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Stability Improvement of a Fully Superconducting Generator by Fuzzy Logic Control

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Abstract. Fully superconducting generator (FSG) is one of the promising applications of superconductors in electric power sector. Meanwhile, transient stability of FSG is an important issue in developing this new machine. An approach is suggested in this paper for the design of a fuzzy logic governor controller (FLC) as a possible mean to improve the FSG stability under transient conditions. In this approach, unsymmetrical non-linear membership functions are used, while the number of FLC parameters to be properly designed is 15 parameters, including scaling factors for input and output variables along with widths and centers of fuzzy sets of input variables. A genetic algorithm is used to optimally choose all these parameters. Simulation results show that the proposed FLC leads to a significant improvement in the transient stability and performance of a FSG connected to an infinite-bus.

Keywords: Fully superconducting generator, Fuzzy logic control, Genetic algorithms, Transient stability.

List of Symbols

P	: Derivative operator w.r.t time.
v, i	: Voltage and current.
L_T	: Transformer self inductance.
R_T	: Transformer resistance.
L_L	: Transmission line self inductance.
R_L	: Transmission line resistance.
R_f	: Resistance of field winding.
M_{fd}	: Mutual inductance between armature and field windings.
H	: Inertia constant.
T_m	: Mechanical torque.
T_e	: Electromagnetic torque.
P_t	: Active power at generator terminal.
Q_t	: Reactive power at generator terminals.
P_o	: Boiler steam pressure.
Y	: Output of a turbine or reheat 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.
ψ	: Flux linkage.
ω_o	: Synchronous speed.
ω	: Speed deviation from synchronous speed.
δ	: Rotor angle with respect to infinite bus.
τ	: Time constant of stage.

1. Introduction

Although copper and aluminum have met most our needs for decades, the demand for conservation and more efficient use of electricity has brought renewed focus on superconductors. The application of superconductors in the field winding of a superconducting generator (SCG) appears to offer this machine a number of potential advantages such as higher efficiency, small size and weight, low synchronous reactance and hence improved steady state stability. On the other hand, the recent development of very low-loss, ultra-fine filament superconducting a.c. wires was the motive for developing another type of superconducting generators, called FSG in which both the field and armature windings are superconducting [1]. Compared with SCG, FSG has more potential to increase efficiency and decrease size and weight.

However, FSG suffers from instability when connecting to the grid [2]. Also, this machine needs current limiting devices to prevent both of the armature and the field windings from quenching during severe fault condition [3]. The characteristics of FSG connected to a power system under many kinds of conditions must be understood exactly, since power system apparatus must be highly reliable. The main difficulty in operating the FSG with a power system is its very slow response. As the field time constant is extremely large, the excitation system is not able to change quickly the field current to restore the FSG stability. Previous studies [4-6], however, have shown that the machine stability along with its transient performance could be highly improved using governor control techniques.

Recently, fuzzy logic control [7] has emerged as one of the most fruitful research areas, and many applications for enhancing power system stability have been reported in literature [8-11]. Fuzzy logic controller (FLC) is essentially a multi-parameter controller, whose performance depends on the selected shape of membership functions, rule base and scaling factors. The work described in this paper is an attempt to employ the utmost power of the well-known FLC for enhancing the FSG stability. To do so, an approach is proposed and used in the design of the controller. This approach is a rather different from that used in [6], and mainly based on unsymmetrical non-linear membership functions for input variables as explained later on in this paper.

2. System Description

A FSG-infinite bus power system, shown in Fig.1, is considered in this study. Two superconducting fault current limiters (CL1, CL2) are connected in parallel and placed between the high-voltage side of the step-up transformer and the sending-end of the transmission line. In normal operation, one of the current limiters is connected to the line, and the other is stand-by and disconnected from the line. The FSG is driven by a three-stage steam turbine, which is controlled by fast acting electro-hydraulic governors fitted to the main and interceptor valves. The mathematical model of the system under study and parameter values are given in the Appendix.

