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PARTICLE SWARM-AIDED DESIGN OF A FUZZY LOGIC-BASED CONTROLLER FOR SUPERCONUCTING GENERATOR

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ABSTRACT:

An approach is suggested in this paper for the design of a fuzzy logic-based governor controller as a possible mean to improve superconducting generator (SCG) stability under transient conditions while it is connected to a very large power system (an infinite-bus). In this approach, the stabilizing signal is based on the instantaneous speed deviation and acceleration of the superconducting generator and on a set of simple control rules. Meanwhile, a tuning parameter is introduced to generate the appropriate control rules, and thus increase the effectiveness of the fuzzy logic-based controller. Particle swarm optimization (PSO) technique is used to search for optimal settings of the fuzzy controller parameters. Simulation results, compared with those using a conventional controller, show that the proposed, PSO-tuned fuzzy controller leads to a significant improvement in the SCG system performance over a range of operating conditions.

في هذا البحث تم اقتراح طريقة لتصميم حاكم - مؤسس علي المنطق الغيمي – كوسيلة ممكنة لتحسين استقرار المولد فائق التوصيل تحت الظروف العابرة عند توصيله بنظام قوى لانهائي. في هذه الطريقة، تؤسس الاشارة الموازنة على القيم اللحظية لكل من الانحراف في سرعة المحرك (عن سرعة التزامن) و معدل التغير الزمني فيها، وكذلك على مجموعة من قواعد التحكم البسيطة. تم تقديم "باراميتر ضبط" للمساعدة في تحديد قواعد التحكم المناسبة، وبالتالي زيادة فعالية الحاكم المقترح. وقد استخدمت طريقة السرب للأمثلة للبحث عن أفضل القيم لثوابت هذا الحاكم. توضح نتائج المحاكاة – مقارنة مع الحاكم التقليدي – أن الحاكم الغيمى المقترح والمصمم بواسطة طريقة السرب يؤدي الى تحسن واضح في أداء واستقرارالمولد فائق التوصيل على مدى من أحوال التشغيل المختلفة.

Keywords : *superconducting generator, Fuzzy logic control, Transient Stability, Particle swarm optimization.*

I. INTRODUCTION

The ability of superconductors to carry large d.c. currents without resistive losses has given rise, since the early 1970's, to considerable international efforts to develop large super-conducting generators [1-3]. The advent of high temperature superconducting (HTS) wires has increased the potential for effective applications of superconductivity in power system industry. Many R&D projects on SCGs have been conducted at utility companies, power plant manufacturers and other organization toward a 200 MW class pilot-machine [4-8].

The application of superconductors to the field windings of SCGs offers these machines a number of potential advantages such as increased efficiency, reduced size and weight, low synchronous reactance and hence improved steady state stability. SCGs have complex structures and require materials different from those used in conventional generators, and some problems (and cost and reliability issues) remain to be solved before utility sized SCGs can be successfully designed and tested. However, a few experimental SCGs of significant power rating have now been constructed, the largest having been recently developed by the Japanese. It passed factory tests successfully with a measured output of 78.7 MW [4].

SCGs also have characteristics that degrade their stability when connected to the power system. Therefore, an important aspect of the design of superconducting generators concerns stability following major system disturbances. The extremely long field winding time constant and the shielding effect of the rotor screens make the damping of mechanical oscillations of SCG very difficult using excitation control. Governor control hence is crucial for stability enhancement of SCGs. The availability of electro-hydraulic governors and fast turbine valving has now made it possible to obtain very fast turbine response.

The work reported in [9] has shown that, the machine's performance can be improved by introducing a conventional (lead) stabilizer in the governor feedback loop, activated by the speed error signal. The conventional stabilizer parameters are fixed to ensure optimum performance at a specific operating point. However, because of the high nonlinearity of the machine/power system combination, the stabilizer's performance tends to be degraded whenever the system operating conditions move significantly away from the specific point.

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 such as [10-12]. 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 controller 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 fuzzy logic controllers [13-14].

More recently, a new heuristic search method called *particle swarm optimization* (PSO) has been introduced [15].

