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A fuzzy set theory based control of superconductive magnetic energy storage unit to improve power system dynamic performance

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Abstract

At present fuzzy logic control is receiving increasing emphasis in process control applications. The paper describes the application of fuzzy logic control in a power system that uses a 12-pulse bridge converter associated with superconductive magnetic energy storage (SMES) unit. The fuzzy control is used in both the frequency and voltage control loops, replacing the conventional control method. The control algorithms have been developed in detail and simulation results are presented. These results clearly indicate the superior performance of fuzzy control during the dynamic period of energy transfer between the power system and SMES unit. © 1997 Elsevier Science S.A.

Keywords: SMES; Fuzzy controller; Computer simulation

1. Introduction

Power system oscillations occur when there are system disturbances such as sudden load-changes or faults. The damping of the system must be such that the synchronous generators can return to their steady state conditions after the disturbances [1]. Especially when the load-end of the transmission line experiences sudden load perturbations, the generators need continuous control to suppress undesirable oscillations in the system. Many countermeasures have been suggested by researchers to increase the damping. These include power system stabilizers [2,3], optimal control of the turbine–governor system [4], and the use of static phase shifters [5].

Since the successful commissioning test of the BPA 30 MJ unit [6], superconductive magnetic energy storage (SMES) systems have received much attention in power system applications. Although the original purpose of the SMES unit is load leveling, an additional function of the SMES unit is the improvement of the system performance, by providing appropriate power modulation [7] during the dynamic period. The SMES can be applied for both active and reactive power compensation at suitable locations of the transmission line for both static and dynamic voltage control and system stability preservation [8,9]. However, some issues associated with the use of SMES unit still remain to be resolved. Two of these issues are: (i) the effective use of $P-Q$ modulation, (ii) the evaluation of their performance after sudden disturbance.

One way to address these issues is to investigate the use of alternative control techniques. At present, the use of fuzzy logic is finding much application in several areas [10,11]. In this paper, the conventional SMES controller proposed [8] is replaced by a rule based fuzzy controller. To demonstrate the effectiveness of the proposed fuzzy controller, its performance is compared with the conventional one. The results show that the SMES unit responds very quickly following a sudden load change due to the effective use of its $P-Q$ modulation capability. The paper begins by outlining the main problems associated with conventional control scheme and then describes the details of the proposed fuzzy logic control scheme. The controller is applied to a test network and the simulation results are presented and discussed.

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2. Problems associated with the use of conventional control

2.1. Review of control strategy

Fig. 1 shows a typical configuration of a single area power system equipped with a SMES unit. Application of a sudden load results in load-voltage and frequency deviations. Following these variations, the SMES unit responds to improve the performance subject to its limitation. The input to the SMES unit is a d.c. voltage E_d. This voltage is continuously varied by a 12-pulse cascaded bridge type ac/dc converter. The converter d.c. output current I_d being unidirectional, the control for the direction and magnitude of the inductor power flow P_d, is achieved by continuously regulating the firing angle α. Fig. 2 shows a diagram of the conventional controlled system and the controller is shown in Fig. 3. A switched capacitor bank is also placed at the load end to provide additional VAr as required for reactive power compensation. The control procedure described in detail in [8] can be summarized as follows:

(i) At first the required inductor voltage E_d is calculated by using the equation

$$E_d = K_0\Delta f - K_{id}\Delta I_d \quad (2.1)$$

$$P_d = E_d I_d \quad (2.2)$$

where K_0 and K_{id} are the gains corresponding to the frequency variation (Δf) and the inductor current variation (ΔI_d) respectively.

(ii) The desired reactive power Q_{dem} can be calculated as

$$Q_{dem} = K_v \Delta V_L \quad (2.3)$$

and

$$Q_{dem} = Q_d + Q_c \quad (2.4)$$

where Q_d is reactive power provided by the SMES unit and Q_c is the reactive power supplied by the switched capacitor; K_v is the gain corresponding to load voltage deviation.

(iii) The SMES unit provides P_d and Q_d to improve the system performance by controlling the firing angles of the 12-pulse converter.