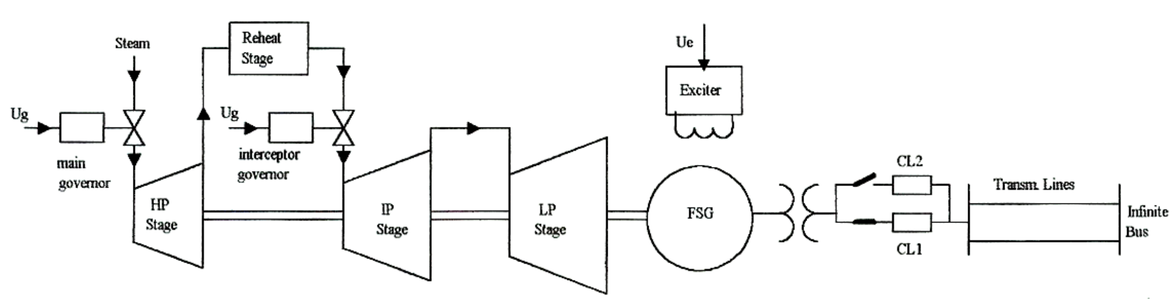


Fig. (1). Fully superconducting turbo-generator.

3. Design Procedure for a Fuzzy Logic Controller

The procedure commonly used in designing a FLC can be summarized as follows:

1. Identification of the FLC input and output variables based on understanding dynamics of the system under study.
2. Defining a universe of discourse for each variable, and a number of partitions (fuzzy subsets) within it, assigning each a linguistic label.
3. Defining a membership function for each fuzzy subset.
4. Choosing appropriate scaling factors for the input and output controller variables.
5. Deciding a defuzzification technique to convert fuzzy values into crisp values.
6. Forming the fuzzy control rules, which assign the fuzzy relationships between the input and output fuzzy subsets.

When the FLC is implemented, the following steps are performed sequentially:

1. Fuzzify the inputs to the controller.
2. Apply an inference mechanism to infer the output contributed from each rule. Then, aggregate all the rules' outputs to form an overall fuzzy output.
3. Use the defuzzification method to obtain a crisp controller output. The basic structure of a FLC is shown in Fig. (2).

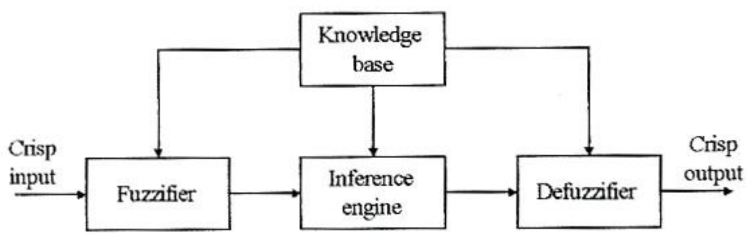


Fig. (2). Basic structure of a fuzzy logic controller.

4. Proposed Fuzzy Logic Controller

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 as shown in Fig. 3, in an aim to damp the rotor oscillations after disturbances, and hence the FSG performance is improved. Speed deviation, ω, and its derivative, $\dot{\omega} = d\omega/dt$, are chosen as FLC input variables. Actually, only ω signal is measured, and from it $\dot{\omega}$ signal is computed as:

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

where T_s is the sampling interval. Two scaling factors, K_A and K_B, are used to map ω and $\dot{\omega}$, respectively into their predefined universes of discourse, which are divided into seven overlapping fuzzy sets; named large positive "LP", medium positive "MP", small positive "SP", zero "ZE", small negative "SN', etc. A 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*] and width "*d*", then its degree of membership μ_x, in this set is defined by the following function:

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

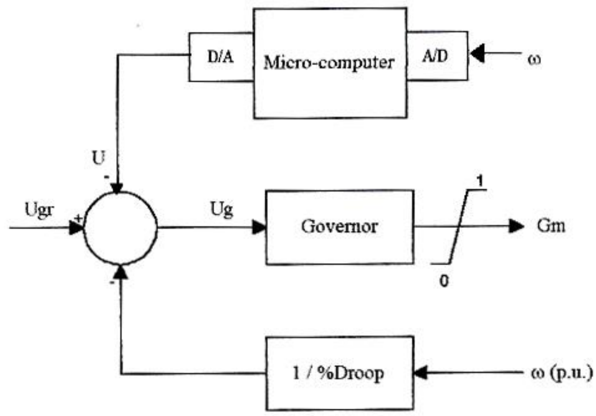


Fig. (3). The governor control system.

