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Optimal Design of a Fuzzy Logic Stabilizer For A Superconducting Generator in a Multi-Machine System Using Particle Swarm Optimozation

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Abstract. This paper presents and describes an approach for the optimal design of a fuzzy logic stabilizer to enhance the stability of a superconducting generator (SCG) in a multi-machine system. The input signals to the proposed fuzzy stabilizer are the SCG speed deviation and acceleration. In this approach, unsymmetrical nonlinear membership functions are used, while number of stabilizer parameters to be properly designed is 15, including scaling factors for input and output variables along with widths and centers of fuzzy sets of input variables. Particle swarm optimization (PSO) technique is employed to search for optimal settings of the fuzzy stabilizer parameters. Simulation results show that the proposed, PSO-tuned fuzzy stabilizer provides good damping to SCG in a multi-machine environment when operating in conjunction with conventional stabilizers on other machines.

Keywords: Fuzzy logic stabilizer, Superconducting generator, Multi-machine system, Particle swarm optimization

1. Introduction

The application of superconductors to electric power apparatus is considered a key technology for the current century. The electric power demand has been steadily increased worldwide. This tendency will continue in the future, and therefore the capacities of the power transmission systems have to increase. Large power systems require developing a more efficient and stabilizing technology for large amounts of power transmission. One promising method is to introduce the superconducting generator (SCG), which has a very low synchronous reactance [1]. Superconducting generators have also many other potential advantages compared with the conventional generators such as higher efficiency and smaller size and weight. The advantages of SCG have drawn more interest in industrial countries since 1970's, such as in Japan where many R&D projects on SCGs were conducted at utility companies, power plant manufacturers and other organization toward 200-MW class pilot machine [2-6]. Despite these advantages, SCG field winding has an extremely large time constant. The excitation system is therefore not able to change quickly the field current to meet the grid requirements under transient conditions. Inevitably, the only control means feasible to enhance SCG stability following power system faults is the fast-acting governors on the steam supplies to the turbine.

Transient stability is one of the most important issues that should be investigated in power system planning, operation, and expansion. It is mainly concerned with maintaining generator synchronization following a sudden and major disturbance or an abrupt change in load or generation power. The importance of this issue increases when considering a superconducting generator in a multi-machine system. In the past, a number of investigations have been conducted to study and improve the behaviour of a superconducting generator in a multi-machine system [7-8], The results reported in [7] show that the incorporation of a SCG in a multi-machine system increases its stability reserve, but slightly reduces the overall damping of the system. However, a good improvement in the performance and stability limits can be achieved by using a conventional lead stabilizer in the governor loop of the SCG [8]. Alternative stabilizers based on adaptive control techniques have been proposed [9-11]. However, the on-line parameter identification is still questionable especially during fault periods. Recently, fuzzy logic control has emerged as one of the most fruitful research areas, and many applications for enhancing power system stability have been reported in literature [12-13]. A recent literature survey on the work done on the fuzzy logic controller and the approaches made to enhance its effectiveness are given in the introduction of Ref. [14]. The fuzzy logic stabilizer is essentially a multi-parameter controller, whose performance depends on the shape of membership functions, rule base and scaling factors. However, the design of a fuzzy stabilizer with satisfactory performance is a rather difficult problem. To overcome this problem, genetic algorithm (GA) was proposed as an efficient technique for the optimal design of power system stabilizers [15-16]. More recently, a new heuristic search method called *particle swarm optimization* (PSO) has been introduced [17-18]. PSO is characterized as a simple concept, easy to implement, and computationally efficient.

Theses features make PSO technique able to accomplish the same goal as GA optimization in a new and faster way. A number of very recent successful applications of PSO on various power system problems have been reported in literature [19-21]. Nevertheless, a new optimization method called "*Biogeography-Based Optimization*" (BBO) has been recently introduced [22]. BBO has common features with GA and PSO, but also it has different characteristics that distinguish it from other population-based optimization techniques. However, BBC method still has a long way to go to prove its validity as an efficient, global search technique. The objective of this paper is to enhance the stability of a SCG in a multi-machine system using fuzzy governor controller optimally designed by the PSO technique.

