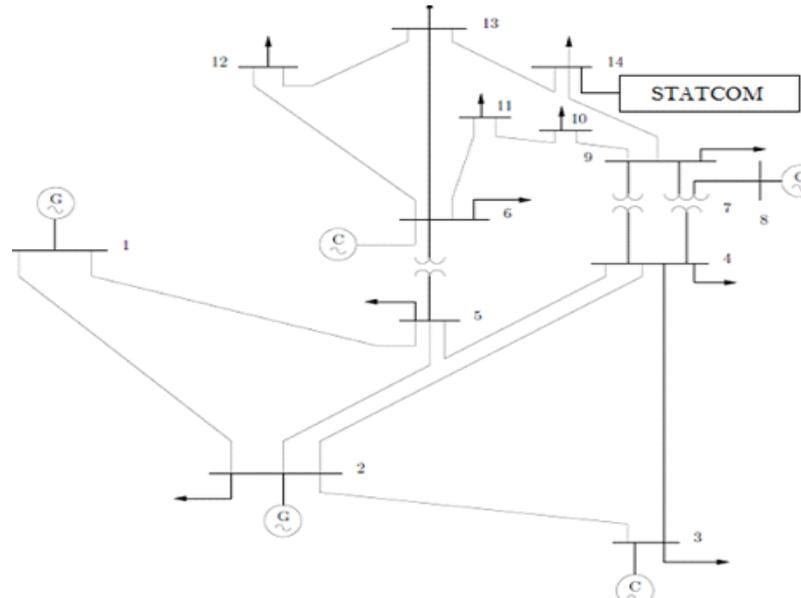


Fig.1: Multi-machine electric power system installed with STATCOM

powers of loads are considered by 40% increasing from the nominal values. Also, in this study, turbine-governor system is also modeled to eliminate steady state error of responses.

Dynamic model of the system with STATCOM: The nonlinear dynamic model of the system installed with STATCOM is given as (1). The detailed explanation is completely presented in (Wang, 1999).

$$\begin{cases} \omega = (P_m - P_e - D\omega) / M \\ \delta = \omega_0(\omega - 1) \\ E_{fd} = (-E_q + E_{fd}) / T_{do}^1 / T_r \\ b_{SVC} = (K_r(V_{ref} - V) - b_{SVC}) \\ E_{fd} = (-E_{fd} + K_a(V_{ref} - V_t)) / T_r \end{cases} \quad (1)$$

where, δ : Rotor angle; ω : Rotor speed (pu); P_m : Mechanical input power; P_e : Electrical output power (pu); M : System inertia (Mj/MVA); E_q : Internal voltage behind x_d (pu); E_{fd} : Equivalent excitation voltage (pu); T_{do} : Time constant of excitation circuit (s); K_a : Regulator gain; T_r : Regulator time constant (s); V_{ref} : Reference voltage (pu); V_t : Terminal voltage (pu).

By controlling m_E , the output voltage of the shunt converter is controlled. By controlling d_E , exchanging active power between the STATCOM and the power system is controlled.

STATCOM controllers: In this study two control strategies are considered for STATCOM:

- DC-voltage regulator
- STATCOM supplementary stabilizer

DC-voltage regulator: In STATCOM, The output real power of the shunt converter must be equal to the input real power or vice versa. In order to maintain the power balance, a DC-voltage regulator is incorporated. DC-voltage is regulated by modulating the phase angle of the shunt converter voltage. In this study the parameters of DC-voltage regulator are considered as $K_{di} = 22.78$ and $K_{dp} = 8.21$.

STATCOM supplementary stabilizer: A stabilizer controller is provided to improve damping of power system oscillations. This controller is considered as a lead-lag compensator and it provides an electrical torque in phase with the speed deviation in order to improve damping of power system oscillations. The transfer function model of the classical stabilizer is as (2). This type of stabilizer consists of a washout filter, a dynamic compensator. Where, U_{in} can be the speed deviation, active power of line, bus voltage or etc and the output signal U_{out} is fed as an auxiliary input signal to the stable.

STATCOM. The washout filter, which essentially is a high pass filter, is used to reset the steady state offset in the output of the PSS. In this study the value of the time constant (T_w) is fixed to 10 s. The dynamic compensator is made up to two lead-lag stages and an additional gain. The adjustable stabilizer parameters are the gain of the

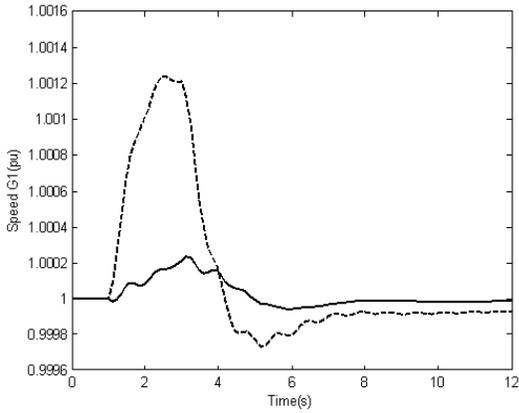


Fig. 2: Speed of generator 1 under fault scenario in the nominal operating condition, Solid (With STATCOM), Dashed (Without STATCOM)