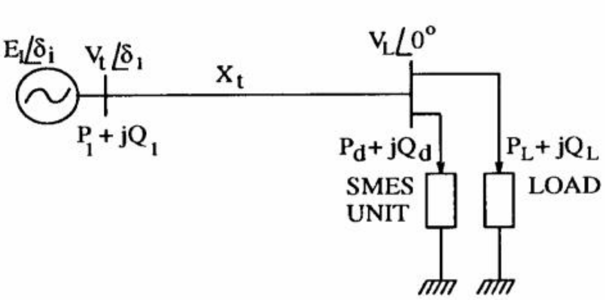

Fig. 1. Single line diagram for the test network.

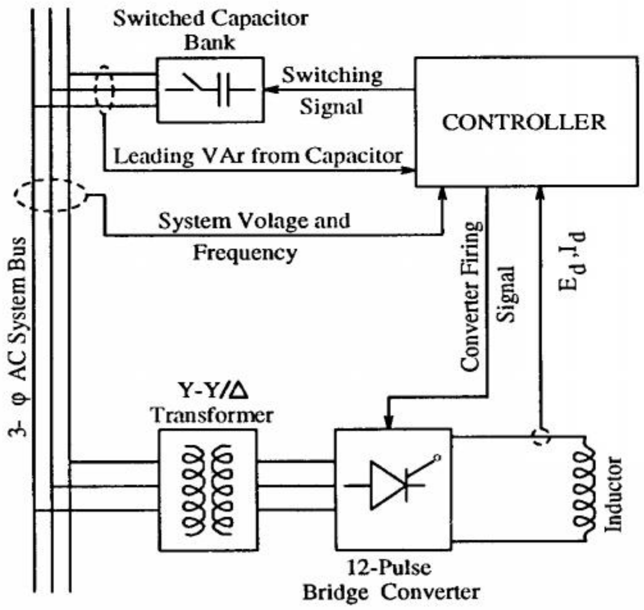

Fig. 2. Schematic diagram of the conventional controlled system.

2.2. Problems arising from the conventional control strategy

The use of Δf (error) signal alone is insufficient to determine the desired value of real power P_d modulation required by the SMES unit. In addition to this error signal, the change in error between successive samples should be used to determine P_d. The absence of this additional signal makes the SMES unit less sensitive to the disturbance. This will in turn result in a larger value of ΔI_d in the SMES unit. A similar problem arises when only load voltage deviation (ΔV_L) is considered to determine the desired value of reactive power modulation Q_d, instead of the change in ΔV_L between successive samples.

3. The proposed fuzzy logic control

The proposed controller along with SMES unit is shown in Fig. 4. The Δf and ΔV_L are the inputs to the corresponding fuzzy controllers. The output of the Fuzzy Frequency Controller (FFC) is P_{dem}, while Q_{dem} is the output of the Fuzzy Voltage Controller (FVC). At any instant, the P–Q modulation of the SMES unit depends on the present value of inductor current I_d. The P–Q regulator decides the actual amount of (P_d, Q_d) to be provided by SMES, and Q_c by switched capacitor bank. Once P_d and Q_d are selected, the firing angles of the 12-pulse converter can be calculated.

Unlike the conventional controller, in the proposed method, the changes in Δf and ΔV_L signals are also

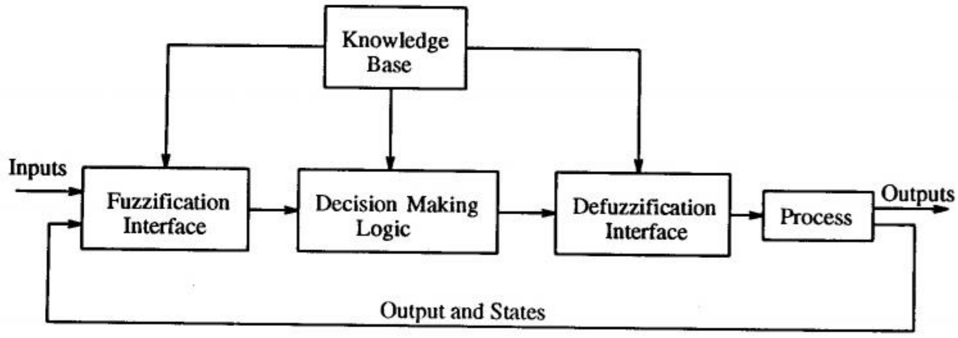

Fig. 3. Basic fuzzy logic controller.