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

ω \ dω/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

Table 1 shows the fuzzy rules that are assigned for the FSG system [6]. Each entry in Table 1 represents a control rule, which takes the form: "IF ω is A, AND $\dot{\omega}$ is B, THEN u is C", where A, B, and C are fuzzy sets as defined by relation (2). 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:

$$\mu_c(u_i) = \min(\mu_A(\omega), \mu_B(\dot{\omega})) \tag{3}$$

The aggregated fuzzy outputs are converted into a single crisp value using the "weighted average" defuzzification method [12], which gives the output control signal as:

$$U = K_u \frac{\sum_{i=1}^{m} \mu_c(u_i).u_i}{\sum_{i=1}^{m} \mu_c(u_i)} \tag{4}$$

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 FLC 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. In reference [6], equally-overlapped, triangle membership functions are used for input variables. Here, the author proposes to increase effectiveness of the FLC by adopting unsymmetrical bell-shaped functions. This could be done by using fuzzy sets with different overlaps.

5. Tuning of FLC Parameters

So far, three adjustable parameters are aforementioned, i.e., K_A , K_B and K_u. To gain more effectiveness from the proposed FLC, additional 12 adjustable parameters (six for ω fuzzy sets, and six for $\dot{\omega}$ sets) are introduced into the design. Namely, d_1, d_2, d_3 and d_4, which stand for widths of fuzzy sets (LP, MP, SP, ZE) of ω, 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 15 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 optimized simultaneously. This is a quite difficult problem to deal with using a trial-and-error approach. However, characteristics of genetic algorithm (GA) [13] make it able to solve such a complex problem. Therefore, GA with tournament selection and two-point crossover is utilized to optimally select these 15 parameters. To do so, the following performance index, *J*, is used:

$$J = \sum_{k=1}^{N} \{[kT.\omega(k)]^2 + [kT.\Delta G_M(k)]^2\} \tag{5}$$

where $\omega(k)$ and $\Delta G_M(k)$ are the deviations of the FSG speed and the governor valve position from their steady state values respectively. The population size in each generation of GA is chosen to be 60 strings. The crossover probability is set at 0.7 and the mutation probability is set at 0.001.

6. Simulation Results

A number of simulation studies were performed to develop and investigate the effectiveness of the proposed FLC. The performance index was evaluated, in all attempts of developing the FLC, in response to a three-phase to ground fault of 100-ms duration at the transformer high voltage terminals, with the rated output (P_t=0.9 p.u, Q_t=0.436 p.u). Variation of the performance index *J* with the number of generations is shown in Fig. 4. The optimal values selected by GA for K_A, K_B and K_u are 0.269, 1.235 and 1.984 respectively. The optimized fuzzy sets for ω and $\dot{\omega}$ have taken the shapes shown in Fig. 5. In Ref. [6], the fuzzy controller was compared with a conventional controller (lead compensator) and the results have shown that the fuzzy controller outperforms the conventional one. Therefore, it was seen to compare the proposed algorithm only with that of Ref. [6], while keeping the response with speed governor (SG) in the figures to show that the machine essentially need an additional control signal. The performance of the FSG system with the proposed fuzzy governor controller following a three-phase short circuit fault for 100 ms, at the operating points [(P_t, Q_t)= (0.9,0.436), (0.8, -0.2) p.u], is shown in Figs. 6 and 7, respectively. Figures 8 and 9 show the system response to a temporary (100 ms long) 5% step increase in the governor set point at the previous loading conditions. All these figures also show the system response with speed governor (SG) only, i.e. without the additional control signal, *U*. The FSG dynamic performance was analyzed using the concept of damping and synchronizing torque components. The results show that the addition of the proposed FLC improves the damping coefficient K_d by 16.5% and 150% at [(P_t, Q_t) = (0.9, 0.436), (0.8, -0.2) p.u] respectively, compared with those using another fuzzy controller [6].

The simulation results show that the proposed FLC results in a significant improvement in the FSG transient behavior and a considerable reduction in the rotor oscillations with acceptable governor valve movements. Also, although the FLC parameters are optimized for particular loading conditions and even for a particular type disturbance, they are robust and lead to more increase in the damping coefficient for other loading condition and disturbance as is shown above. Meanwhile, although the time response with the proposed approach shows slight difference when compared with that of Ref. [6], quantitive measures in terms of the performance index and damping coefficient show some improvements.