2. System under Study

The multi-machine system under consideration is shown in Fig. (1). It is a twelve-bus four-machine power system. The machine at bus 3 is a superconducting generator, while the other three machines are conventional generators. The four generating units are connected to four load areas as shown in the figure. Based on Park's d-q axis representation, each conventional machine is modelled by seven non-linear differential equations [23]. The order of SCG model is increased to nine to accommodate the double-screened rotor. Transmission lines are modeled using the π-method, and the loads are represented by constant impedances. Each conventional generator is equipped with a typical excitation system and a conventional power system stabilizer (PSS) having the transfer function $G_s(1+0.15s)/(1+0.015s)$ [24], where G_s is a gain. The block diagram of the excitation system is shown in Fig. (2). In this study, the mechanical input to each conventional generator is assumed constant. Meanwhile, a detailed representation for the prime mover of the SCG is used, because it is the main concern of this study. The SCG is driven by a three-stage steam turbine with reheat. The turbine is controlled by fast acting electro-hydraulic governors fitted to the main and interceptor valves, which are working in unison. Mathematical models for SCG, turbine and governors, along with the system parameters are given in the Appendix.

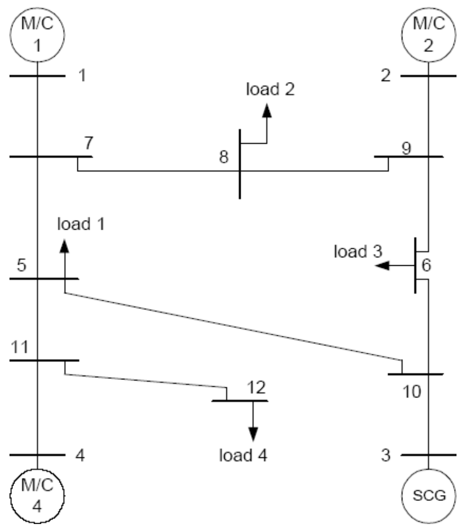


Fig. (1). Four-machine power system

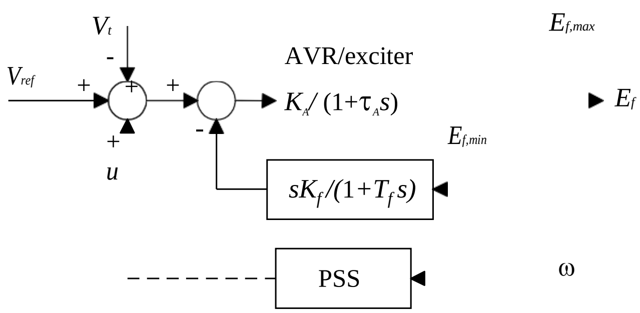


Fig. (2). Excitation system block diagram

3. Particle Swarm Optimization

Particle swarm optimization (PSO) models the behavior and cooperation aspects of individual members within a social system. In this model, the system is populated with individual particles, referred to as "swarm", representing possible solutions to the problem considered. Particles fly around in a multidimensional search space. During flight, each particle adjusts its position according to its own experience, and experience of neighbouring particles, making use of the best position encountered by itself and its neighbours. In PSO algorithm, each solution is represented as a particle in a swarm, having a position and velocity. Each position coordinate represents a parameter value. Thus, for an n-dimensional optimization, each particle has a position in n-dimensional space that represents a solution [18]. The PSO starts with generation of initial swarm particles, assigning a random position and a random velocity for each particle. Then, PSO algorithm evaluates each particle's fitness using a predefined fitness (objective) function. The position with the highest fitness value in the entire run is referred to as "global best position" (g_{best}). Meanwhile, each particle keeps track of its highest fitness value. The location of this value is called "personal best position" (p_{best}). The algorithm then proceeds by updating the velocity of each particle using its current velocity and its distance from g_{best} and p_{best} according to the following equation:

$$v_i^k = w^k v_i^{k-1} + c_1 r_1 (p_{best,i} - x_i^{k-1}) + c_2 r_2 (g_{best,i} - x_i^{k-1}) \tag{1}$$

i = 1, 2, 3,.................. m

v_i^k is the velocity of particle i at iteration k

x_i^k is the position of particle i at iteration k

r_1, r_2 are uniformly distributed random numbers in the range [0, 1]

c_1, c_2 are positive constants

w^k is the inertia weight at iteration k

m is the number of particles in a swarm

As originally developed, large inertia weight is recommended at initial stages of the search process to enhance the global exploration, while lower values of the inertia weight are preferred at final stages to improve local exploration. The inertia weight can be decreased either linearly over search iterations or in a non-linear form as follows [18]:

$$w^k = \alpha\, w^{k-1} \tag{2}$$

Where α is a decrement constant. Another important parameter of PSO procedure is the maximum velocity (V_{max}) of a particle in any given dimension. This parameter determines the resolution with which the search space is explored. After updating the velocities, the position of each particle is modified according to the following equation:

$$x_i^k = x_i^{k-1} + v_i^k \tag{3}$$

The algorithm proceeds by updating the best position of each particle according to its new position; the global best position is then updated as well. This procedure is repeated until a specified termination condition is met.

