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Stabilizer design based on STATCOM using Simulated Annealing

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Abstract: This paper presents the application of Static Synchronous Compensator (STATCOM) to enhance damping of Low Frequency Oscillations at a single-machine infinite-bus power system installed with a STATCOM as cast study. STATCOM is considered in order to damping of Low Frequency Oscillations. Therefore the supplementary stabilizer based STATCOM (like power system stabilizer) is designed to reach defined purpose. A Meta heuristic optimization method named Simulated Annealing (SA) is used to tuning STATCOM supplementary stabilizer controller. To show effectiveness of the proposed method, the proposed method is compared with another optimization method named Genetic Algorithms (GA). Several linear time-domain simulation tests visibly show the validity of proposed method in damping of power system oscillations. Also Simulation results emphasis on the better performance of SA in comparison with GA.

Key words: Flexible AC Transmission Systems, Static Synchronous Compensator, Low Frequency Oscillations, Simulated Annealing, Genetic Algorithms

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 power flow and 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 *et al*., 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. The STATCOM is one of the important 'FACTS' devices and can be used for dynamic compensation of power systems to provide voltage support and stability improvement (Gyugyi *et al*., 1990; Gyugyi, 1979; Schauder *et al*., 1993; Schauder *et al*., 1995; Ekanayake *et al*., 1995; Saad-Saoud *et al*., 1998; Trainner *et al*., 1994; Ainsworth *et al*., 1998; Mori *et al*., 1993). In (Wang *et al*., 1999) a unified Phillips-Heffron model (Heffron *et al*., 1952) of power systems installed with a STATCOM is established. STATCOM has developed from a switch mode voltage-source converter configuration with an energy-storage device (DC capacitor). Also, the STATCOM can be used for voltage support and transient stability improvement by damping of low frequency power system oscillations. Low frequency oscillations (LFO) in electric power system occur frequently due to disturbances such as changes in loading conditions or a loss of a transmission line or a generating unit. These oscillations need to be controlled to maintain system stability. In past decays power system stabilizer or PSS was applied for damping power system oscillations. Recently new power system controllers like as FACTS devices are presented as power system stabilizer. Many in the past have presented lead-Lag type UPFC stabilizers (Tambey *et al*., 2003). They are designed for a specific operating condition using linearized models. More advanced control schemes such as self-tuning control (Cheng *et al*., 1986), Particle-Swarm method (Al-Awami *et al*., 2007) and fuzzy logic control (Mishra *et al*., 2000; Eldamaty *et al*., 2005) offer better dynamic performances than fixed parameter controllers. Fuzzy control design is attractive because it does not require a mathematical model of the system under study and it can cover a wide range of operating conditions and is simple to implement.

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The objective of this paper is to investigate the ability of optimization methods such as Simulated Annealing (SA) and Genetic Algorithms (GA) for STATCOM supplementary stabilizer design. A Sigel Machine Infinite Bus (SMIB) power system installed with a STATCOM is considered as case study and a STATCOM based stabilizer whose parameters are tuned using SA and GA is considered as power system stabilizer. Different load conditions are considered to show effectiveness of the proposed methods and also comparing the performance of these two methods. Simulation results show the validity of proposed methods in LFO damping.

2. Illustrative test:

Fig.1 shows the case study system in this paper. The system is a Single Machine Infinite Bus (SMIB) power system with STATCOM installed.

3. System modeling:

3.1. Nonlinear model:

A non-linear dynamic model of the system is derived by disregarding the resistances of all components of the system (generator, transformer, transmission line and shunt converter transformer) and the transients of the transmission lines and transformer of the STATCOM. The nonlinear dynamic model is given as below (1) (Wang *et al*., 1999).

$$\begin{cases} \dot{\omega} = \left(P_m - P_e - D\omega\right)/M \\ \dot{\delta} = \omega_0\left(\omega - 1\right) \\ \dot{E}'_q = \left(-E_q + E_{fd}\right)/T'_{do} \\ \dot{E}_{fd} = \left(-E_{fd} + K_a\left(V_{ref} - V_t\right)\right)/T_a \\ \dot{V}_{dc} = \dfrac{3m_E}{4C_{dc}}\left(\sin\left(\delta_E\right)I_{Ed} + \cos\left(\delta_E\right)I_{Eq}\right) \end{cases} \tag{1}$$

