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An efficient fuzzy controlled system for superconducting magnetic energy storage unit

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Superconducting magnetic energy storage (SMES) controllers must be capable of providing appropriate stabilizing signals to the power system over a broad range of operating conditions and disturbances. Traditional SMES controllers rely greatly on robust linear design methods. Recently, control methods using fuzzy logic have shown promising results. These fuzzy logic controllers (FLCs) are based on empirical rules. In this paper a systematic approach for FLC design is proposed. The membership functions of input–output variables are generated on-line, applicable to any type of disturbance. The performance of the proposed control is compared with an eigenvalue based traditional PI controller, and simulation results are presented and discussed. © 1998 Elsevier Science Ltd

Keywords: energy storage, SMES, fuzzy controller

I. Introduction

The high complexity and non-linearity of power systems have created a great deal of challenge to power system control engineers. One of the most important problems in power systems is the damping of low frequency oscillations. If no adequate damping is available, the oscillations may be sustained for minutes and grow to cause system separation [1].

Many kinds of stabilizers have been proposed to improve the stability of a synchronous generator. Superconducting magnetic energy storage (SMES) units were originally proposed as energy storage units having the same purpose as pumped hydro units. Such units have recently found application as stabilizers for power systems [2].

The superconducting magnetic energy system is designed to store electric energy in the low loss superconducting coil. Power can be absorbed or released from the coil according to the system requirement. The control is performed by changing the firing angle of the converters in the SMES unit, which rapidly moves the d.c. output voltage up or down in order to achieve the desired power interchange. The use of Grate Turn Off (GTO) converters makes it possible for the SMES unit to operate in four quadrant modes [3]. However, the effective use of the SMES unit greatly depends on its control strategy. The schematic diagram of the SMES unit is shown in Figure 1.

Different types of controllers for the SMES unit have been proposed in the literature [4–6]. Refs. [4,5] deal with small disturbances only. A Proportional Integral (PI) controller (Figure 2(a)) was proposed for the SMES unit in Ref. [6] to furnish active power compensation to the system following a disturbance. Both small and large disturbance have been considered. Based on the assigned eigenvalues, the controller parameters K_P and K_I are determined.

As an alternative to these controls, recently fuzzy logic control (FLC) has found wide applications to various control problems [7,8]. In this paper, a simple fuzzy logic controller as shown in Figure 2(b) is proposed for the SMES unit, replacing the PI controller. The special feature of the proposed model is the generation of membership functions at the very beginning, using sensed frequency signals. So, whatever the grade of disturbance may be, the proposed fuzzy control algorithm will automatically generate the appropriate membership functions. Unlike the PI controller, the power compensation P_{sm} from the SMES unit is obtained directly from the FLC output, which makes it more sensitive to the system requirement. Also, the gain of the control loop is changed automatically depending on the operating conditions.

The simulations are carried out for both small load disturbance as well as large load disturbance in a single line infinite bus system. A comprehensive control strategy is developed, and simulation results are compared and discussed.

II. Configuration of the system

Figure 3 shows the studied system with a synchronous generator connected to the infinite bus through a transmission

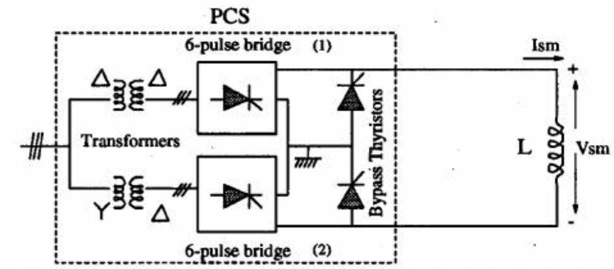

Figure 1. Schematic diagram of the SMES unit

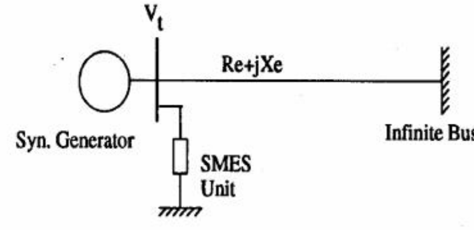

Figure 3. The power system with a SMES unit

line and a SMES unit. The generator is equipped with an automatic voltage regulator (AVR), and its governing system is of the reheat turbine type [6].