4. Fuzzy Logic Stabilizer

In this section, the determination of an efficient control signal, *u*, based on fuzzy logic is described. This signal is then introduced into the governor side of the SCG turbine as shown in Fig. (3).

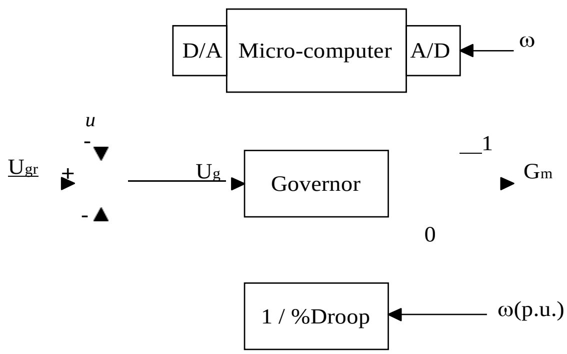


Fig. (3). The governor control system

Speed deviation, , and its derivative, $\dot{\omega}$, are chosen as input variables. Actual speed is the only signal to be measured. Then signal is determined, and $\dot{\omega}$ signal is computed as:

$$\dot{\omega}(k) = [\omega(k) - \omega(k-1)] / T_s \qquad (4)$$

where T_s is the sampling interval. Two scaling factors, K_A and K_B, are used to map and $\dot{\omega}$, respectively into their predefined universes of discourse, which are divided into seven overlapping fuzzy sets; named positive large "PL", positive medium "PM", positive small "PS", zero "ZE", negative small "NS', negative medium "NM", and negative large "NL". A non-linear (nearly bell-shaped) membership function is assigned for each fuzzy set such that if a crisp input "x" belongs to a set of range [a-b], width "d" and center "c", then its degree of membership μ_x, in this set is defined by the following function:

$$\mu_x = \begin{cases} (2(x-a)/d)^2 & \text{if a} \le \text{x} \le c \\ (2(b-x)/d)^2 & \text{if c} \le \text{x} \le b \\ 0 & \text{else} \end{cases} \qquad (5)$$

Table (1) shows the fuzzy rules that are assigned for the SCG system. Each entry in Table (1) represents a control rule, which takes the form: "IF is A, AND $\dot{\omega}$ is B, THEN *u* is C", where A, B, and C are fuzzy sets as defined by relation (5).

These fuzzy rules are individually applied on the fuzzified inputs, resulting in an output fuzzy set, for each rule, clipped to a degree defined as:

$$\mu_c(u_i) = \min(\mu_A(\omega), \mu_B(\dot{\omega})) \tag{6}$$

The aggregated fuzzy outputs are converted into a single crisp value using the "weighted average" defuzzification method, which gives the output control signal as:

$$u = K_u \frac{\sum_{i=1}^{m} \mu_c(u_i).u_i}{\sum_{i=1}^{m} \mu_c(u_i)} \tag{7}$$

where K_u is a scaling factor, m is the number of rules giving contribution to the fuzzy output at the sampling instant considered, and u_i is the center value of the fuzzy set in consequent i. According to the structure of fuzzy logic stabilizer described above, the number of fuzzy sets, to which an input value belongs at a time, depends on how much overlap between adjacent fuzzy sets is.

Table (1). Fuzzy logic control rules for SCG system

ω \ ***d*ω/*dt***	**NL**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PL**
NL	NS	PS	PM	PM	PM	PL	PL
NM	NS	NS	PS	PS	PM	PM	PL
NS	NM	NS	NS	PS	PS	PM	PM
ZE	NM	NM	NS	ZE	PS	PM	PM
PS	NM	NM	NS	NS	PS	PM	PM
PM	NL	NM	NS	NS	PS	PS	PS
PL	NL	NL	NM	NM	NS	NS	PS