3.2. Linear model:

A linear dynamic model is obtained by linearising the non-linear model around nominal operating condition. The linearised model is given as (2).

$$\begin{cases} \Delta\dot{\delta} = w_0\Delta w \\ \Delta\dot{\omega} = \left(-\Delta P_e - D\Delta\omega\right)/M \\ \Delta\dot{E}^{/}_q = (-\Delta E_q + \Delta E_{fd})/T^{/}_{do} \\ \Delta\dot{E}_{fd} = -\left(1/T_A\right)\Delta E_{fd} - \left(K_A/T_A\right)\Delta V_t \\ \Delta\dot{v}_{dc} = K_7\Delta\delta + K_8\Delta E^{/}_q - K_9\Delta v_{dc} + K_{ce}\Delta m_E + K_{c\delta e}\Delta\delta_E \end{cases} \tag{2}$$

Where

$$\Delta P_e = K_1\Delta\delta + K_2\Delta E^{/}_q + K_{pd}\Delta v_{dc} + K_{pe}\Delta m_E + K_{p\delta E}\Delta\delta_E$$

$$\Delta E_q = K_4\Delta\delta + K_3\Delta E^{/}_q + K_{qd}\Delta v_{dc} + K_{qe}\Delta m_E + K_{q\delta E}\Delta\delta_E$$

$$\Delta V_t = K_5\Delta\delta + K_6\Delta E^{/}_q + K_{vd}\Delta v_{dc} + K_{ve}\Delta m_E + K_{v\delta E}\Delta\delta_E$$

Figure 2 shows the transfer function model of the system including STATCOM. The model has constant parameters which are denoted by K_{ij}. These constant parameters are function of the system parameters and the initial operating condition. The control vector U in Fig. 2 is defined as (3).

$$U = [\Delta m_E \quad \Delta\delta_E]^T \tag{3}$$

Where:

Δm_E: Deviation in pulse width modulation index m_E of shunt inverter. By controlling m_E, the output voltage of the shunt converter is controlled.

Δd_E: Deviation in phase angle of the shunt inverter voltage. By controlling d_E, exchanging active power between the STATCOM and the power system is controlled.

It should be noted that K_{pu}, K_{qu}, K_{vu} and K_{cu} in Fig. 2 are the row vectors and defined as follows:

$$K_{pu} = [K_{pe} \quad K_{p\delta e}]; K_{qu} = [K_{qe} \quad K_{q\delta e}];$$
$$K_{vu} = [K_{ve} \quad K_{v\delta e}]; K_{cu} = [K_{ce} \quad K_{c\delta e}]$$

3.3. State Space Model:

The dynamic model of the system in state-space form is obtained as (4).

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{w} \\ \Delta\dot{E}_q^{/} \\ \Delta\dot{E}_{fd} \\ \Delta\dot{v}_{dc} \end{bmatrix} = \begin{bmatrix} 0 & w_0 & 0 & 0 & 0 \\ -\frac{K_1}{M} & 0 & -\frac{K_2}{M} & 0 & -\frac{K_{pd}}{M} \\ -\frac{K_4}{T_{do}^{/}} & 0 & -\frac{K_3}{T_{do}^{/}} & \frac{1}{T_{do}^{/}} & -\frac{K_{qd}}{T_{do}^{/}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \times \begin{bmatrix} \Delta\delta \\ \Delta w \\ \Delta E_q^{/} \\ \Delta E_{fd} \\ \Delta v_{dc} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ -\frac{K_{pe}}{M} & -\frac{K_{p\delta e}}{M} \\ -\frac{K_{qe}}{T_{do}^{/}} & -\frac{K_{q\delta e}}{T_{do}^{/}} \\ -\frac{K_A K_{ve}}{T_A} & -\frac{K_A K_{v\delta e}}{T_A} \\ Kce & K_{c\delta e} \end{bmatrix} \times \begin{bmatrix} \Delta m_E \\ \Delta\delta_E \end{bmatrix} \qquad (4)$$

The typical values of system parameters for nominal operating condition are given in appendix.