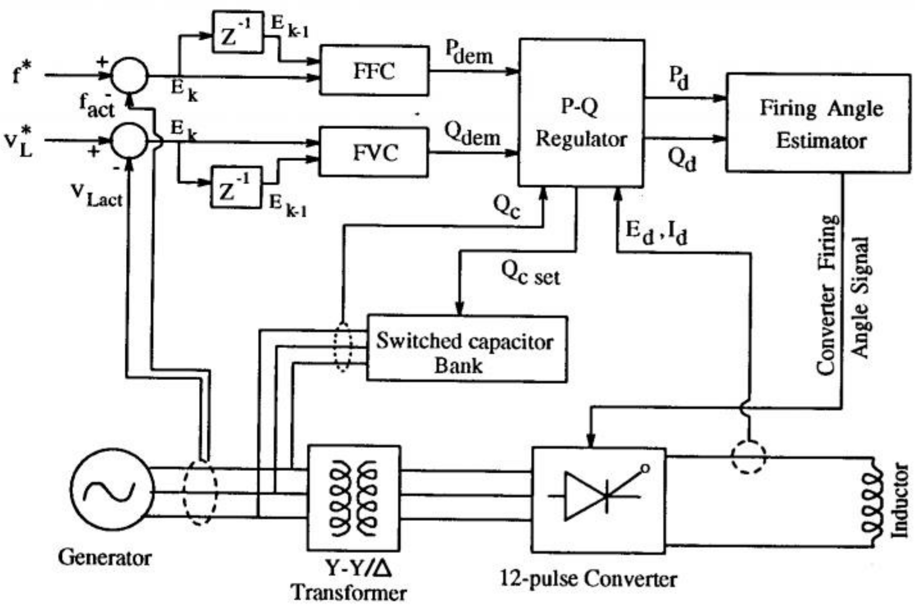

Fig. 4. Fuzzy controller for the SMES unit.

considered as explained below. In general, the input variables considered in the fuzzy rule base are

$$E(k) = R(k) - C(k)$$

$$\mathrm{CE}(k) = E(k) - E(k-1),$$

where $E(k)$ is the loop error (present deviation), $\mathrm{CE}(k)$ is the change in loop error, $R(k)$ is the reference signal, $C(k)$ is the present signal, and k is the sampling interval.

The structure of a general rule can be given as:

IF $E(K)$ is X AND $\mathrm{CE}(K)$ is Y THEN $U(K)$ is Z.

Here $U(K)$ is either P_{dem} (MW) or Q_{dem} (MVAr).

The variables can be expressed as per unit quantities as follows:

$$e(\mathrm{p.u.}) = E(k)/\mathrm{GE}$$

$$\mathrm{ce}(\mathrm{p.u.}) = \mathrm{CE}(k)/\mathrm{GCE}$$

where GE and GCE are the respective gain factors of the controllers. Fig. 5 shows the membership functions of e(p.u.), ce(p.u.) and their respective output variable. Note that the fuzzy subsets for output variable has an asymmetrical shape causing more crowding near the origin. This allows precision control near the steady state operating point. Also large number of subsets is selected to obtain accurate control.

Table 1 gives the rule base matrix for the frequency and voltage controllers. The steps for frequency control can be summarized as follows:

1. Sample the reference frequency f^* and the actual frequency f_{act}.
2. Compute error (e) and change of error (ce) in their respective p.u. values are as follows:

   $$e(k) = (f^*(k) - f(k))/\mathrm{GE}$$

   $$\mathrm{ce}(k) = (e(k) - e(k-1))/\mathrm{GCE}$$

3. Identify the interval indices for e(p.u.) and ce(p.u.) respectively, by the comparison method.
4. Compute the degree of membership of e(p.u.) and ce(p.u.) for the relevant fuzzy subsets.
5. Identify the four valid rules in Table 1 and calculate the degree of membership μ_{R_i} using MIN operator.