5. PSO-Based Stabilizer Parameters Selection

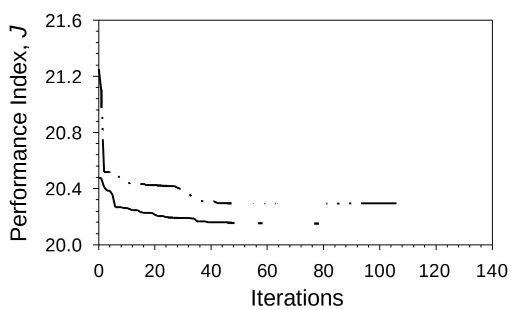
The tuning parameters of the fuzzy stabilizer are K_A, K_B and K_u. Additional twelve adjustable parameters (six for fuzzy sets, and six for $\dot{\omega}$ sets) are introduced to enhance the effectiveness of the proposed fuzzy stabilizer. Namely, d_1, d_2, d_3 and d_4, which stand for widths of fuzzy sets (LP, MP, SP, ZE) of , and C_2 and C_3 which stand for centers of fuzzy sets (MP, SP) respectively. Similarly, d'_1, d'_2, d'_3, d'_4, C'_2 and $C'3$ are assigned for $\dot{\omega}$ fuzzy sets. Therefore, we have now fifteen parameters (K_A, K_B, K_u, d_1, d_2, d_3, d_4, C_2, C_3, d'_1, d'_2 , d'_3, d'_4, C'_2, C'_3) to be optimally chosen. This task is achieved using PSO technique. First, a quadratic performance index is defined as:

$$J = \left(\sum_{k=1}^{N} [\omega(k)]^2\right)^{0.5} \tag{8}$$

where $\omega(k)$ is the deviations of the SCG speed from the steady state value. The problem of designing a fuzzy logic stabilizer is then transformed into an optimization problem, where PSO is utilized off-line to select the stabilizer parameters. The proposed stabilizer was designed at the loads and operating points of case #1 shown in Table (5). However, like many recursive and stochastic methods, PSO itself has a number of parameters to be properly specified. The main PSO parameters are the initial inertia weight, w^0, and the maximum allowable velocity, V_{max}. The initial inertia weight is set at 1, and V_{max} at 12.5% of the search space of each variable. The swarm size of PSO is chosen to be 60 particles. Other parameters are set as decrement constant α=0.98, and c_1= c_2 =2.

6. Simulation Results

In this study, the SCG exciter voltage and the mechanical input to all conventional generators were kept constant during transients. The optimization process was carried out in response to a three-phase to ground fault of 200-ms duration at bus 5 at the end of line 5-10. Variation of the performance index J with the number of iterations is shown in Fig. (4), which indicates that J converges to 20.2 after 120 iterations. The performance index J was recalculated when the conventional stabilizer is installed with the SCG instead of the fuzzy stabilizer. In this case, it was found J =21.1, which is less than that with the proposed fuzzy stabilizer. The optimal fuzzy stabilizer parameters selected by PSO are K_A=0.584, K_B=0.358, K_u=1.616. The optimized fuzzy sets for and ω have taken the shapes shown in Fig. (5).