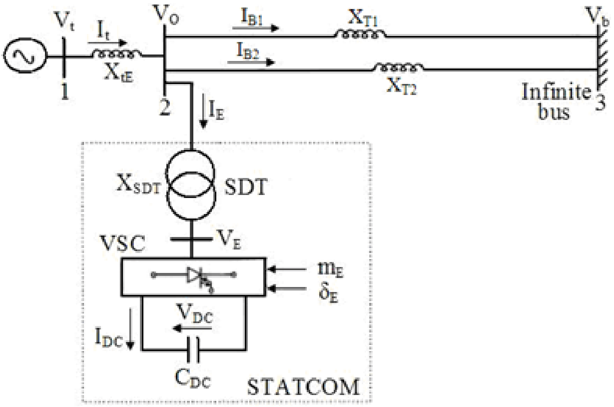

Fig. 1: A single-machine infinite-bus power system installed with STATCOM

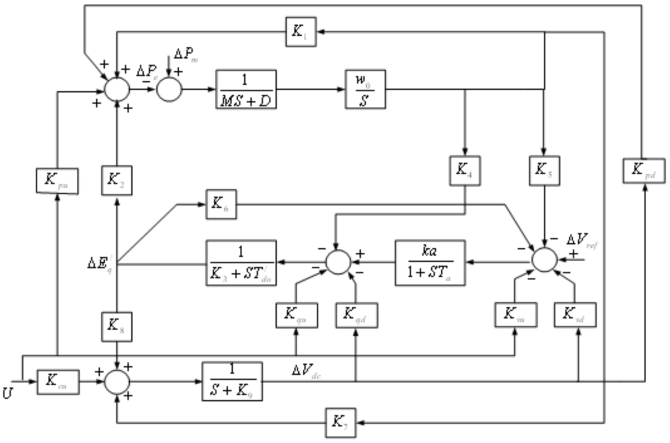

Fig. 2: Transfer function model of the system including STATCOM

STATCOM Controllers:

The STATCOM control system comprises two controllers:

- DC-voltage regulator
- Power system oscillation-damping controller

4.1. DC-voltage regulator:

The STATCOM needs to a DC voltage regulator to regulate DC-link voltage. DC-voltage is regulated by modulating the phase angle of the shunt converter voltage. A P-I type controller is considered as voltage regulator here. The parameters of DC-voltage regulator are considered as follow for this research: K_{di}=39.8 and K_{dp}=0.5778.

4.2. Supplementary stabilizer:

A stabilizer is provided to improve power system oscillations damping. This controller is commonly considered as a lead-lag compensator. However an electrical torque in phase with the speed deviation must be produced in order to improve the damping of the system oscillation. The transfer function block diagram of the stabilizer is shown in Fig. 3.

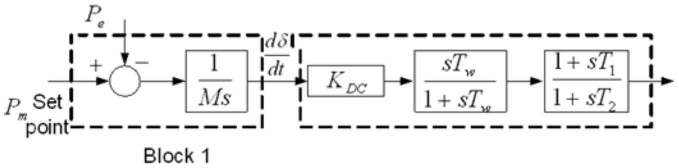

Fig. 3: The Structure of classical stabilizer

5. Eigen value analysis:

For the nominal operating condition the eigenvalues of the system are obtained using state-space model of the system presented in (4) and these eigenvalues are shown in Table 1. It is clearly seen that the system is unstable and needs to power system stabilizer (damping controller) for stability.

Table 1: Eigen-values of the closed-loop system without stabilizer

-17.1146
+0.0213±3.711i
-0.5401±0.4991i

Stabilizer controllers design themselves have been a topic of interest for decades, especially in form of Power System Stabilizers (PSS). But PSS cannot control power transmission and also cannot support power system stability under large disturbances like 3-phase fault at terminals of generator. For these problems, in this paper a stabilizer controller based STATCOM is provided to mitigate power system oscillations. Two optimization methods such as SA and GA are considered for tuning stabilizer controller parameters. In the next section an introduction about SA is presented.