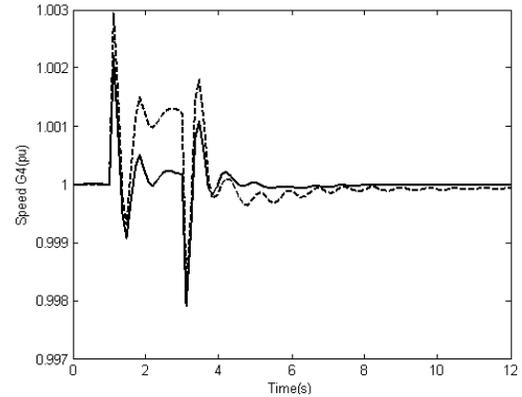


Fig. 5: Speed of generator 4 under fault scenario in the nominal operating condition, Solid (With STATCOM), Dashed (Without STATCOM)

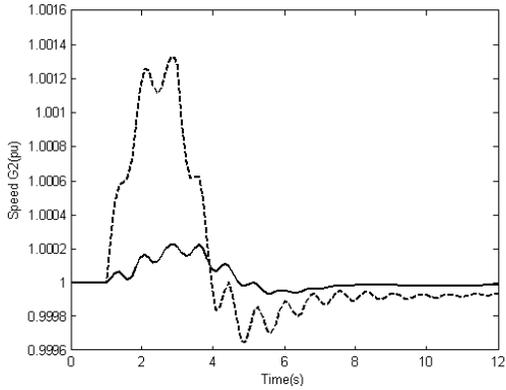


Fig. 3: Speed of generator 2 under fault scenario in the nominal operating condition

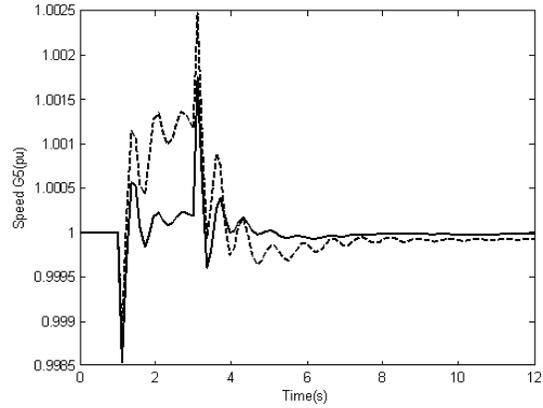


Fig. 6: Speed of generator 5 under fault scenario in the nominal operating condition, Solid (With STATCOM), Dashed (Without STATCOM)

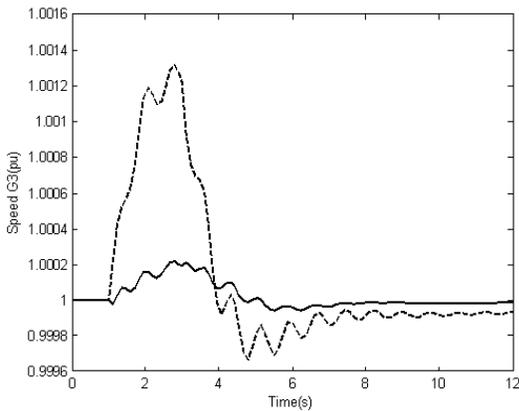


Fig. 4: Speed of generator 3 under fault scenario in the nominal operating condition, Solid (With STATCOM), Dashed (Without STATCOM)

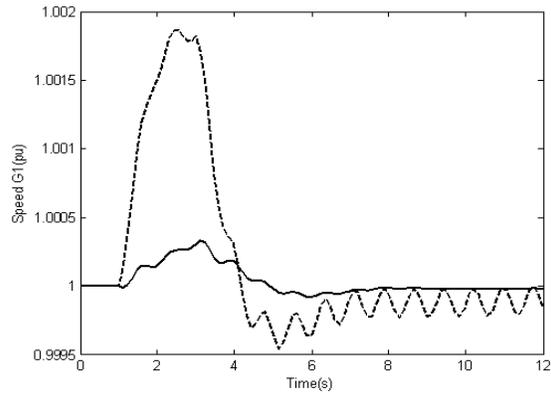


Fig. 7: Speed of generator 1 under fault scenario in the heavy operating condition, Solid (With STATCOM), Dashed (Without STATCOM)