-------- with linear and symmetrical functions

_____ with non-linear & unsymmetrical functions

Fig. (4). Convergence of performance index with different designs

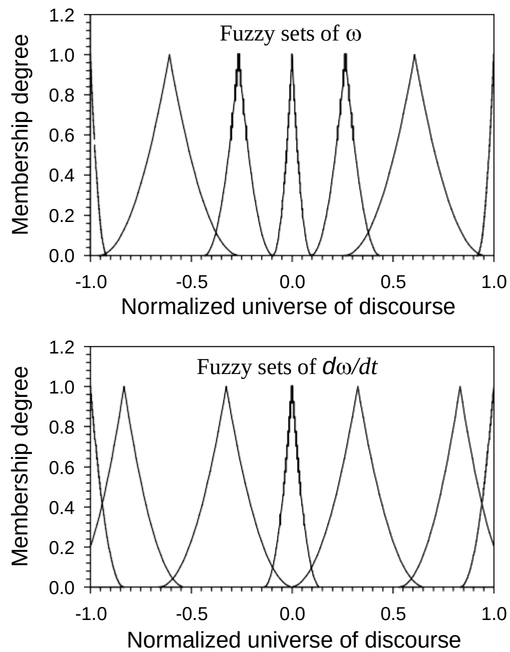


Fig. (5). Optimized fuzzy sets of ω and *d*ω/*dt*

Since there is no infinite-bus, machine 4 was taken as a reference unit. The rotor angles of the other machines are shown with respect to that of the reference unit. The multi-machine system performance was obtained at three situations. First, when the four generators are not equipped with stabilizers. Second, when each conventional generator is equipped with a conventional PSS, while the SCG is stabilized via a governor lead stabilizer [8]. Third, as in second, but the governor lead stabilizer is replaced with the governor fuzzy stabilizer designed above. The SCG performance is shown in Fig. (6), Fig. (7), and Fig. (8). These figures also show the performance of other machines in the system. Fig. (9) shows the system response to the same fault, but with loads and operating points given under case #2 in Table (5) in the Appendix. The simulation results show that the incorporation of the proposed PSO-based fuzzy stabilizer in the governor loop of the SCG leads to a significant improvement in the SCG performance and an appreciable increase in damping of the rotor oscillations with a reduction in the rotor first swing. This can clearly be noticed from Figs. (6a), (6c) and Fig. (7). Fig. (10) shows that the fuzzy stabilizer damps well the SCG oscillations when it swings against the other machines in the system. This gives an indication that the proposed stabilizer is able to damp multimode oscillations in the system under study.

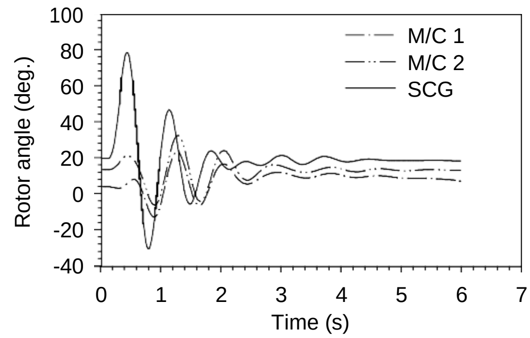


Fig. (6-a). System response to SC at operating point #1, all machines without stabilizer

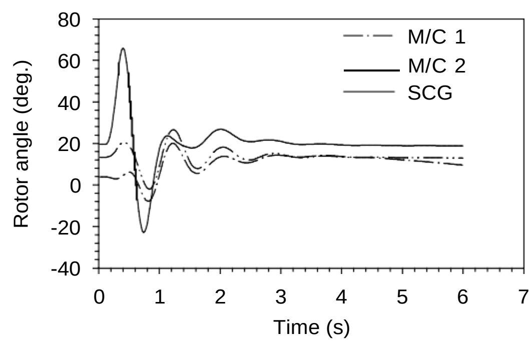


Fig. (6-b). System response to SC at operating point #1, conventional machines with PSS and SCG with lead stabilizer

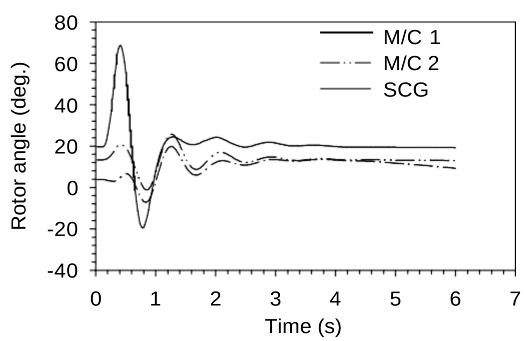


Fig. (6-c). System response to SC at operating point #1, conventional machines with PSS and SCG with fuzzy logic stabilizer