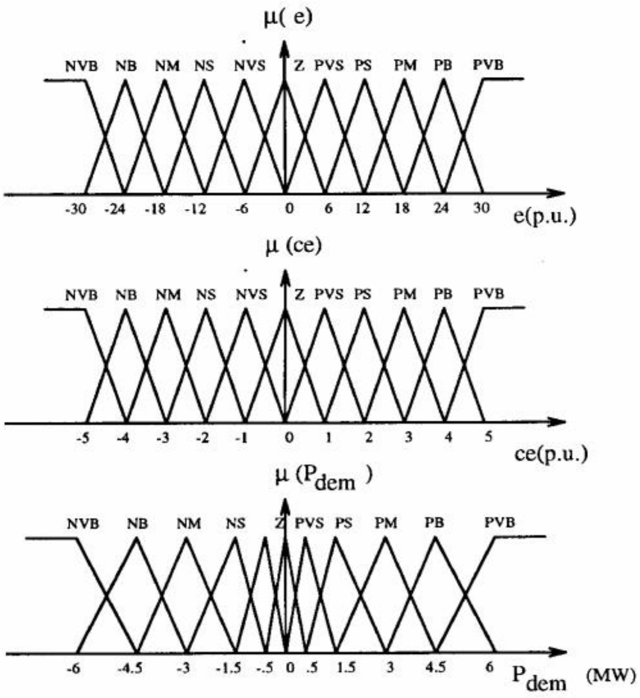

Fig. 5. Membership functions of the fuzzy frequency controller (FFC).

6. Retrieve power demand P_{dem} for each rule from Table 1.
7. Calculate the crisp value of P_{dem} by height defuzzification method as follows:

$$P_{\mathrm{dem}}=\frac{\mu_{\mathrm{R1}}P_{\mathrm{d1}}+\mu_{\mathrm{R2}}P_{\mathrm{d2}}+\mu_{\mathrm{R3}}P_{\mathrm{d3}}+\mu_{\mathrm{R4}}P_{\mathrm{d4}}}{\mu_{\mathrm{R1}}+\mu_{\mathrm{R2}}+\mu_{\mathrm{R3}}+\mu_{\mathrm{R4}}} \tag{3.1}$$

The control of the voltage loop is done in the same way except that the gain factors GE and GCE are different.

The actual real and reactive power consumed by the SMES unit (P_{d}, Q_{d}) determined by the P–Q regulator, depend on the present value of the inductor current I_{d}. Limitations on the firing angle α to the regions $5° \leq |\alpha| \leq 165°$ restrain the (P_{d}, Q_{d}) consumption of the SMES unit. The region of available for (P_{d}, Q_{d}) for two quadrant operation is shown in Fig. 6. Four quadrant operation [12] can be exercised when capacitive VAr is required for compensation. The switched capacitor bank provides additional VAr (Q_{c}) when required. Therefore, the net reactive compensation provided by SMES unit along with switched capacitor is

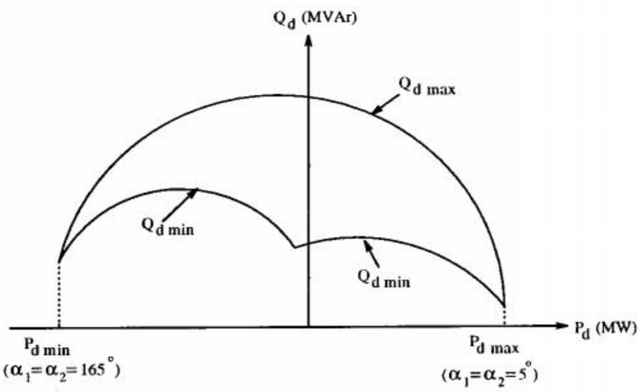

Fig. 6. A typical P–Q modulation diagram under two quadrant operation.

$$Q_{\mathrm{net}}=Q_{\mathrm{d}}+Q_{\mathrm{c}} \tag{3.2}$$

For a particular value of I_{d}, maximum P_{d} is obtained at $\alpha=5°$ and minimum P_{d} at $\alpha=165°$. The P–Q modulation shows that the maximum Q_{d} can be obtained in equal α mode (when $\alpha_1=\alpha_2$) and the minimum Q_{d} curve has a bend at the intersection point of the two semicircular loci. For a particular value of P_{d}, if the desired value of Q_{d} falls outside the available area, it is restricted to the nearest point of the boundary of the curve. It is desirable to set the rated inductor current I_{d0} such that the maximum allowable energy absorption equals the maximum allowable energy discharge. This makes the SMES unit equally effective in damping swings caused by sudden increase or decrease