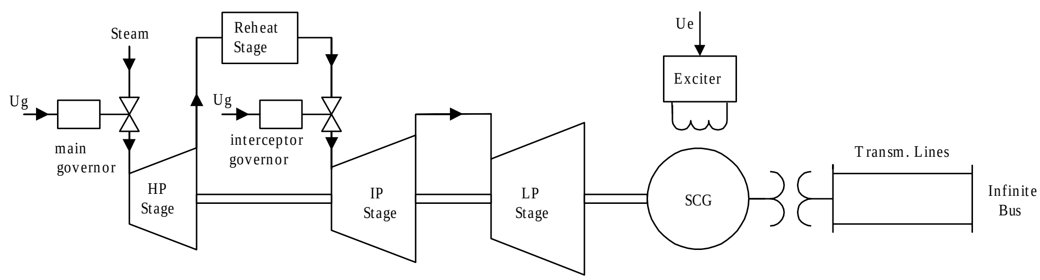


Fig.1 Superconducting turbo-generator system

Generally, 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 [16-18]. This paper presents an approach to enhance stability of a SCG-infinite bus power system using a fuzzy-based governor controller optimally designed by the PSO technique.

II. SYSTEM DESCRIBTION

The system considered is a single SCG connected to an infinite bus power system as shown in Fig. 1. The SCG has superconducting field windings in the rotor, surrounded by two separate screens. The inner screen, which has a relatively long time constant, shields the superconducting field windings from external, time varying magnetic fields. The outer screen serves as a damper and has a substantially shorter time constant than that of the inner screen [19]. The SCG is driven by a three-stage steam turbine with reheat between the high pressure and intermediate pressure stages. The turbine is controlled by fast acting electro-hydraulic governors fitted to the main and interceptor valves, which are working in unison. The exciter voltage, U_e , of the SCG is kept constant during transients. The mathematical model is given in Appendix A, while the parameter values and physical constraints are given in Appendix B.

III. FUZZY LOGIC-BASED CONTROLLER

The control objective is to generate a supplementary stabilizing signal based on fuzzy logic, and then add it to the governor loop as shown in Fig. 2, in order to enhance the damping of the rotor oscillations after disturbances, and hence to improve the transient and dynamic performance of the system. The generator condition is defined at every sampling time in terms of its speed deviation and scaled acceleration, [ω, $F_* \, d\omega/dt$], where F is a predefined scaling factor. This condition represents a certain point, Z, in the [ω, $F_* \, d\omega/dt$] phase plane as shown in Fig. 3. The polar displacement $D(k)$ of this point from the origin, and the corresponding angle $\theta(k)$ are computed as:

$$D(k) = [(\omega(k))^2 + (F * \dot{\omega}(k))^2]^{0.5} \tag{1}$$

$$\theta(k) = \tan^{-1}(F * \dot{\omega}(k) / \omega(k)) \tag{2}$$

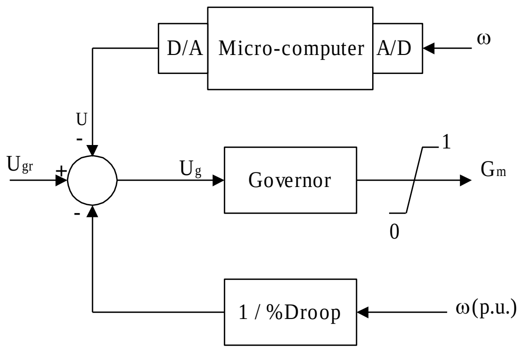


Fig.2 The governor control system

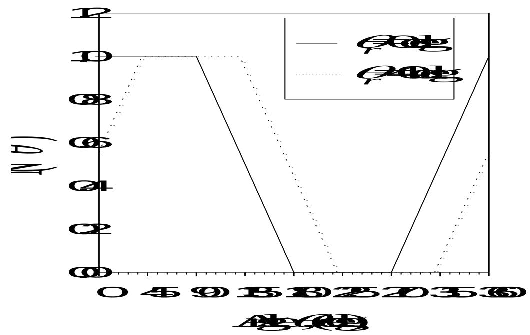


Fig.4 Membership function as defined in (3)