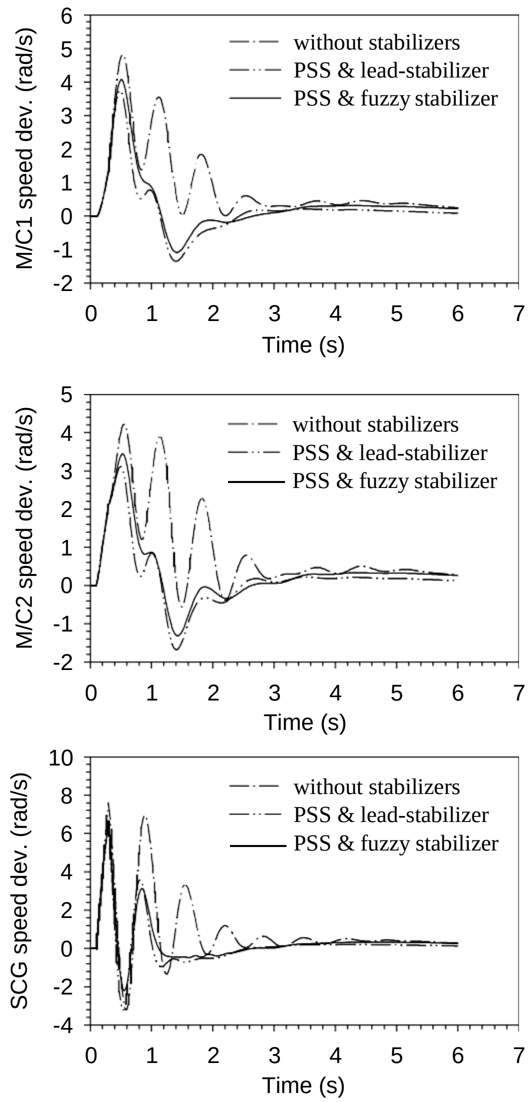


Fig. (7). System response to SC for 200 ms at operating point #1

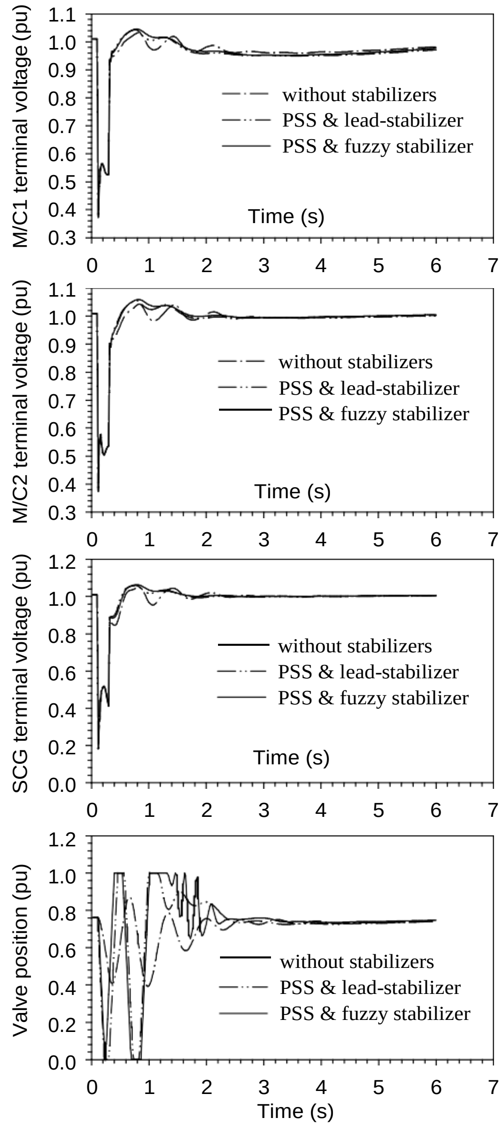


Fig. (8). System response to SC for 200 ms at operating point #1

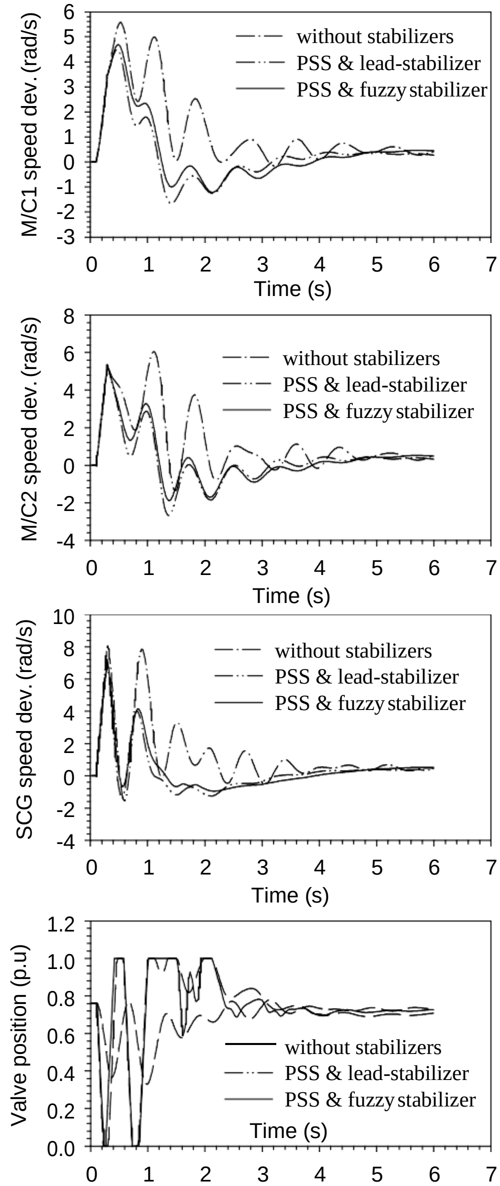


Fig. (9). System response to SC for 200 ms at operating point #2

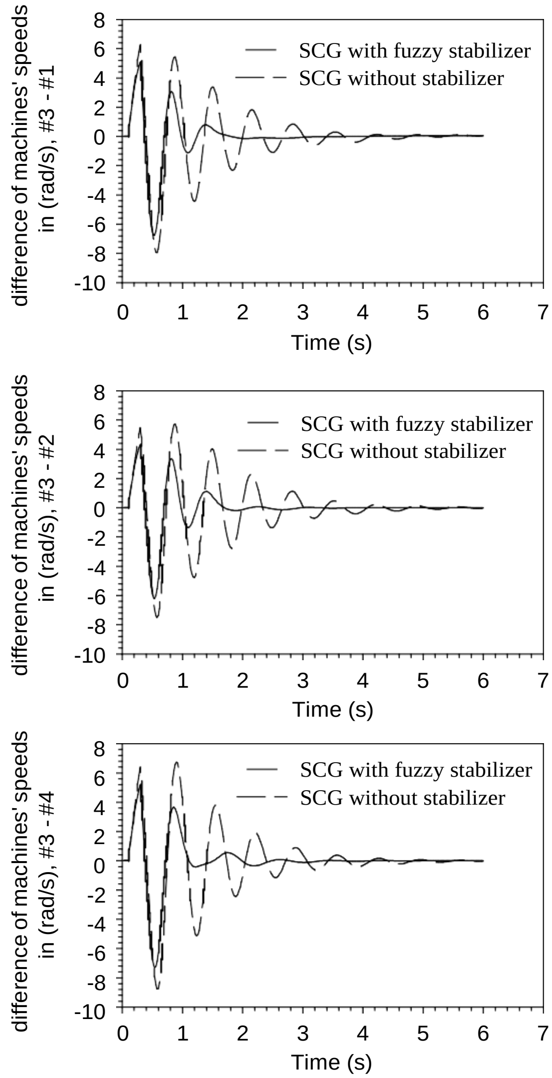


Fig. (10). System response to SC for 200 ms at operating point #1

7. Conclusion

This paper has proposed an approach for the design of a fuzzy logic stabilizer for transient performance improvement of a superconducting generator (SCG) operating in a multi-machine system. A set of fuzzy decision rules relating the SCG status, in terms of its speed deviation and acceleration, to the control action required was assigned based on previous experience with controller design. A performance index was defined, and then PSO technique was used to optimize a set of unknown stabilizer parameters at the specified