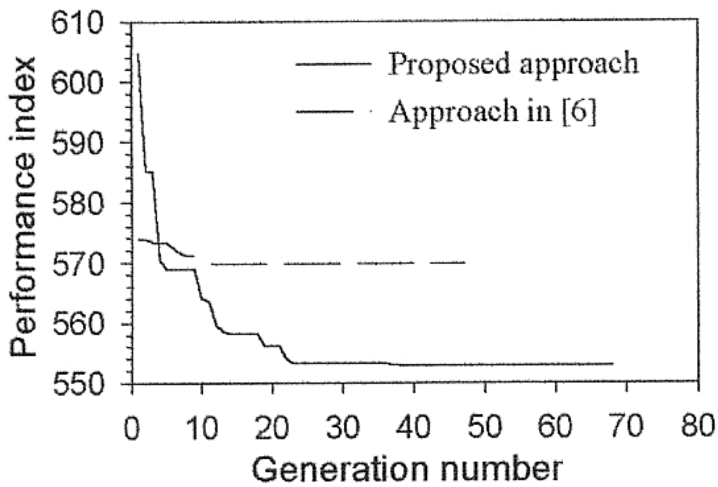


Fig. (4). Performance index convergence.

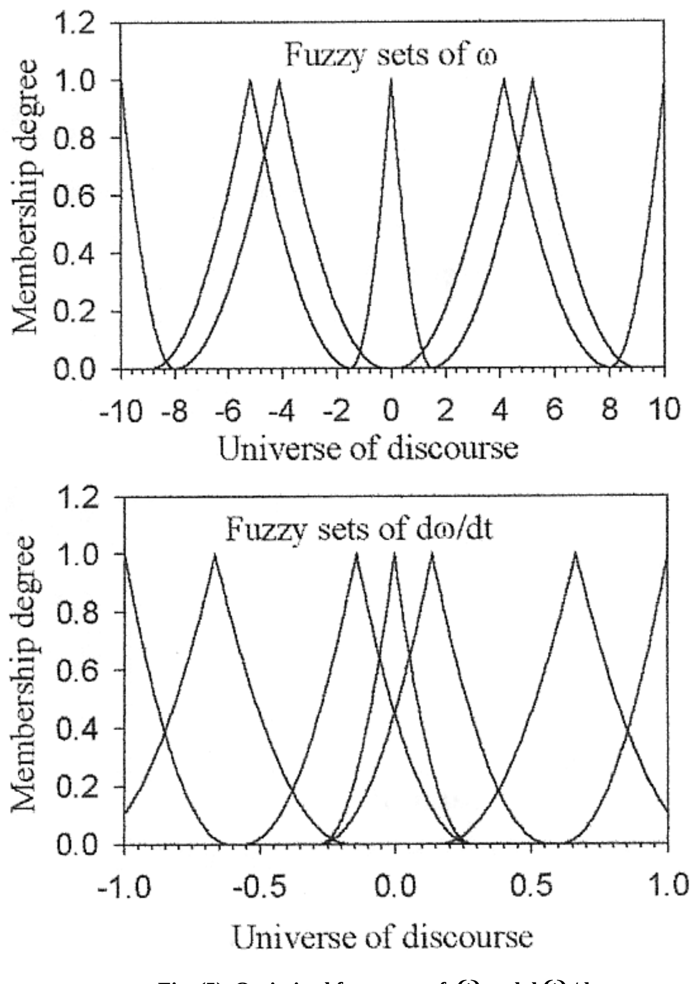
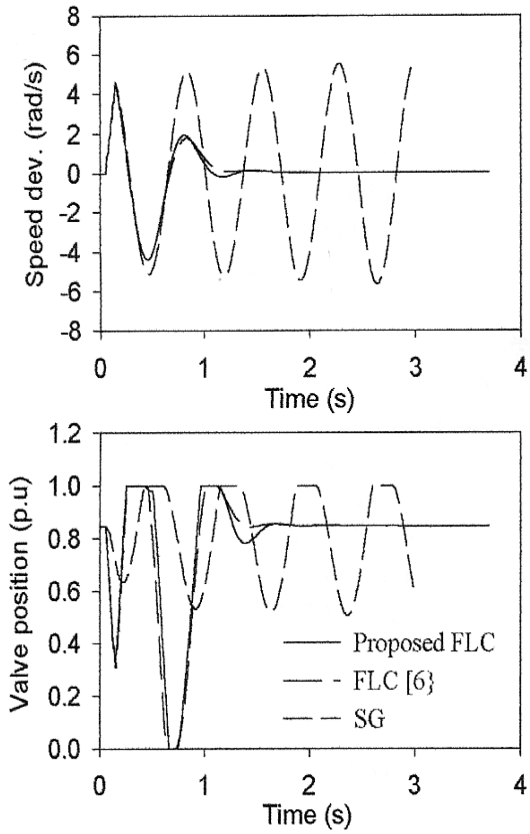
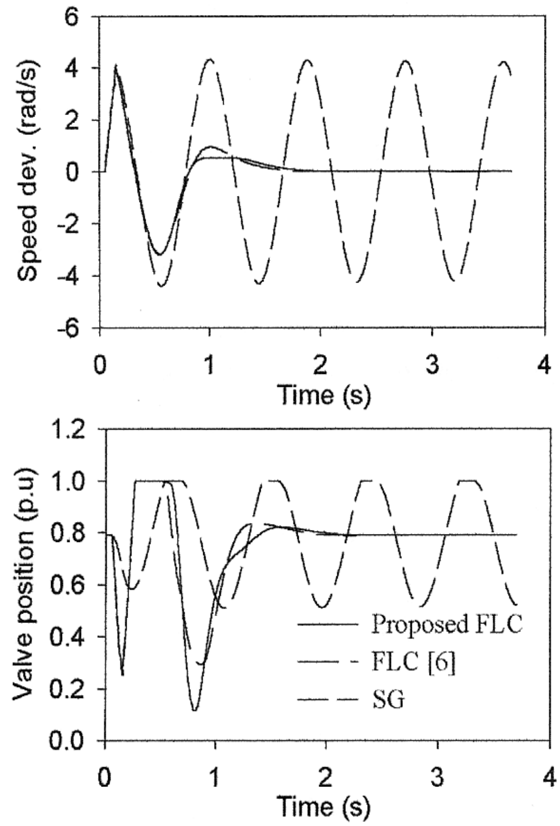