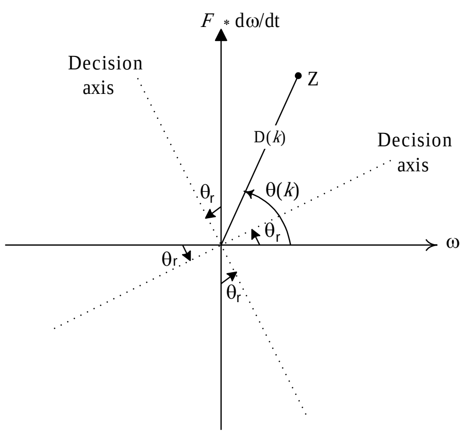


Fig. 3 Definition of SCG condition in phase plane

The phase plane is divided into four quadrants. Each quadrant has simple control rules according to the degree of deceleration and/or acceleration control required to restore the machine condition, after the disturbance, to the origin of the phase plane as soon as possible with an acceptable performance. Two fuzzy membership functions, shown in Fig. 4, N(θ) associated with the desired deceleration and P(θ) associated with the desired acceleration, are defined in terms of the polar angle defined by (2) to reflect the actions of the control rules. The defining relations for N(θ) and P(θ) are:

$$N(\theta)=\begin{cases} 1 & \\ (\theta_1-\theta)/(\theta_1-\theta_i) & \\ 0 & \\ (\theta-\theta_2)/(\theta_f-\theta_2) & \end{cases} \quad \text{for} \quad \begin{cases} \theta \le \theta_i \\ \theta_i < \theta \le \theta_1 \\ \theta_1 < \theta \le \theta_2 \\ \theta_2 < \theta \le \theta_f \end{cases} \qquad (3)$$

$$P(\theta)=1-N(\theta) \qquad \text{for all } \theta \qquad (4)$$

The angles θ_i , θ_1 , θ_2 , and θ_f are normally fixed at 90, 180, 270 and 360 degrees respectively with excitation control of conventional generators [11]. The fuzzy membership functions described by (3) and (4) can be portrayed in terms of a pair of what can be termed "decision axes," shown in Fig. 3, on the phase plane. The author found that, for best results, the angles θ_i to θ_f should again progress in 90 degree steps, but that an offset angle θ_r between the phase plane axis set and the decision axis set should be introduced as shown in Fig. 3 [20]. This offset angle, which can be regarded as a new tuning parameter, is hence introduced when designing the fuzzy logic controller. It specifies the best location for each quadrant with its particular control rules on the phase plane. In effect, the offset angle rotates the decision axis set anti-clockwise until the minimum of a predefined performance index is obtained. This has the effect in turn of changing the final shapes of fuzzy membership functions over the whole universe of discourse, i.e. another set of control rules is generated according to the degree of rotation. The resulting two membership functions then lead to a governor control signal, U(k), given by:

$$U(k) = G(k)\,[\,N(\theta(k)) - P(\theta(k))]\,U_{max} \qquad (5)$$

where G(k) is the gain whose value is defined as:

$$G(k) = D(k)/D_r \qquad \text{for } D(k)<D_r \qquad (6)$$

$$G(k) = 1 \qquad \text{for } D(k)\ge D_r \qquad (7)$$

The parameter D_r is a set value of polar displacement at which the gain is required to saturate at unity.

IV. FUZZY CONTROLLER PARAMETERS SELECTION

In this section, the fuzzy controller parameters F, D_r , and θ_r are optimized using the PSO technique. For this purpose, the following performance index, J , is defined:

$$J=\sum_{k=1}^{N}\{[kT.\omega(k)]^2+[\Delta\delta(k)]^2+[\Delta G_M]^2\} \qquad (8)$$

where $\Delta\delta(k)=(\delta(k)-\delta_o)$ denotes the deviations (in radians) of the instantaneous rotor angle from its steady state value, δ_o, and $\Delta G_M(k)=(G_M(k)-G_{Mo})$ is the deviation of the instantaneous governor valve position $G_M(k)$ from its value in the steady state, G_{Mo}. As is seen, the speed deviation, $\omega(k)$, is weighted by the elapsed time kT. Thus, a low value of J corresponds to a small settling time, a small steady state error, and small overshoots in rotor speed, rotor angle and valve position.