6. 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:

$$r \leq e^{[f(p_{old})-f(p_{new})]/T} \tag{5}$$

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 (6).

$$P^{new}=dP^{old} \tag{6}$$

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 $T\approx 0$.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 (7).

$$T_n=f(T_0, T_N, N, n) \tag{7}$$

Where, *f* decreases with time. Some potential cooling schedules are as follows:

a. Linearly decreasing: $T_n=T_0-n(T_0-T_n)/N$
b. Geometrically decreasing: $T_n=0.99\ T_{n-1}$
c. Hayjek optimal: $T_n=c/log(1+n)$, where *c* is the smallest variation required to get out of any local minimum.

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:

In this section the parameters of the proposed stabilizer controller are tuned using SA. Two control parameters of the STATCOM (m_E and δ_E) can be modulated in order to produce the damping torque. The parameter m_E is modulated to output of stabilizer and speed deviation Dw is also considered as input of stabilizer. The structure of supplementary stabilizer controller has been shown in Fig. 3. The parameters in Fig. 3 are as follow:
K_{DC}: the stabilizer gain
T_W: the parameter of washout block
T_1 and T_2: the parameters of compensation block

The optimum values of K_{DC}, T_1 and T_2 which minimize an array of different performance indexes are accurately computed using SA and T_W is considered equal to 10. In optimization methods, the first step is to define a performance index for optimal search. In this study the performance index is considered as (8). In fact, the performance index is the Integral of the Time multiplied Absolute value of the Error (*ITAE*).

$$\mathrm{ITAE}=\int_0^t t\left|\Delta\omega\right|dt+\int_0^t t\left|\Delta V_{DC}\right|dt \tag{8}$$

Where, Dw is the frequency deviation, DV_{DC} is the deviation of DC voltage and parameter "t" in ITAE is the simulation time. It is clear to understand that the controller with lower ITAE is better than the other controllers. To compute the optimum parameter values, a 0.1 step change in mechanical torque (DTm) is assumed and the performance index is minimized using SA. The optimum values of K_{DC}, T_1 and T_2, resulting from minimizing the performance index is presented in Table 2. Also in order to show effectiveness of SA method, the parameters of stabilizer controller are tuned using the other optimization method, GA. In GA case, the performance index is considered as SA case and the optimal parameters of stabilizer controller are obtained as shown in Table 3.

Table 2: Optimum values of stabilizer controller parameters using SA

K_{DC}	348.791
T_1	0.2803
T_2	0.0112

Table 3: Optimum values of stabilizer controller parameters using GA

K_{DC}	410.971
T_1	0.481
T_2	0.2

8. Simulation results:

In this section, the designed SA and GA based stabilizers are applied to system in order to damping low frequency oscillations. In order to study and analysis system performance under system uncertainties (controller robustness), two operating conditions are considered as follow:

Case 1: Nominal operating condition
Case 2: Heavy operating condition

The parameters for two cases are presented in appendix. SA and GA stabilizer controllers have been designed for the nominal operating condition. In order to demonstrate the robustness performance of the proposed method, The *ITAE* is calculated following 10% step change in the reference mechanical torque (DT_m) at all operating conditions (Nominal and Heavy) and results are shown at Tables 4. Following step change, the SA based stabilizer has better performance than the GA based stabilizer at all operating conditions.

Table 4: 10% Step increase in the reference mechanical torque (?T_m)

	The calculated ITAE	
	GA Stabilizer	SA Stabilizer
0.073	0.033	Nominal operating condition
0.088	0.039	Heavy operating condition

For case 1 the simulation result are also shown in Fig. 4. The simulation results show that applying the supplementary control signal greatly enhances the damping of the generator angle oscillations and therefore the system becomes more stable. The SA stabilizer performs better than the GA controller. For case 2, the simulation results are shown in Fig. 5. Under this condition, while the performance of GA supplementary controller becomes poor, the SA controller has a stable and robust performance. It can be concluded that the SA supplementary controller have suitable parameter adaptation in comparing with the GA supplementary controller when operating condition changes.