Table 1
Rule base for frequency and voltage controllers

ce	*e*										
	NVB	NB	NM	NS	NVS	Z	PVS	PS	PM	PB	PVB
NVB	NVB	NVB	NVB	NVB	NVB	NVB	NB	NM	NS	NVS	Z
NB	NVB	NVB	NVB	NVB	NVB	NB	NM	NS	NVS	Z	PVS
NM	NVB	NVB	NVB	NVB	NB	NM	NS	NVS	Z	PVS	PS
NS	NVB	NVB	NVB	NB	NM	NS	NVS	Z	PVS	PS	PM
NVS	NVB	NVB	NB	NM	NS	NVS	Z	PVS	PS	PM	PB
Z	NVB	NB	NM	NS	NVS	Z	PVS	PS	PM	PB	PVB
PVS	NB	NM	NS	NVS	Z	PVS	PS	PM	PB	PVB	PVB
PS	NM	NS	NVS	Z	PVS	PS	PM	PB	PVB	PVB	PVB
PM	NS	NVS	Z	PVS	PS	PM	PB	PVB	PVB	PVB	PVB
PB	NVS	Z	PVS	PS	PM	PB	PVB	PVB	PVB	PVB	PVB
PVB	Z	PVS	PS	PM	PB	PVB	PVB	PVB	PVB	PVB	PVB

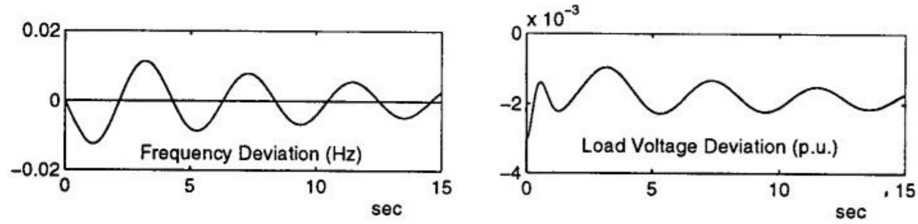

Fig. 7. Response of the power system without SMES unit due to a step loading of (0.005 + j0.005) p.u. [case 1].

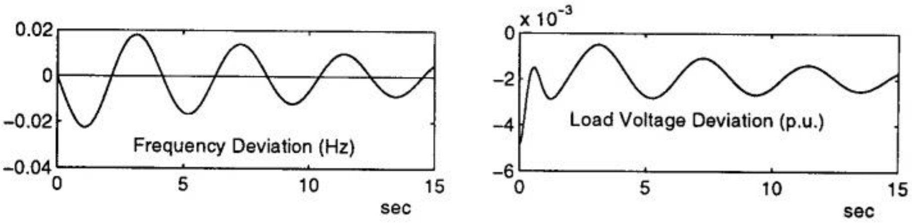

Fig. 8. Response of the power system without SMES unit due to a step loading of (0.008 + j0.008) p.u. [case 2].

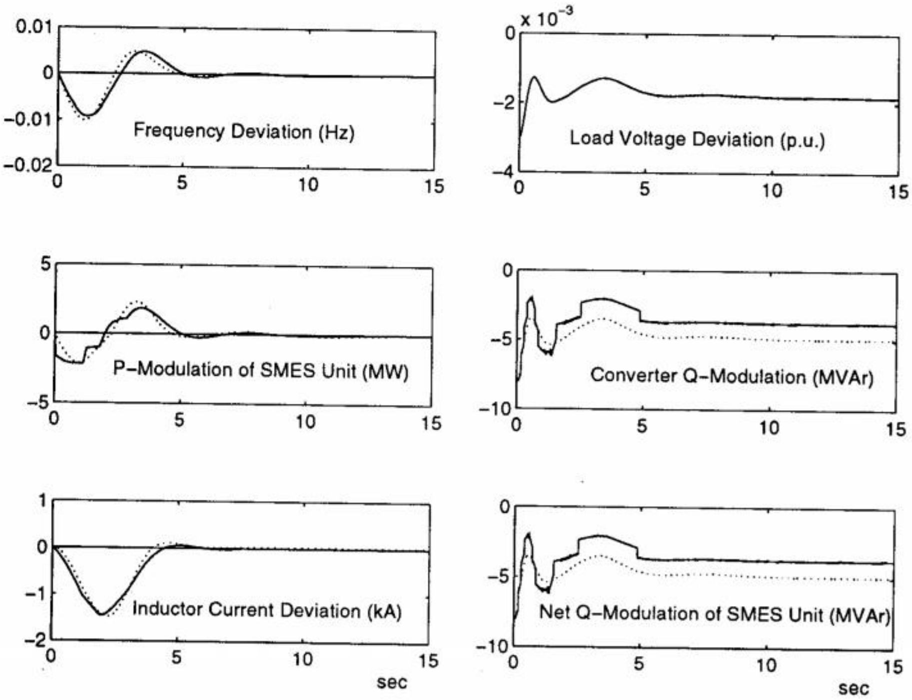

Fig. 9. Response of the power system after addition of the SMES unit using fuzzy logic control [case 1]. ··· Conventional; —— Fuzzy.

in load. When the inductor current reaches either of these limits, the P_d–Δf control loop is discontinued till the frequency deviation swings to the other side.