The PSO algorithm iteratively updates the velocity of each particle using its current velocity and its distance from "global best position" (g_{best}) and "personal best position" (p_{best}) according to the following equation:

$$v_i^k = w^k v_i^{k-1} + c_1 r_1 (p_{best,i} - x_i^{k-1}) + c_2 r_2 (g_{best,i} - x_i^{k-1}) \tag{9}$$

where:

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

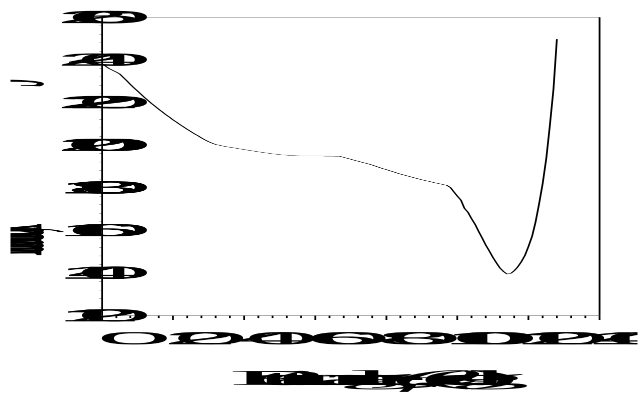
w^k is the inertia weight at iteration k, decreasing as $w^k = \alpha\, w^k$.

m is the number of particles in a swarm, and α is a decrement constant.

PSO technique 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}. w^0 is set at 1, and V_{max} at 12.5% of the search space for each tuning parameters. The swarm size is chosen to be 60 particles. Other parameters are set as decrement constant α=0.98, and $c_1 = c_2 = 2$.

V. SIMULATION RESULTS

The author's previous attempts to develop the fuzzy controller presented here were made by changing the width of acceleration sector (from θ_1 to θ_2) with various values of θ_i and/or θ_f. The performance index was evaluated, in all cases, in response to a three-phase to ground fault of 120-ms duration with the operating point (P_t=0.8 p.u, Q_t=0.6 p.u). From these investigations, it was noticed that the introduction of θ_r in the manner shown in the paper causes a significant improvement in the system performance as shown in Fig.5 [20].



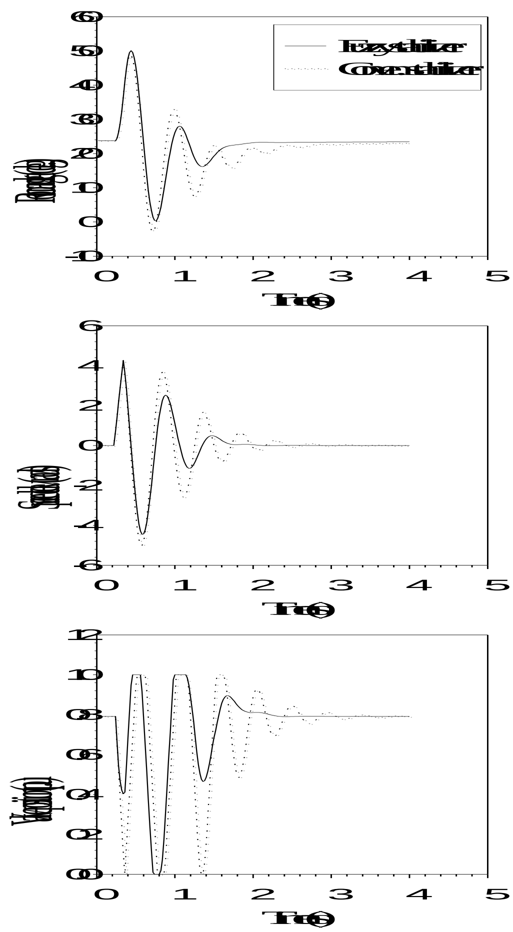


Fig.5 Performance index vs. θ_r for response to 3-phase SC at P_t=0.8 pu, Q_t=0.6 pu

Variation of the performance index *J* with the number of iterations made by the PSO technique at different seed values is shown in Fig. 6. The optimal values selected by PSO for *F*, D_r , and θ_r are 0.327, 7.735, and 113.54^o respectively. The optimized membership functions N(θ) and P(θ) take then the forms shown in Fig. 7.