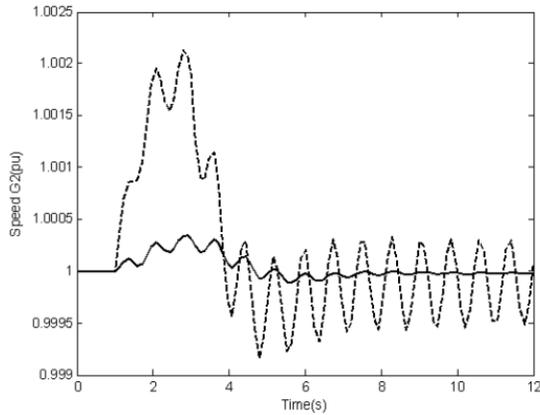


Fig. 8: Speed of generator 2 under fault scenario in the heavy operating condition, Solid (With STATCOM), Dashed (Without STATCOM)

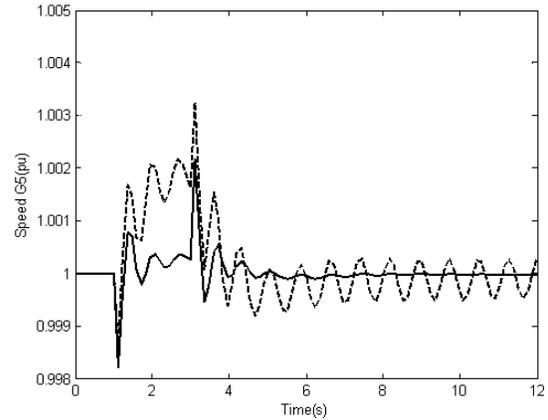


Fig. 11: Speed of generator 5 under fault scenario in the heavy operating condition, Solid (With STATCOM), Dashed (Without STATCOM)

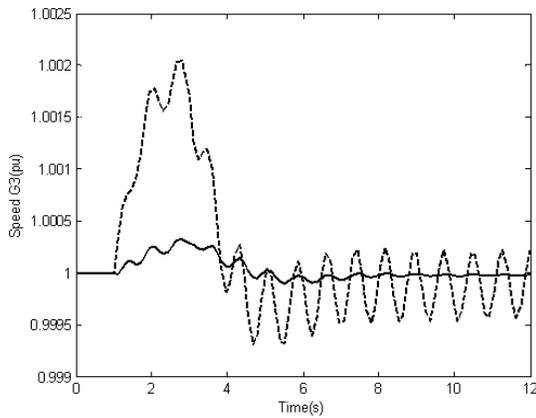


Fig. 9: Speed of generator 3 under fault scenario in the heavy operating condition, Solid (With STATCOM), Dashed (Without STATCOM)

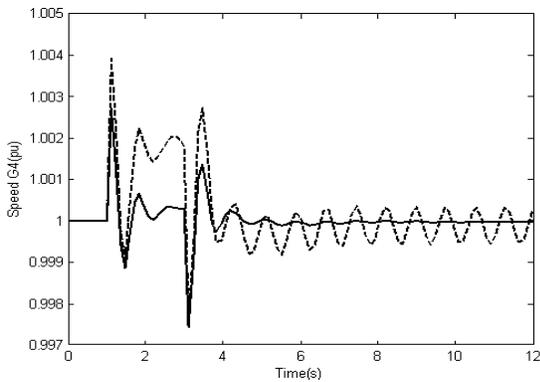


Fig. 10: Speed of generator 4 under fault scenario in the heavy operating condition, Solid (With STATCOM), Dashed (Without STATCOM)

Stabilizer, K_{DC} , and the time constants, T1–T4. The lead-lag block present in the system provides phase lead compensation for the phase lag that is introduced in the circuit between the STATCOM input and the electrical torque:

$$U_{out} = \frac{KST_w}{1 + ST_w} \frac{1 + ST_1}{1 + ST_2} \frac{1 + ST_3}{1 + ST_4} U_{in} \quad (2)$$

In this study SA is used for tuning the proposed stabilizer parameters. In the next section an introduction about SA is presented.

Simulated annealing: In the early 1980s the method of Simulated Annealing (SA) was introduced in 1983 based on ideas formulated in the early 1950s. This method simulates the annealing process in which a substance is heated above its melting temperature and then gradually cooled to produce the crystalline lattice, which minimizes its energy probability distribution. This crystalline lattice, composed of millions of atoms perfectly aligned, is a beautiful example of nature finding an optimal structure. However, quickly cooling or quenching the liquid retards the crystal formation, and the substance becomes an amorphous mass with a higher than optimum energy state. The key to crystal formation is carefully controlling the rate of change of temperature.