loads. The results of non-linear simulation study show the effectiveness of the proposed PSO-tuned fuzzy stabilizer in damping the rotor oscillations and therefore enhancing the SCG stability.

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9. Appendix

The mathematical model of SCG [16]:

$$p\psi_f = \omega_o [V_f - i_f R_f] \quad (9)$$

$$p\psi_d = \omega_o [V_d + i_d R_a + \psi_q] + \psi_q \omega \quad (10)$$

$$p\psi_{D1} = -\omega_o i_{D1} R_{D1} \quad (11)$$

$$p\psi_{D2} = -\omega_o i_{D2} R_{D2} \quad (12)$$

$$p\psi_q = \omega_o [V_q + i_q R_a - \psi_d] - \psi_d \omega \quad (13)$$

$$p\psi_{Q1} = -\omega_o i_{Q1} R_{Q1} \quad (14)$$

$$p\psi_{Q2} = -\omega_o i_{Q2} R_{Q2} \quad (15)$$

$$p\delta = \omega \quad (16)$$

$$p\omega = \frac{\omega_o}{2H}[T_m - T_e] \quad (17)$$

$$T_e = \psi_d i_q - \psi_q i_d \quad (18)$$

P : derivative operator

ψ : flux linkage

ω_o : synchronous speed (rad/s)

ω : rotor speed deviation from synchronous speed (rad/s)