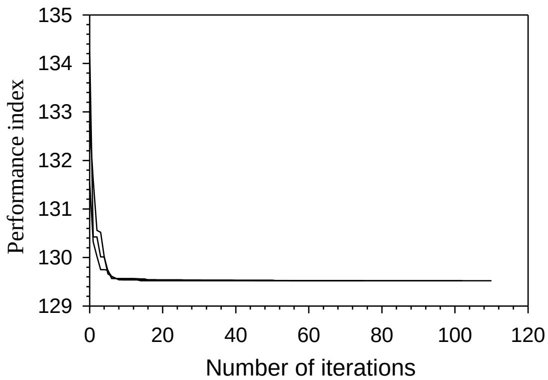


Fig. 6 Performance index convergence with iterations at different seed values

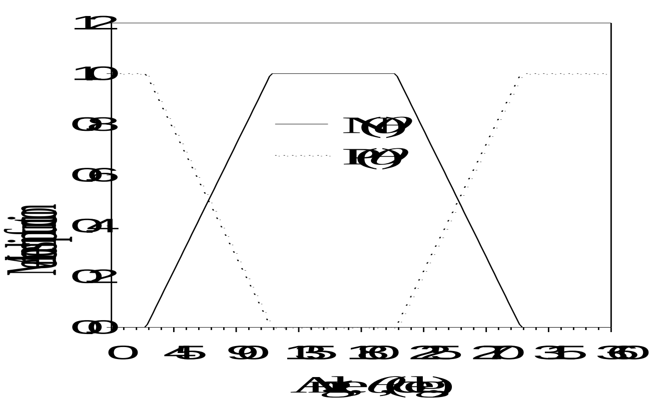


Fig. 7 Optimized membership functions at θ_r = 113.5^o

Performance of the SCG system with the designed fuzzy controller following a 3-phase short circuit fault, at the operating points [(P_t, Q_t) = (0.8,0.6), (0.9, 0) p.u], is shown in Figs. 8 and 9 respectively. Figure 10 shows the system response to a 5% pulse change in the governor set point at the first loading conditions.

The simulation results illustrate that, the PSO-based fuzzy stabilizer brings about a significant improvement in the system behavior and a considerable reduction in the valve movements and rotor oscillations. The results thus demonstrate clearly that, for the system and disturbances studied, the proposed PSO-tuned fuzzy stabilizer can provide useful performance improvements with respect to the conventional lead stabilizer examined [15].

It is worthy to mention here that there is no easy physical interpretation of the angle θ_r , except that it is an angular displacement between the phase plane axes, to which the system conditions, i.e. [ω and F_* dω/dt] are referred, and the

Fig. 8 Response to a 3-phase s.c. at P_t=0.8 pu, Q_t=0.6 pu

decision axes which determine the type of control action to be taken. The effect of re-orientating the decision axes can be illustrated by considering a typical operating condition e.g. shaft speed increasing (i.e. F_* dω/dt positive). Assuming constant gain G(*k*), with no re-orientation, (i.e. θ_r= 0^o), any negative speed deviation (shaft speed minus synchronous speed) is enough to cause the commencement of changes in the control variables, N(θ) and P(θ), and hence in U(*k*) according to Fig. 3 and equations (3) , (4) and (5). With re-orientation by a relatively small angle (e.g. θ_r= 20^o), an amount of negative speed deviation can occur, such that θ, which is defined by (2), is less than or equal to (90^o + θ_r), before N(θ), P(θ), and U(*k*) are affected. In practice, it has been found that θ_r values of up to about 114^o are desirable. With large θ_r, substantial changes in the acceleration and speed deviation conditions for a particular control action obviously occur. Also, with large θ_r , a radical change in the control action occurs for certain ranges of speed deviation and acceleration. For example, when θ_r is set at 113.5^o, θ values of up to 23.5^o cause accelerating control action, as opposed to a decelerating control action when θ_r is set at 0 degree.