The algorithmic analog to this process begins with a random guess of the cost function variable values. Heating means randomly modifying the variable values. Higher heat implies greater random fluctuations. The cost function returns the output, f , associated with a set of variables. If the output decreases, then the new variable set replaces the old variable set. If the output increases, then the output is accepted provided that:

$$r \leq e[f(P_{new})]/T \tag{3}$$

where, r is a uniform random number and T is a variable analogous to temperature. Otherwise, the new variable set is rejected. Thus, even if a variable set leads to a worse cost, it can be accepted with a certain probability. The new variable set is found by taking a random step from the old variable Set as (4):

$$P^{new} = dP^{old} \tag{4}$$

The variable d is either uniformly or normally distributed about P^{old} . This control variable sets the step size so that, at the beginning of the process, the algorithm is forced to make large changes in variable values. At times the changes move the algorithm away from the optimum, which forces the algorithm to explore new regions of variable space. After a certain number of iterations, the new variable sets no longer lead to lower costs. At this point the value of T and d decrease by a certain percent and the algorithm repeats. The algorithm stops when $T=0$. The decrease in T is known as the cooling schedule. Many different cooling schedules are possible. If the initial temperature is T_0 and the ending temperature is T_N , then the temperature at step n is given by (5):

$$T_n = f(T_0, T_N, N, n) \tag{5}$$

where; f decreases with time. Some potential cooling schedules are as follows:

Linearly decreasing: $T_n = T_0 - n(T_0 - T_N)/N$
 Geometrically decreasing: $T_n = 0.99 T_{n-1}$

Hayjek optimal:

$$T_n = c/\log(1+n),$$

where, c is the smallest variation required to get out of any local minimum.

Many other variations are possible. The temperature is usually lowered slowly so that the algorithm has a chance to find the correct valley before trying to get to the lowest point in the valley. This algorithm has been applied successfully to a wide variety of problems (Randy and Sue, 2004).

SA based stabilizer design: In this section the parameters of the proposed stabilizer are tuned using SA.

Two control parameters of the STATCOM (m_E, δ_E) can be modulated in order to produce the damping torque. The parameter m_E is modulated to output of damping controller and power of line between bus 13 and bus 14 is also considered as input of damping controller. The

Table 1: Optimal parameters of stabilizer using SA

Parameter	K	T ₁	T ₂	T ₃	T ₄
Optimal value	1.06	0.79	0.16	0.79	0.16

optimum values of K and T₁-T₄ which minimize an array of different performance indexes are accurately computed using SA. In optimization methods, the first step is to define a performance index for optimal search. In this study the performance index is considered as (6). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (ITAE):

$$ITAE = \int_0^1 t|\Delta\omega_1|dt + \int_0^1 t|\Delta\omega_2|dt + \int_0^1 t|\Delta\omega_3|dt + \int_0^1 t|\Delta\omega_4|dt + \int_0^1 t|\Delta\omega_5|dt \tag{6}$$

where, D shows the frequency deviations. It is clear to understand that the controller with lower ITAE is better than the other controllers. To compute the optimum parameter values, a 8 cycle three phase fault is assumed in bus 2 and the performance index is minimized using SA. The optimum values of parameters, resulting from minimizing the performance index is presented in Table 1.

RESULTS AND DISCUSSION

In this section, the tuned supplementary stabilizer is incorporated with STATCOM. In order to study and analysis system performance under different scenarios, fault scenario is considered as follows:

Fault Scenario: disconnection of the line between bus 2 and bus 4 by breaker

It is worth to mention that in the fault scenario, the line is disconnected by breaker and after one second the line is connected again.

The simulation results are presented in Fig. 2-11. Each figure contains two plots; solid line which indicates on the system installed with STATCOM and dashed line for system without STATCOM.

As it is clear in Fig. 2-6, in normal operation condition, STATCOM could damp the generator angle oscillations faster in comparison with the case of the lack of STATCOM. It means that by applying the supplementary stabilizer signal the system becomes more stable.

With changing operating condition from nominal to heavy, looking to Fig. 7-11, the performance of system without STATCOM becomes poor, but the system with STATCOM has a stable and robust performance. The

results clearly show that in large electric power systems, STATCOM can successfully increase damping of power system oscillations and the system with STATCOM is more robust and stable after disturbances, either in normal or heavy operation conditions.

CONCLUSION

In this study Simulated Annealing (SA) method has been successfully exerted to adjust supplementary STATCOM parameters. A multi-machine electric power system installed with a STATCOM with various load conditions and disturbances has been assumed to demonstrate the ability of STATCOM in damping of power system oscillations. Considering real world type disturbances such as line disconnection guarantee the results in order to implementation of controller in industry. Simulation results demonstrated that the designed STATCOM capable to guarantee the robust stability and robust performance under a different load conditions and disturbances. Also, simulation results show that the SA technique has an excellent capability in STATCOM parameters tuning. Application to a multi-machine electric power system which is near to practical systems can increase admission of the technique for real world applications.

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