4. Results of the proposed *P*–*Q* control

The single area system of Fig. 1 is considered as a test network. The purpose is to highlight the behavior of SMES under fuzzy logic control scheme and its economical advantage over the conventional scheme. The degree of impact on the power system would depend on the type of the power system and the nature of the load. The section begins with system modeling followed by the simulation results and performance evaluation. Finally, economic aspects are presented. The following aspects are discussed in details in the sub-sections:

(a) system behavior without SMES unit;

(b) its performance with SMES unit using non-fuzzy controller;

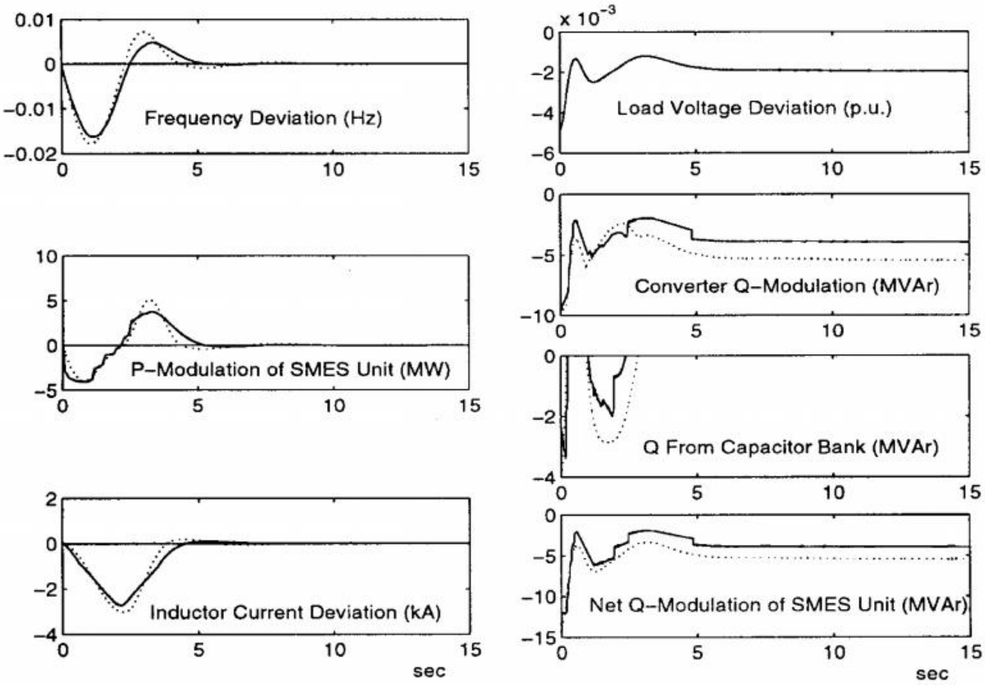

Fig. 10. Response of the power system after addition of the SMES unit using fuzzy logic control [case 2]. ··· Conventional; —— Fuzzy.

(c) its performance with SMES unit using fuzzy controller.

4.1. System modeling [14]

The following assumptions are made in the system modeling:

1. The reheat turbine type thermal plant supplies to a single generator whose capacity is 2000 MW.
2. The generator is equipped with automatic voltage regulator (AVR) with stabilizing speed feedback.
3. The generator is cylindrical rotor type and the resistances of the generator and the line are negligible in comparison with the reactances.
4. Strong coupling is present between P–f and Q–V loops. The coupling effect can be shown as follows.