Fig. 9 Response to a 3-phase s.c. at P_t=0.9 pu, Q_t=0 pu

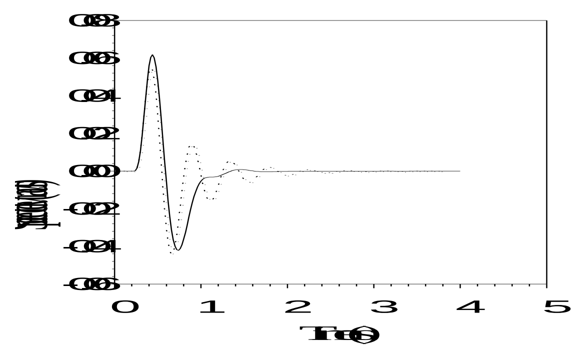
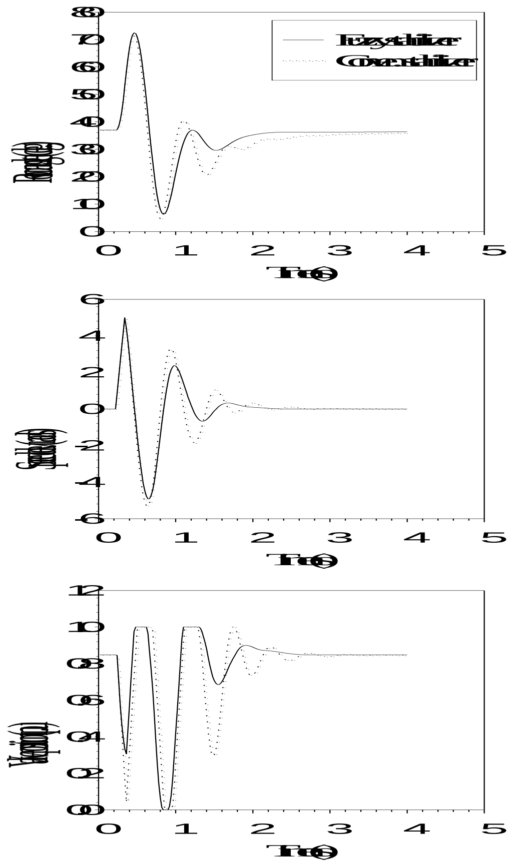


Fig. 10 Response to a 5% pulse in U_{gr} at P_t=0.8 pu, Q_t=0.6 pu

VI. DAMPING AND SYNCHRONIZING TOURQUES ANALYSIS

In this section, effects of the designed fuzzy stabilizer and the conventional stabilizer [21] on the SCG dynamic performance are investigated using the concept of damping and synchronizing torques, which was initially introduced by Demello and Concordia [22]. This concept indicates that, at any given frequency of rotor oscillations, there exists oscillatory electrical torque acting on the rotor which has the same frequency and whose amplitude is proportional to the amplitude of the oscillations. The change in this torque ΔT_e can be divided into two components: one is in time phase with, and proportional to the rotor angle deviation $\Delta\delta$. This is called the "synchronizing torque". The other, which is in time phase



with and proportional to the rotor speed deviation ω is called the "damping torque". Therefore, the change in electrical torque can be written as follows:

$$\Delta T_e = K_s \Delta\delta + K_d \omega \tag{10}$$

where K_s and K_d are the synchronizing and damping coefficients respectively. It is now well recognized that, machine stability is highly degraded if there is lack of either or both of synchronizing and damping torques. The values of K_s and K_d are determined from the time responses of electrical torque, rotor angle and rotor speed, using the technique explained in [23]. In that technique, the error between the actual torque deviation and that obtained by summing the damping and synchronizing torque components is defined as:

$$E(t) = \Delta T_e(t) - [K_s \Delta\delta(t) + K_d \omega(t)] \tag{11}$$

The error squares can be summed over the simulation time period. Minimizing this summation with respect to K_s and K_d yields the following dependent algebraic equations:

$$\sum_n \Delta T_e \Delta\delta = K_s \sum_n (\Delta\delta)^2 + K_d \sum_n \omega\Delta\delta \tag{12}$$

$$\sum_n \Delta T_e \omega = K_d \sum_n \omega^2 + K_s \sum_n \omega\Delta\delta \tag{13}$$

Solving the equations (12) and (13) gives the values of K_s and K_d, where n is the discrete-simulation time. A summarized comparison of the PSO-tuned fuzzy stabilizer and conventional stabilizer [21] is shown in Table 1.

From this table, it can also be concluded that, the PSO-tuned fuzzy stabilizer outperforms the conventional stabilizer at the operating points studied. It provides the SCG system with higher levels of damping and synchronizing torques.

