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Abstract: Provided that superconducting magnetic energy storage (SMES) is located near the consumer in the power system, levelling of fluctuating load power and compensation of reactive power can be achieved. Thus, loss in the power system can be reduced and the power system stability can be improved. In this paper, an SMES control strategy for levelling the fluctuating load power based on Lukasiewicz logic is proposed. The control characteristics are discussed by comparing a simulation with the control results of other methods proposed by the authors. The variance achieved by the proposed method is smaller than those obtained with the other control methods. Thus, the proposed control method is superior to other control methods.

List of principal symbols

$a_1, a_2, a_3, b_1, b_2, b_3$ = coefficients
$C_1, C_2, C_3, C_4, C_5, C_6$ = fuzzy sets
E = r.m.s. value of the line-to-line source voltage
$e_a(t)$ = source voltage in A-phase
$h_n(t)$ = ratio of the nth harmonic current to I
I = mean value of the fundamental component in the load current
$i_{La}(t)$ = load current in A-phase
I_{max} = maximum value of the coil current for W_{max}
$i_{sc}(t)$ = current flowing through the superconducting coil
L = inductance of the superconducting coil
$m_f(t)$ = component of the fringe wave
M'_S = presumed sustained component of load power
$m_S(t)$ = component of the sustained wave
P_1, P_2 = fuzzy sets
P_C, q_C = active and reactive power released or absorbed by the power control system
P_C^*, q_C^* = active and reactive power demands released or absorbed by the power control system
P_L, q_L = active and reactive power produced in the load
p_S, q_S = active and reactive power on the source side
p_S^*, q_S^* = active and reactive power demands on the source side
$p_S^*(t: t - \Delta t)$ = active power demand at time t predicted at time $t - \Delta t$
$p_S^*(t - \Delta t: t - 2\Delta t)$ = active power demand at time $t - \Delta t$ predicted at time $t - 2\Delta t$
$p_S^*(t + \Delta t: t)$ = active power demand at time $t + \Delta t$ predicted at time t
P_{u1}, P_{u2} = fuzzy sets
Q_E, Q_I = energy capacity and current rating of the SMES
u_1, u_2, u_3, u = points of the intersection of the membership functions
u_k = defuzzificated value
v = variance of the active power on the source side
W_{max} = maximum value of the energy stored in the SMES
x_1, x_2, x_3 = state variables
y = a variable
δ = a function
$\mu_{C1}, \mu_{C2}, \mu_{C3}, \mu_{C4}, \mu_{C5}, \mu_{C6}$ = membership functions
μ_{P1}, μ_{N1} = membership functions for the fuzzy sets P_1 and P_2
μ_{Pu1}, μ_{Nu1} = membership functions for the fuzzy sets P_{u1} and P_{u2}
$\phi_1(t)$ = phase angle of the fundamental component in the load current
ω = 377, rad/s

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1 Introduction

Superconducting magnetic energy storage (SMES) has a superconducting coil in which a semipermanent current is circulating. Electric energy can be stored in SMES in the form of magnetic energy. Thus, the superconducting coil has a high efficiency because its electrical resistance is almost zero and little energy is dissipated in it.

Provided the SMES is near the consumer in the power system, levelling of the fluctuating load power and compensation of the reactive power can be achieved. Thus, loss in the power system can be reduced and power system stability can be improved. The SMES control strategy has been studied for levelling a daily or a short-term load variation using the compact SMES [1].

Fluctuation of the load power is generally regarded as the overlap of two waves: a long periodic wave (sustained wave) and a short periodic wave (fringe wave). If the load fluctuation is levelled to a constant, a large-capacity SMES is required. However, if only the fringe wave in the load fluctuation is levelled, small-capacity SMES is sufficient. The authors have proposed an SMES control strategy for levelling fluctuating load power using the estimation function [2] and fuzzy logic [3–5]. These methods can level the fluctuating load power well, and a control strategy using fuzzy logic can level the fluctuating load power better than one using the estimation function. The proposed strategy using fuzzy logic is based on direct approximate reasoning.