The d.c. magnetic coil of the SMES unit is connected to the a.c. grid through a power conversion system (PCS) which includes an inverter/rectifier. When there is a sudden disturbance in the power system, the transformation of electrical energy by the SMES unit is done almost immediately depending on the system requirement. The converter unit is force-commutated and α is the firing angle of SCR. If $\alpha < 90°$, the converter works as a rectifier (charging mode). If $\alpha > 90°$, the converter works as an inverter (discharging mode). Real power can be absorbed from or delivered to the power system by controlling the sequential firing angles of thyristors [9]. In order to effectively control the power balance of the synchronous generator during dynamic period, the SMES unit is located at the generator bus. The current and voltage of superconducting inductor are related as

$$I_{sm} = \frac{1}{L_{sm}} \int_{t_0}^{t} V_{sm}\, d\tau + I_{sm0}$$

where I_{sm0} is the initial current of the inductor. The real power absorbed or delivered by the SMES unit is

$$P_{sm} = V_{sm} I_{sm}$$

If P_{sm} is positive, power is transferred from the power system to the SMES unit. While if the P_{sm} is negative, power is released from the SMES unit. The energy stored in the superconducting inductor is

$$W_{sm} = W_{sm0} + \int_{t_0}^{t} P_{sm}\, d\tau$$

where $W_{sm0} = \frac{1}{2} L_{sm} I_{sm}^2$ is the initial energy in the inductor.

Because of constraints of hardware implementation, both the voltage and current have upper and lower limits [6]. For the SMES modelled, the limits are:

$$-0.438 \le V_{sm} \le 0.438$$

$$0.31 I_{sm0} \le I_{sm} \le 1.38 I_{sm0}$$

All the system data of the generator and SMES unit are given in the Appendix.

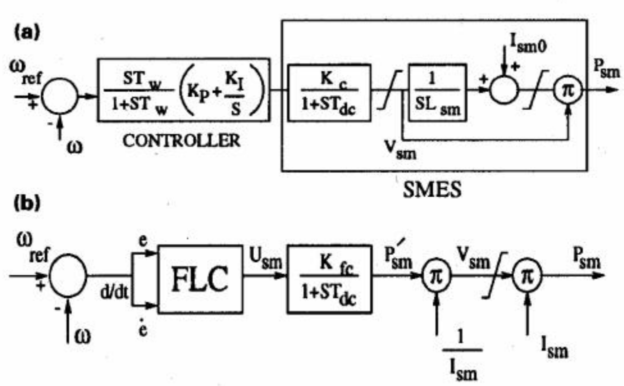

Figure 2. SMES controllers: (a) PI controller; (b) simple fuzzy logic controller

III. The proposed control scheme

III.1 *Fuzzy controller*

The basic structure of the proposed fuzzy logic controller is shown in Figure 4. The development of the fuzzy logic approach here is limited to the controller structure and design. More detailed discussions on fuzzy logic controllers are widely available (see, for example, Refs. [7,8]). Using the knowledge gained from experience, generator speed deviation (e) and acceleration ($\dot{e}$) of the synchronous generator are chosen as the input signals to the fuzzy controller. The acceleration signals can be derived from the two successive error signals. If u is defined as the control output, then each control rule R_i is of the form:

IF e is A_i and $\dot{e}$ is B_i, THEN u is C_i

where A_i, B_i and C_i are fuzzy sets with triangular membership functions as shown, normalized between -1 and 1, in Figure 5. The linguistic variables are:

PVB, positive very big; PB, positive big; PM, positive medium; PS, positive small; Z, zero; NVB, negative very big; NB, negative big; NM, negative medium; NS, negative small.The same fuzzy sets are used for each variable of interest; only the base value is changed. These bases are W_{b1} and W_{b2} for the speed deviation and acceleration respectively. Both the input signals to FLC are normalized with respect to their base values producing a normalized control output. A specific signal may have non-zero membership in more than one set. Similarly, a specific

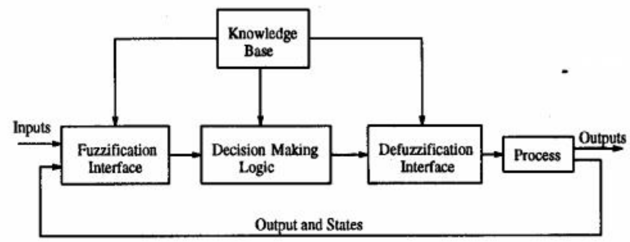

Figure 4. Basic fuzzy controller

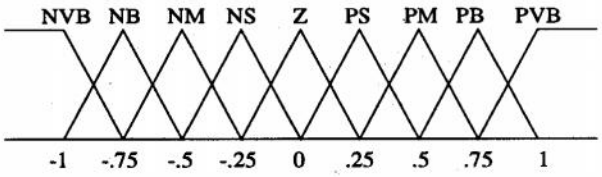

Figure 5. Membership functions of input variables

control signal may represent the contribution of more than one rule. Rule conditions are joined by using minimum intersection operator so that the resulting membership function for a rule is:

$$\mu(e, \dot{e}) = \min(\mu_{Ai}(e), \mu_{Bi}(\dot{e}))$$

The suggested control output from rule i is the centre of the membership function C_i. Rules are then combined using the centre-of-gravity method to determine a normalized control output U_{sm}:

$$U_{sm} = \frac{\sum_{1}^{n} \mu_{Ri}(e, \dot{e}).U_i}{\sum_{1}^{n} \mu_{Ri}(e, \dot{e})}$$

III.2 *Design steps*

So far, the development of FLC is general. A particular control design requires specification of all control rules and membership functions. The control rules are designed from an understanding of the desired effect of the controller. For example, consider the rule:

IF e is NS and $\dot{e}$ is PS, THEN u is Z

This rule anticipates that as the system stabilizes the SMES power is no longer needed. The complete set of control rules is shown in Table 1. The control rules are symmetric under the assumption that, if necessary, any asymmetry could be best handled through scaling. In addition, adjacent regions in the rule table allow only nearest neighbour changes in the control output (NB to NM, NM to NS and so on). This ensures that small changes in e and $\dot{e}$ result in small changes in u.

In the present fuzzy modelling it is assumed that the fundamental control laws change quantitatively not qualitatively with the operating conditions. In this vein, control rules and membership functions are designed once as above.

To cope with various types of disturbances the base value W_{b2} for $\dot{e}$ is generated on-line when the system experiences any disturbance from its steady state operating condition. W_{b2} can be calculated using the first few samples of e. The base W_{b1} for e is then determined by using the relationship

$$W_{b1} = K_b W_{b2}$$

where K_b *is* a constant and has to be determined once off-line. The procedure of determination of K_b is as follows:

(1) Obtain the maximum values $W_{b1,max}$ and $W_{b2,max}$ for the pair e and $\dot{e}$ by simulating a significant disturbance of sufficiently large magnitude.
(2) From their relationship, determine the value of K_b as:

$$K_b = \frac{W_{b1,\max}}{W_{b2,\max}}$$

From this study, K_b was determined as 0.03 in the presence of SMES unit.