Table 1: Comparison of PSO-tuned fuzzy stabilizer and conventional stabilizer

(P_t, Q_t) p.u	**(0.8, 0.6)**			**(0.9, 0)**	
	J	**K_d**	**k_s**	**K_d**	**k_s**
Fuzzy stabilizer	**129.5**	**0.017**	**2.035**	**0.019**	**1.435**
Conventional stabilizer [21]	**261.7**	**0.014**	**2.011**	**0.015**	**1.412**

VII. CONCLUSION

The paper has described the application of a fuzzy logic-based approach for stability enhancement of superconducting generators. In this approach, a new parameter (rotation angle θ_r) was introduced to enhance the effectiveness of the fuzzy controller in damping the mechanical oscillations of the system studied over a range of operating conditions and disturbances. A PSO technique was used to optimize the set of unknown controller parameters. Results of nonlinear simulation studies show the effectiveness of the proposed controller in enhancing SCG stability.

APPENDIX A

The mathematical model of the SCG:

$$p\psi_d = \omega_o[V_d + i_d R_a + \psi_q] + \psi_q \omega \tag{A1}$$

$$p\psi_q = \omega_o[V_q + i_q R_a - \psi_d] - \psi_d \omega \tag{A2}$$

$$p\psi_{D1} = -\omega_o i_{D1} R_{D1} \tag{A3}$$

$$p\psi_{Q1} = -\omega_o i_{Q1} R_{Q1} \tag{A4}$$

$$p\psi_{D2} = -\omega_o i_{D2} R_{D2} \tag{A5}$$

$$p\psi_{Q2} = -\omega_o i_{Q2} R_{Q2} \tag{A6}$$

$$p\psi_f = \omega_o[V_f - i_f R_f] \tag{A7}$$

$$p\delta = \omega \tag{A8}$$

$$p\omega = \frac{\omega_o}{2H}[T_m - T_e] \tag{A9}$$

$$T_e = \psi_d i_q - \psi_q i_d \tag{A10}$$

ω_o: synchronous speed

ω: rotor speed deviation with respect to synchronous speed

The mathematical model of the turbine and governor system:

$$pY_{HP} = (G_M P_o - Y_{HP}) / \tau_{HP} \tag{A11}$$

$$pY_{RH} = (Y_{HP} - Y_{RH}) / \tau_{RH} \qquad \text{(A12)}$$

$$pY_{IP} = (G_I Y_{RH} - Y_{IP}) / \tau_{IP} \qquad \text{(A13)}$$

$$pY_{LP} = (Y_{IP} - Y_{LP}) / \tau_{LP} \qquad \text{(A14)}$$

$$pG_M = (U_g - G_M) / \tau_{GM} \qquad \text{(A15)}$$

$$pG_I = (U_g - G_I) / \tau_{GI} \qquad \text{(A16)}$$

The output mechanical torque is given as:

$$T_m = F_{HP} Y_{HP} + F_{IP} Y_{IP} + F_{LP} Y_{LP} \qquad \text{(A17)}$$

G_M and G_I : main and interceptor valve positions
U_g: governor actuating signal
The definitions of variables not defined in the paper can be found in references [9], [21] cited above.

APPENDIX B

The parameters of the system studied (all inductance and resistance values in pu and all time constants in seconds) are:
Superconducting generator parameters [21]:
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 kW.s/kVA
Transformer and transmission line parameters:
X_T=0.15, R_T=0.003, X_L=0.05, R_L=0.005
Turbine and governor parameters:
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
Valve position and movement constraints are defined by:
$0 \le (G_M, G_I) \le 1$ and $-6.7 \le (pG_M, pG_I) \le 6.7$

REFERENCES

[1] J. H. Parker, Jr., and R. A. Towne, "Design of large superconducting turbine generators for electric utility application", IEEE Trans. Power Apparatus and Systems, vol. 98, pp. 2241-2250, 1979.

[2] J. L. Smith, Jr., "Overview of the development of superconducting synchronous generator", IEEE Trans. Magnetics, vol. 19, pp. 522-528, 1983.

[3] N. Maki, K. Yamaguchi, M. Takahashi, and R. Shiobara, "Development of superconducting AC generator", IEEE Trans. Magnetics, vol. 24, no. 2, pp.792-795, 1988.

[4] T. Shimada, M. Shibuya, R. Takahashi, Y. Imai, et. al., "Recent progress on 70 MW class superconducting generators", IEEE Trans. Applied Superconductivity, vol. 9, no. 2, pp. 1189-1192, 1999.