Fig. (5). Optimized fuzzy sets of ω and d ω /dt.


Speed dev. (rad/s)
Time (s)
Valve position (p.u)
Time (s)
Proposed FLC
FLC [6}
SG


Speed dev. (rad/s)
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Proposed FLC
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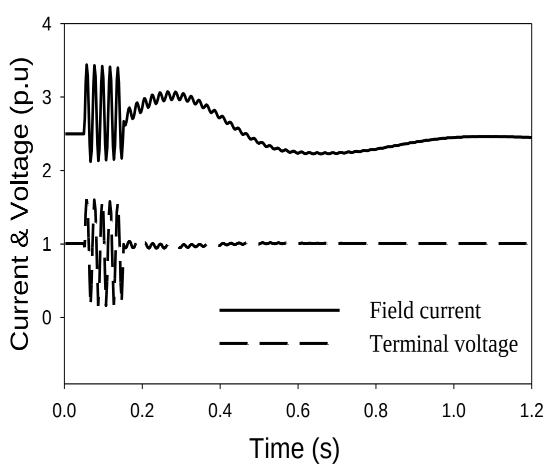
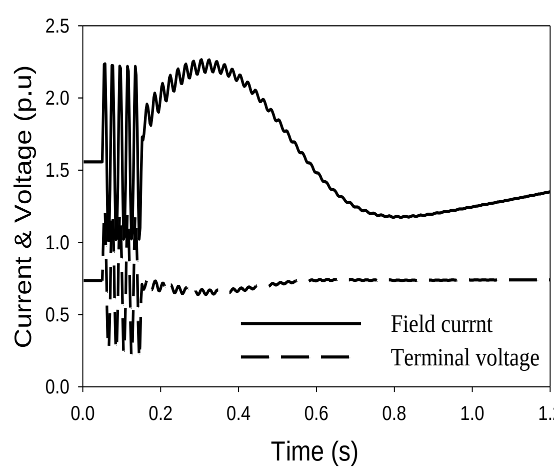

Current & Voltage (p.u)
Time (s)
Field current
Terminal voltage


Current & Voltage (p.u)
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Terminal voltage

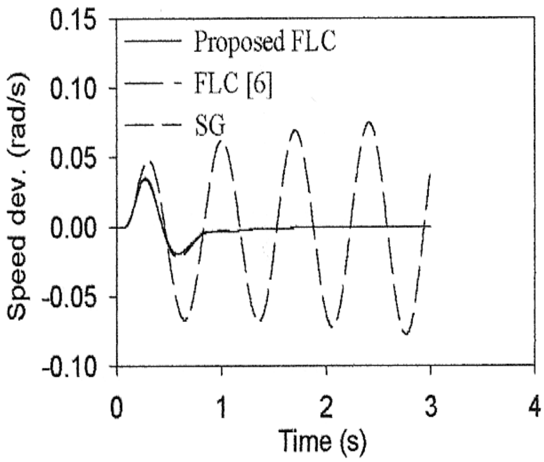

Fig. (8). Response to a pulse in U_{gr} at P_t=0.9 pu, Q_t=0.436 pu.