Table 2
Performance comparison of fuzzy and non-fuzzy controlled power system with SMES unit (Case 2)

System behavior	Without SMES	SMES (conventional)	SMES (fuzzy)
Frequency			
Deviation Δf (Hz)	−0.023	−0.0186	−0.0174
Settling time (s)	>15	8.963	7.042
Overshoot (Hz)	0.018 (max.)	0.0075 (max.)	0.005 (max.)
Inductor current			
Deviation ΔI_d (kA)	...	3.06	2.72
Settling time (s)	...	11.1	9.86
Overshoot (kA)	...	0.2	0.1
Q_c (MVAr)	...	4 (max.)	3.4 (max.)

In general, the active and reactive power taken by a load are functions of frequency and voltage. Hence,

$$\Delta P \approx \frac{\partial P}{\partial f}\Delta f + \frac{\partial P}{\partial |V|}\Delta|V|$$

$$\Delta Q \approx \frac{\partial Q}{\partial f}\Delta f + \frac{\partial P}{\partial |V|}\Delta|V| \quad (4.1)$$

where ΔP and ΔQ are the changes in the real and reactive loads as caused by relatively small variations Δf and $\Delta|V|$ in frequency and voltage.

Let the step load change causing the disturbance be $(\Delta P_L + j\Delta Q_L)$. The consequent changes in frequency and voltage, Δf and ΔV_L, would in turn affect the loading. Therefore, the net change in real and reactive loading ΔP_{LN} and ΔQ_{LN} can be expressed as

$$\Delta P_{LN} \approx \Delta P_L + \frac{\partial P_L}{\partial f}\Delta f + \frac{\partial P_L}{\partial |V_L|}\Delta|V_L|$$

$$\Delta Q_{LN} \approx \Delta Q_L + \frac{\partial Q_L}{\partial f}\Delta f + \frac{\partial Q_L}{\partial |V_L|}\Delta|V_L| \quad (4.2)$$

$\partial Q_L/\partial f$ is neglected because of its less practical importance [13].

The net incremental power ΔP_1 out of the synchronous machine is given by the sum of ΔP_G (the incremental generator power due to governor action) and $-(2H/f^0)(\mathrm{d}/\mathrm{d}t)\Delta f$ (the power derived out of the inertia of the rotor through speed change). Hence,

$$\Delta P_1 = \Delta P_G - \frac{2H}{f^0}\frac{\mathrm{d}}{\mathrm{d}t}\Delta f \quad (4.3)$$

With the addition of SMES unit at the load end, the active and reactive powers balance at the generator bus can be represented as

$$\Delta P_1 = \Delta P_{LN} + \Delta P_d \quad (4.4)$$

$$\Delta Q_1 = \Delta Q_{LN} + \Delta Q_d + \Delta Q_t \quad (4.5)$$

where ΔQ_t is the change of reactive power loss in the transmission line.

Using Eqs. (4.2), (4.3) and (4.4), the following is obtained:

$$\Delta P_G - \frac{2H}{f^0}\frac{\mathrm{d}}{\mathrm{d}t}\Delta f = \Delta P_L + \frac{\partial P_L}{\partial f}\Delta f + \frac{\partial P_L}{\partial |V_L|}\Delta |V_L| + \Delta P_d$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\Delta f = \frac{f^0}{2H}\left[\Delta P_G - \Delta P_L - \Delta P_d - \frac{\partial P_L}{\partial f}\Delta f - \frac{\partial P_L}{\partial |V_L|}\Delta |V_L|\right] \quad (4.6)$$

4.2. Simulation results

Non-linear dynamic equations are used in the solution process. They are solved using 4th order R–K method. The time interval chosen is 0.0015 s.

Two case-studies were conducted on the system: case 1 corresponding to sudden load change of (0.005 + j0.005) p.u. and case 2 corresponding to (0.008 + j0.008) p.u. The parameters are given in Appendix B.

The frequency and load voltage deviations of the power system without SMES unit for the above two cases are shown in Figs. 7 and 8 respectively. In case 1, the maximum frequency and load–voltage deviations are − 0.0126 Hz and − 0.00306 p.u. respectively. The maximum frequency and load-voltage deviations in the case 2 are − 0.023 Hz and − 0.00428 p.u. respectively. Finally, the load-voltage deviation tends to stabilizes at − 0.00173 p.u. in case 1 and 0.002 p.u. in case 2 respectively. The performance of the AVR shows that it is fast enough to pull back the voltage following a sudden application of load (see Figs. 7 and 8).

The coupling effect between the $Q-V$ and $P-f$ loops is the main cause for the oscillations.