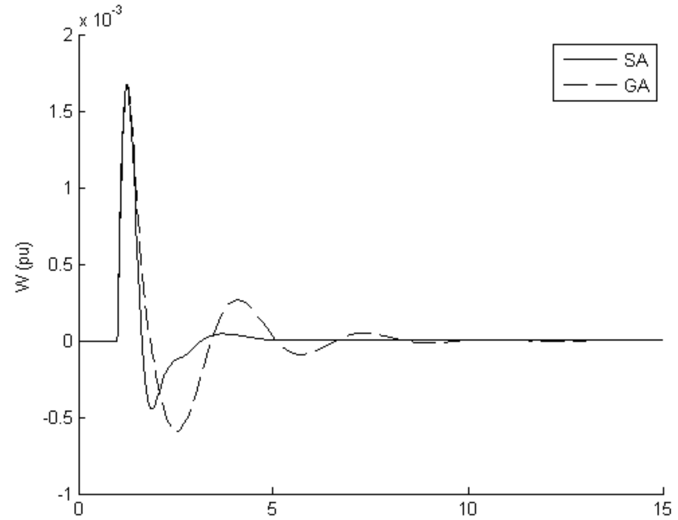

Fig. 4: Dynamic response Dω for case 1

Conclusions:

In this paper Simulated Annealing and Genetic Algorithms have been successfully applied to design stabilizer controller based STATCOM. A Single Machine Infinite Bus power system installed with a STATCOM with various load conditions has been assumed to demonstrate the methods. Simulation results demonstrated that the designed controllers capable to guarantee the robust stability and robust performance under a different load conditions. Also, simulation results show that the SA method has an excellent capability in power system oscillations damping and power system stability enhancement under small disturbances in comparison with GA method.

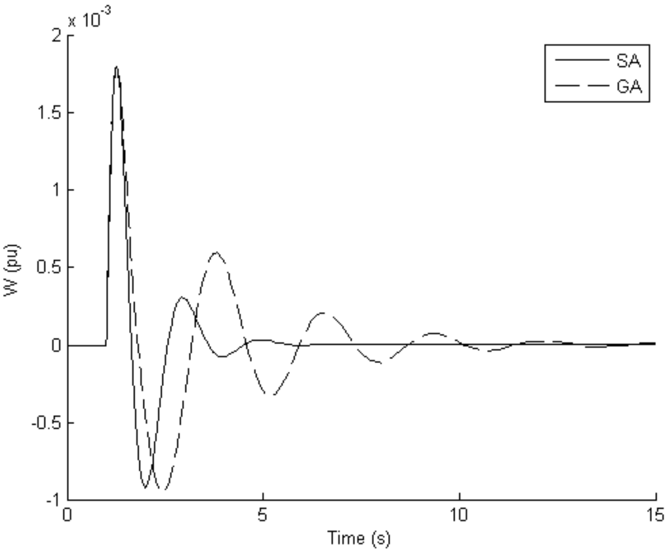

Fig. 5: Dynamic response Dω for case 2

Appendix:

The nominal parameters and nominal operating condition of the system are listed in Table 5. Also system operating conditions are defined as Table 6 (Operating condition 1 is the nominal operating condition).

Table 5: System parameters

Generator	M = 8 Mj/MVA	T'_{do} = 5.044 s	X_d = 1 p.u.
	X_q = 0.6 p.u.	X′d = 0.3 p.u.	D = 0
Excitation system		K_a = 10	T_a = 0.05 s
Transformers		X_{te} = 0.1 p.u.	X_{SDT} = 0.1 p.u.
Transmission lines		X_{T1} = 1 p.u.	X_{T2} = 1.25 p.u.
DC link parameters		V_{DC} = 2 p.u.	C_{DC} = 3 p.u.

Table 6: System operating conditions

Operating condition 1	P = 1 p.u.	Q = 0.2 p.u.	V_t =1.03 p.u.
Operating condition 2	P = 1.1 p.u.	Q = 0.35 p.u.	V_t =1.03 p.u.

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