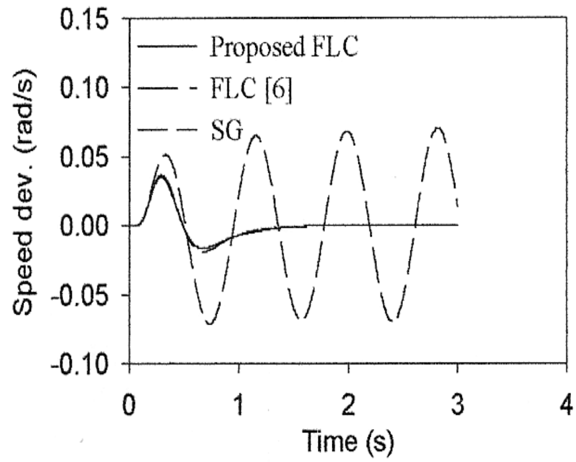

Fig. (9). Response to a pulse in U_{gr} at P_t=0.8 pu, Q_t=-0.2 pu.

7. Conclusion

This paper has presented and developed an approach for the design of a FLC for stability enhancement of a FSG. The main features of this approach are:

1. Using non-linear, unsymmetrical membership functions for the variables input to the controller.
2. Optimizing the shapes of these functions by utilizing GA to optimally assign the widths and centers of input variables' fuzzy sets. Simulation results show that the proposed controller is an efficient in enhancing FSG stability, and also provides the FSG system with more damping of the mechanical-mode oscillations than the previous FLC [6] does.

8. References

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9. Appendix

The mathematical model of the FSG:

$$p\psi_f = \omega_o[v_f - i_f R_f]$$

$$p\psi_d = \omega_o[v_d + \psi_q] + \psi_q \omega$$

$$p\psi_q = \omega_o[v_q - \psi_d] - \psi_d \omega$$

$$p\delta = \omega$$

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

$$T_e = \psi_d i_q - \psi_q i_d$$

The mathematical model of the turbine and governor system:

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

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

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

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

$$T_m = F_{HP} Y_{HP} + F_{IP} Y_{IP} + F_{LP} Y_{LP}$$

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

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

Parameters of the system studied are:

S=1100 MVA, L_f=0.77, L_d=L_q=0.53, M_{fd}=0.53, R_f=0.0000029,R_T=0.003, X_T=0.15, R_L=0.0075, X_L=0.195, H=3 kW.s/kVA, 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

تحسين استقرار مولد فائق التوصيل بواسطة التحكم المنطقي الغيمي

رجائي عبد الفتاح صالح

قسم الهندسة الكهربائية، كلية الهندسة– جامعة القصيم

القصيم– المملكة العربية السعودية

(قُدم للنشر في ٢٠٠٧/٥/٢٨م؛ وقُبل للنشر في ٢٠٠٧/١١/٢٧م)

ملخص البحث. تعتبر المولدات الفائقة التوصيل أحد التطبيقات الواعدة للموصلات الفائقة التوصيل في قطاع القوى الكهربية. كذلك تعد دراسة استقرار هذه المولدات عند تعرضها لاهتزازات في الشبكة الكهربية من الأمور الهامة في تطويرها. ونظرًا لأن الثابت الزمني لملفات المجال الفائقة التوصيل كبير جدًّا، فإن الوسيلة الأساسية المتاحة لتحسين الاستقرار العابر لهذه المولدات هي ضبط الحاكم. يقدم هذا البحث طريقة فعالة لتصميم ضابط غيمي، وذلك لإخماد الذبذبات الميكانيكية وتحسين الاستقرار لمولد فائق التوصيل متصل بنظام قوي لانهائي في الظروف العابرة. تم في هذه الدراسة استخدام دوال عضوية غير خطية وغير متماثلة الاتساع لكل من الانحراف في سرعة المولد ومعدل التغير في السرعة، واللذان يمثلان المتغيرات الداخلة للضابط الغيمي. تضم مجموعة ثوابت الضابط ١٥عنصرًا يجب اختيارها بعناية. تم استخدام طريقة الخواريزم الوراثي لتحديد القيم المثلى لثوابت الضابط. توضح نتائج المحاكاة أن الضابط المقترح يؤدي إلى تحسن جيد في أداء واستقرار النظام المدروس على مدى واسع من أحوال التشغيل.