Thus the membership functions of the input variables are normalized between -1 to 1 with respect to their generated bases for a particular system and operating condition. The FLC output U_{sm} is also a normalized quantity. The required SMES power P_{sm} can be determined from U_{sm} as:

$$P_{sm} = \frac{K_{cf}}{1 + sT_{dc}} U_{sm}$$

where K_{cf} is the gain of the control loop, T_{dc} is the delay time. The SMES voltage V_{sm} is then calculated from this P_{sm} and the sensed current I_{sm}. If the magnitude of V_{sm} lies beyond $V_{sm,max}$ in the rectifier mode or in the inverter mode, the actual value of V_{sm} is set equal to the corresponding limiting value. In such a case, the V_{sm} settling signal along with the sensed I_{sm} signal gives the active power required to flow through the converter.

The FLC gain K_{cf} is determined on-line following any disturbance. If $V_{sm,max}$ and $I_{sm,max}$ are the maximum voltage and current limits for a particular SMES unit, then

$$K_{cf} = \frac{W_{b2}}{W_{b,\max}} V_{sm,\max} I_{sm,\max}$$

where W_{b2} is the present base of $\dot{e}$. The value of K_{cf} is not fixed but is adapted depending on the operating condition and disturbance.

IV. Computer simulation

In order to demonstrate the beneficial damping effect of the proposed fuzzy controller, computer simulations based on system non-linear differential equations are carried out for

Table 1. Rule base structure for FFC and FVC

d(error)/dt	Error								
	NVB	NB	NM	NS	Z	PS	PM	PB	PVB
NVB	NVB	NVB	NVB	NVB	NVB	NB	NM	NS	Z
NB	NVB	NVB	NVB	NVB	NB	NM	NS	Z	PS
NM	NVB	NVB	NVB	NB	NM	NS	Z	PS	PM
NS	NVB	NVB	NB	NM	NS	Z	PS	PM	PB
Z	NVB	NB	NM	NS	Z	PS	PM	PB	PM
PS	NB	NM	NS	Z	PS	PM	PB	PM	PVB
PM	NM	NS	Z	PS	PM	PB	PM	PVB	PVB
PB	NS	Z	PS	PM	PB	PM	PVB	PVB	PVB
PVB	Z	PS	PM	PB	PM	PVB	PVB	PVB	PVB

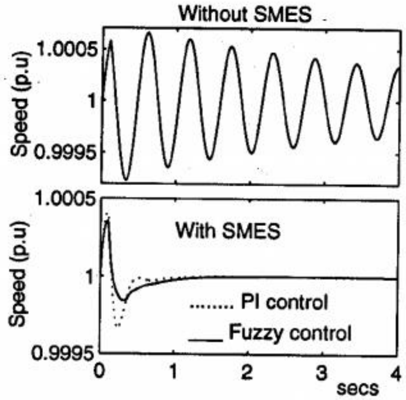

Figure 6. System performance under small disturbance

both small as well as large load disturbance. The differential equations are solved by using the fourth-order Runge–Kutta method. All the non-linearities such as exciter ceiling voltage, SMES voltage limits and inductor current limits have been included.

Figure 6 shows the system responses with 1.2% step

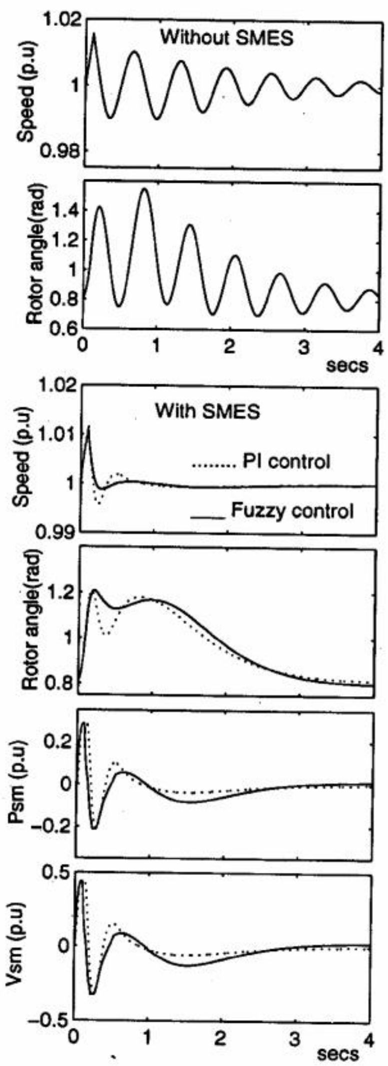

Figure 7. System performance with and without SMES unit for $P_0 = 0.8$ p.u.