The responses of the power system with a 4 MJ SMES unit under the same disturbances for both the cases mentioned above are shown in Figs. 9 and 10 respectively.

In both these cases, the P-modulation by the SMES unit reduces the oscillation in the frequency while Q-modulation along with the reactive power provided by the switched capacitor bank improves the load voltage profiles. However, Fig. 10 clearly show the advantage of fuzzy logic controller over conventional controller in every aspect. The performance comparison is shown in Table 2.

4.3. Performance evaluation

4.3.1. Case 1 [load change (0.005 + j 0.005) p.u.]

When conventional controller is used, the maximum frequency deviation is 0.0105 Hz; and this occurs at an expense of change in the inductor current of − 1.5 kA. Meanwhile, the fuzzy controller limits the frequency deviation to 0.0093 Hz at the expense of inductor current change of − 1.48 kA. It is evident from Fig. 9 that the fuzzy controller can provide better compensation with less deviation of inductor current. This ensures the effective use of its power modulation. There is not much gain in voltage control loop except that the reactive power compensation provided by fuzzy controller is less than the conventional one for the similar load voltage profiles.

4.3.2. Case 2 [Load change of (0.008 + j 0.008) p.u.]

Compared to the results of case 1, the fuzzy controller shows significant development for the larger disturbance. Fig. 10 shows that the P-modulation by the SMES unit with fuzzy controller reduces the frequency oscillation by almost 24.3% compared with 18.9% reduction by the conventional controller. Significant improvements in the first overshoot and settling time are also clearly observed. The inductor current deviation is much less than that of conventional controller. Like the previous case, the effective use of active and reactive power modulation is also ensured.

With the help of switched capacitor bank, the Q_{net} supplied by SMES unit substantially reduces the voltage deviation. In Figs. 8 and 9, it is observed that due to fast AVR action, the load-voltage goes up within a few seconds. During the initial period immediately after the sudden increase in load, the slope of the voltage deviation is very large and negative. Notice that the maximum voltage deviations are same with and without the SMES unit. It is as expected since compensation cannot be provided due to propagation delay time. The negative voltage deviation requires capacitive VAr and initial values of Q_{dem} are accordingly chosen by FVC after satisfying the requirement of P_d. Like FFC, the FVC also considers the change in ΔV_L as a dominant factor in the first cycle. In the later stage mainly voltage deviation determines the desired compensation Q_{dem}. It is seen that with less VAr compensation, the FVC is able to maintain same voltage deviation like the conventional controller. The overall performance of fuzzy controller shows a clear edge over the non-fuzzy one.

When operated in the two quadrant mode, the SMES unit itself absorbs inductive VAr in addition to ΔQ_L

due to sudden load application. Therefore switching of static capacitors are needed during the dynamic variation of the load-voltage. But with four quadrant operation the amount of switching capacitance needed is much less than that of two quadrant operation. In case 1, it is observed that the four quadrant operation obviates the use of switched capacitor bank. There is no advantage on P-modulation in four-quadrant mode.

4.4. Economic aspect

One of the most important criteria of using SMES unit either for load leveling and/or the improvement of power system performance is that it should be economically viable. With the proposed mode of control the fluctuation of inductor current is smaller. This clearly indicates that the SMES unit with fuzzy logic control is able to handle much bigger disturbances within the same capacity as compared with other controllers. Fig. 10 shows that the rating of switched capacitor bank can be decreased with the proposed mode of control which further decreases the cost of the SMES unit.

5. Conclusions

This paper presents a new method of controlling the SMES unit for improving the transient performance of the single area system. Fuzzy logic was used to design frequency and voltage controllers to generate required control signals for the SMES unit. Direct generation of control signals for the 12-pulse converter from active and reactive power modulation using both error signals and change in successive error signals, makes the proposed controller more sensitive. As a result, $P-Q$ modulation is effectively used. Under smaller disturbances, fuzzy logic controller provides a little gain in system frequency damping and inductor current variations. However, when the degree of disturbance increases, fuzzy control shows its clear superiority in every aspect over the conventional controller.

In the proposed mode of control it is observed that the time taken to damp the system oscillations is comparatively smaller. Also this occurs with a smaller deviation of the inductor current. This paper suggests that with the use of fuzzy logic control, the size of the SMES unit can be reduced and the rating of the switched capacitor bank can be made smaller.

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