[5] H. Tsukiji, T. Hoshino, and I. Muta, "Output power limit of 200 MW class brushless super-conducting generator excited with magnetic flux pump", IEEE Trans. Applied Superconductivity, vol. 11, no.1, pp.2335-2338, 2001.

[6] K. Amm, "100 MVA HTS Generator Development Update", DOE HTS Wire Workshop, January 19-20, 2005. Available: http://events.energetics.com/wire05/

[7] M. Maki, "Design study of high-temperature superconducting generators for wind power systems", Journal of Physics: Conf. Ser. 97 012155 (6pp), 2008.

[8] K. F. Goddard, B. Lukasik, and J. K. Sykulski, "Alternative Designs of High-Temperature Superconducting Synchronous Generators", IEEE Trans. Applied Superconductivity, vol. 19, no.6, pp. 3805-3811, 2010.

[9] M. A. A. S. Alyan and Y. H. Rahim, "The role of governor control in transient stability of superconducting turbo-generators", IEEE. Trans. Energy Conversion, vol. 2, no. 1, pp. 38–46, 1987.

[10] M.A.M. Hassan, O.P. Malik, and G.S. Hope, "A fuzzy logic based stabilizer for a synchronous machine", IEEE Trans. Energy Conversion, vol. 6, no. 3, pp. 407-413, 1991.

[11] T. Hiyama, "Robustness of fuzzy logic power system stabilizers applied to multi-machine power system", IEEE Trans. Energy Conversion, vol. 9, no. 3, pp. 451-459, 1994.

[12] K.A. El-metwally and O.P. Malik, "Fuzzy logic power system stabilizer", IEE Proc., Pt.C., vol. 142, no. 3, pp. 277-281, 1995.

[13] J. Wen, S. Cheng; O. P. Malik, "A synchronous generator fuzzy excitation controller optimally designed with a genetic algorithm", IEEE Trans. Power Systems, vol. 13, no. 3, pp. 884-889, 1998.

[14] R. A. F. Saleh, "Genetic Algorithm-Tuned Fuzzy Logic-Based Governor Controller for a Fully Superconducting Generator", Proceeding of the Ninth International Middle East Power Systems Conference (MEPCON 2003), Shebin El-Kom, Egypt, pp. 125-130, December 16-18, 2003.

[15] R. Eberhart and Y. Shi., "Particle swarm optimization: developments, applications and resources", Proc. the 2001 Congress on Evolutionary Computation, vol. 1, pp.81-86, 2001.

[16] M. A. Abido, "Optimal design of power system stabilizers using particle swarm optimization", IEEE Trans. Energy Conversion, vol. 17, no. 3, pp. 406-413, 2002.

[17] Z. L. Gaing, "Particle swarm optimization to solving the economic dispatch considering the generator constraints", IEEE Trans. Power Systems, vol. 18, no. 3, pp.1187-1195, 2003.

[18] A. A. Abou El-Ela, T. Fetouh, M. A. Bishr, and R.A.F. Saleh, "Power systems operation using particle swarm optimization technique", Electric Power Systems Research 78, pp. 1906-1913, 2008.

[19] P. J. Lawrenson, T. J. E. Miller, J. M. Stephenson, and A. H. M. S. Ula, "Damping and screening in the synchronous superconducting generator," Proc. IEE, vol. 123, no. 8, pp. 787–794, 1976.

[20] R. A. F. Saleh and H. R. Bolton, "A fuzzy logic based controller for a superconducting generator," in Proceedings of 34th Universities Power Engineering Conference, UPEC'99, vol. 1, pp. 1–4, 1999.

[21] G. A. Morsy, A. Kinawy, and S. M. Osheba, "Frequency domain analysis of a superconducting generator," Electric Power Systems Research 30, pp. 107–113, 1994.

[22] F. P. Demello, and C. Concordia, "Concepts of synchronous machine stability as affected by excitation control", IEEE Trans. Power Apparatus and Systems, vol. 88, no. 4, pp.316-329, 1969.

[23] R. T. H. Alden, and A. A. Shaltout, "Analysis of damping and synchronizing torques", IEEE Trans. Power Apparatus and Systems, vol. 98, no. 5, pp.1696-1700, 1979.