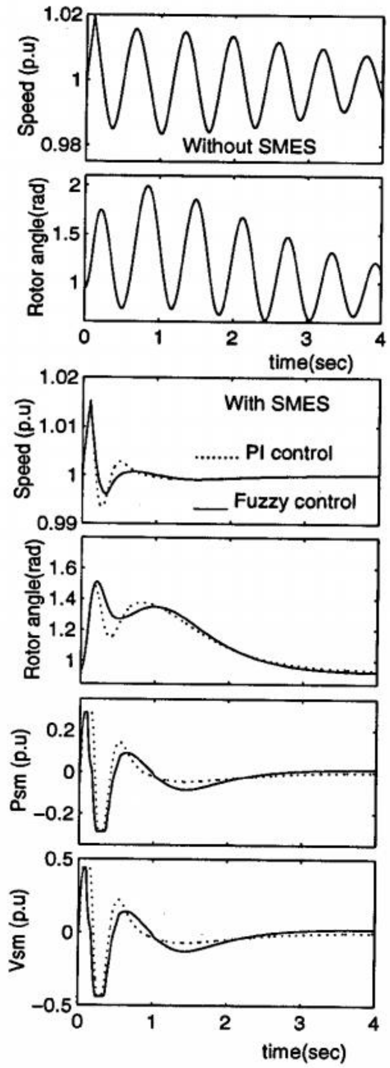

Figure 8. System performance with and without SMES unit for $P_0 = 1.0$ p.u.

change in load. Further, a three-phase fault of 100 ms duration is simulated at the middle of the transmission line with three different initial air-gap power (P_0) values of 0.8 p.u., 1.0 p.u., and 1.2 p.u., respectively. The results of the studies are shown in Figures 7–9 respectively. For the sake of comparison, the performances of the traditional PI controller are also shown in each figure.

V. Performance evaluation

Figure 7 shows the system performances with and without the SMES unit following the large disturbance ($P_0 = 0.8$ p.u). The damping of the system frequency is not satisfactory without the SMES unit. With the addition of SMES, the damping is improved significantly. At the initial period, the frequency deviation with PI and fuzzy controller are almost same. It is due to the delay time T_{dc} which is accounted for the SMES power transfer to the system. However, as the time increases, the FLC shows a clear edge over PI controller. Though both the controllers make use of nearly the same maximum SMES power, a better performance is obtained due to the efficient harnessing of the SMES power P_{sm} by FLC. It is evident from the Figure 7 that the second and third peaks of the generator speed are almost diminished with the