δ : rotor angle with respect to infinite bus

H : inertia constant

T_m : mechanical torque

The mathematical model of the turbine and governor system [16, 26]:

$$pY_{HP} = (G_M P_o - Y_{HP}) / \tau_{HP} \quad (19)$$

$$pY_{RH} = (Y_{HP} - Y_{RH}) / \tau_{RH} \quad (20)$$

$$pY_{IP} = (G_I Y_{RH} - Y_{IP}) / \tau_{IP} \quad (21)$$

$$pY_{LP} = (Y_{IP} - Y_{LP}) / \tau_{LP} \quad (22)$$

$$T_m = F_{HP} Y_{HP} + F_{IP} Y_{IP} + F_{LP} Y_{LP} \quad (23)$$

$$pG_M = (U_g - G_M) / \tau_{GM} \quad (24)$$

$$pG_I = (U_g - G_I) / \tau_{GI} \quad (25)$$

P_o : boiler steam pressure

Y : output of a turbine or reheat stage

τ : time constant of stage

G_M , G_I : main and interceptor valve positions
F : fractional contribution of the turbine stage into T_m
U_g : governor actuating signal
The definitions of variables and parameters not defined in the paper can be found in references [8, 25].
Parameters of SCG (M/C #3), turbine and governor systems (inductance and resistance values in p.u; time constants in seconds)

L_f= 0.541, L_d=L_q= 0.5435, L_{D1}=L_{Q1}= 0.2567, L_{D2}=L_{Q2}= 0.4225, L_{fd}=L_{fD1}=L_{dD1}=L_{dD2}=L_{D1D2}= 0.237, L_{fD2}= 0.3898, L_{qQ1}=L_{qQ2}=L_{Q1Q2}=0.237, τ_f=750, R_d=R_q= 0.003, R_{D1}=R_{Q1}=0.01008, R_{D2}=R_{Q2}=0.00134, H=3 s , τ_{GM} =τ_{GI} =0.1, τ_{HP} =0.1, τ_{RH} =10, τ_{IP} =τ_{LP} =0.3, P_o = 1.2 p.u. , F_{HP} = 0.26, F_{IP} = 0.42, F_{LP} = 0.32

Table (2). Parameters of conventional generators

Parameter symbol	M/C #1	M/C #2	M/C #4
L_d (p.u)	2.11	2.13	0.898
L_q (p.u)	2.02	2.07	0.646
M_{dF}=M_{dD}= M_{FD} (p.u)	1.955	1.88	0.658
M_{qQ} (p.u)	1.865	1.82	0.406
L_F (p.u)	2.089	2.12	0.724
L_D (p.u)	2.07	1.97	0.668
L_Q (p.u)	1.93	1.88	0.457
R_a (p.u)	0.0046	0.0029	0.0014
R_F (p.u)	0.00013	0.00092	0.00026
R_D (p.u)	0.02	0.018	0.012
R_Q (p.u)	0.024	0.0212	0.02
H (s)	2.32	2.52	5.15

Table (3). Parameters of excitation systems and PSS

Parameter Symbol	M/C 1	M/C 2	M/C 4
K_A	200	4	200
T_A (s)	0.3575	0.02	0.02
T_f (s)	1.0	0.05	1.0
K_f	0.0529	0.05	.01
$E_{f\,min}$ (p.u)	-5.73	0.0	0.0
$E_{f\,max}$ (p.u)	5.73	4.46	7.32
G_s	0.03	0.03	0.04

Table (4). Parameters of transmission lines in p.u

Bus #	***R***	**j*X***	**j*Y***
1-7	0.0	0.12	0.0
7-8	0.009	0.152	0.0688
8-9	0.088	0.1055	0.0982
9-2	0.0	0.12	0.0
9-6	0.009	0.152	0.0688
6-10	0.009	0.152	0.0688
10-3	0.0	0.12	0.0
10-5	0.0088	0.1055	0.0982
7-5	0.009	0.152	0.0688
5-11	0.009	0.152	0.0688
11-4	0.0	0.12	0.0
11-12	0.018	0.304	0.0344

Table (5). Loads and operating points

	***P* + j*Q* (p.u)**	
	Case #1	**Case # 2**
Load 1	-0.5 -j0.309	-0.8-j0.48
Load 2	-0.3 -j0.155	-0.3-j0.18
Load 3	-0.25-j0.155	-0.3-j0.18
Load 4	-0.25-j0.155	-0.3-j0.18
M/C 1	0.12 +j 0.058	0.2237+j0.14
M/C 2	0.2 +j0.04	0.5 +j0.111
M/C 4	0.235+j 0.154	0.235 +j0.2587
SCG	0.75 +j0.11	0.75 +j0.2037

تصميم أمثل لموازن غيمي المنطق لمولد فائق التوصيل في نظام متعدد الآلات باستخدام طريقة السرب

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