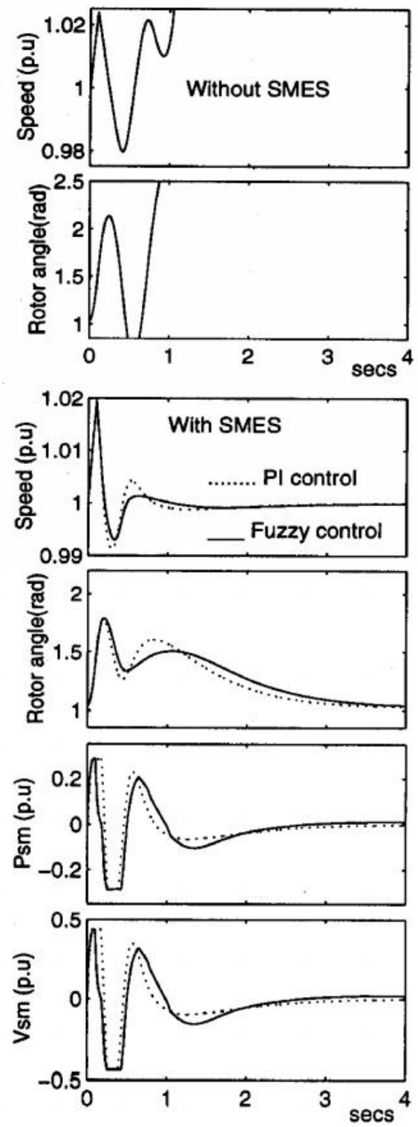

Figure 9. System performance with and without SMES unit for $P_0 = 1.2$ p.u.

proposed mode of control. This eventually reduces the settling time of the speed which in turn brings the SMES unit in more advantageous position for subsequent use.

For the initial operating condition $P_0 = 1.0$ p.u., the speed deviation is oscillatory without the SMES unit. The application of the SMES unit removes such oscillations and the system stabilizes within 1.5 s. Although initial performances of the controllers are similar, again the FLC has proved its supremacy over PI controller. With the addition of the SMES unit, the second and third peaks of the generator speed are reduced by 54.8% and 79.8% respectively when a PI controller is used. Compared to these results, the FLC provides a 73% and 93.4% reduction for those two peaks respectively. The SMES voltage used by controllers during power transfer reaches its upper and lower limits. A careful observation of Figure 8 shows that the FLC is more sensitive to the system error and its changes, because the compensating power P_{sm} is directly obtained from these errors unlike the PI controller where V_{sm} is the corresponding output. Besides, for the system stabilization, the power P_{sm} is directly responsible and the voltage V_{sm} is indirectly responsible.

When P_0 is 1.2 p.u., the system becomes unstable without the SMES unit (Figure 9). However, the addition of the SMES not only makes the system stable but also the settling time decreases substantially. Like other operating conditions as mentioned above, the fuzzy controller enjoys additional advantages during the transformation of electric power. As a result, improved performances are obtained with FLC, as is evident in the figure. This certifies the efficient use of the SMES power with the proposed mode of control.

Several other types of disturbance were also studied. In all these cases the performance of the FLC was superior to that of the PI controller. These results are not shown for the sake of brevity. The effect of utilizing the reactive power capability of the SMES unit as an additional benefit for stabilization is currently under study.

VI. Conclusion

In this paper, a simple fuzzy control strategy for the SMES unit is explained. The damping of the synchronous generator is greatly improved by the SMES unit with the proposed control system. Speed deviation and acceleration have been used for on-line generation of fuzzy membership functions after the disturbance. Thus, the control system is sensitive to any kind of disturbance. The power compensation of the SMES unit is directly obtained from the fuzzy controller. The scheme proposed in the present paper makes effective use of active power modulation of the SMES unit and hence its economic advantage is expected to be stronger than that of earlier schemes. The control strategy is simple and does not require heavy computation, and, therefore, implementation is feasible.

VII. References

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Appendix A System data and initial conditions [1,6]

All parameters are expressed in p.u. unless stated otherwise.

A.1 Generator and transmission line

Base 160 MVA, 15 kV. Generator 160 MVA, 15 kV, 0.85 p.f. Exciter 375 V, 926 A

$X_d' = 0.245$ $X_d = 1.70$ $X_q = 1.64$ $R_a = 0.001096$
$M_g = 4.74$ $D_g = 0$ $R_e = 0.02$ $X_e = 0.4$
$T_{q0}' = 0.075$ s $T_{d0}' = 5.9$ s

A.2 SMES Unit [6]

$I_{sm0} = 0.6495$ p.u. $V_{sm0} = 0$ p.u. $L_{sm} = 0.5$ H
$W_{sm0} = 6.0$ MJ $T_{dc} = 0.026$ s