In this paper, an SMES control strategy for levelling fluctuating load power based on the Lukasiewicz logic is proposed and its control characteristics are investigated by simulation. The production rules are constructed according to the levelling of the active power on the source side and the energy stored in the SMES. The power demand is decided by approximate reasoning based on Lukasiewicz logic. The control results obtained with the strategy proposed are superior to those of other control strategies which have been proposed by the authors.

2 Load power fluctuation and levelling

2.1 Load power fluctuation

The active and reactive power in the power station of an electric railway fluctuates with time. Effective use of power facilities can be realised by levelling the fluctuating active power and compensating the reactive power using power control equipment with an energy storage element.

The fluctuation of load power can be regarded as an irregular variation superimposed on the sustained wave and the fringe wave, which is treated only in a probabilistic manner. The sustained wave is a long periodic component and the fringe wave is a short periodic component. The load power fluctuation shown in Fig. 1 is used in this paper [6]. The source voltage and the load current are expressed by

$$e_a(t) = \sqrt{(2)}E \sin(\omega t) \quad (1)$$

$$i_{La}(t) = \sqrt{(2)}I\{1 + m_s(t)\}\{1 + m_f(t)\} \times [\sin\{\omega t - \phi_1(t)\} + h_5(t)\sin(5\omega t) + h_7(t)\sin(7\omega t) + h_{11}(t)\sin(11\omega t) + h_{13}(t)\sin(13\omega t)] \quad (2)$$

In the following, the load currents are assumed to be symmetrical in three phases. The voltage, current and energy are normalised by E(V), I(A) and $\sqrt{(3)}EI \times 1$ (W s), respectively.

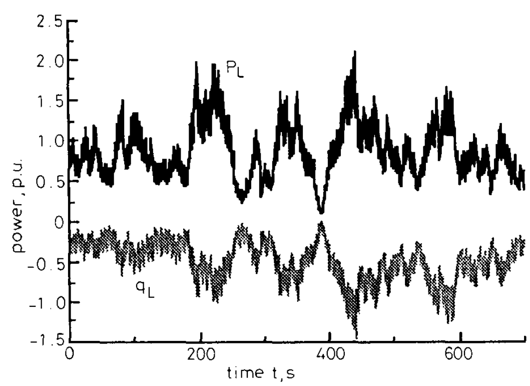

Fig. 1 *Load power fluctuation*

2.2 Levelling of active power and compensation of reactive power with SMES

Fig. 2 shows the power control system installed near the consumer. This power control system is composed of the SMES and acts as energy storage equipment and VAR compensator. It levels the fluctuation of the load power and compensates the reactive power produced in the load.

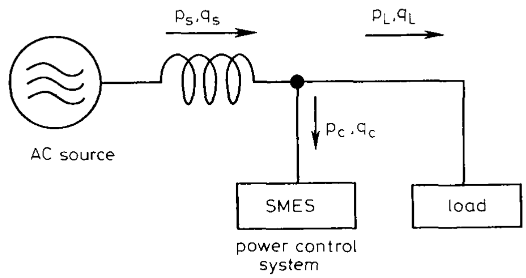

Fig. 2 *Power control system*

The active power p_L and the reactive power q_L as defined in Reference 7, fluctuate with time. If this power system is not in use, the load power fluctuates in the source line. However, the active power p_S on the source side can be levelled by releasing or absorbing the energy from the SMES, and the reactive power q_S can be also compensated.

As p_L and q_L can be measured, the power demands p_C^* and q_C^* of the power control system are calculated from the power demand p_S^* and q_S^* on the source side by

$$p_C^* = p_S^* - p_L$$
$$q_C^* = q_S^* - q_L \quad (3)$$

The difference between p_L and p_S^* is the active power p_C^*, which the SMES should release or absorb.

The integrated value of the difference between p_L and p_S is the quantity of energy released or absorbed by the SMES. As the difference between the released energy and the absorbed energy approaches zero, the energy storage capacity of the SMES can be reduced. As the purpose of this power control is to level the active power, the fluctuation of the active power on the source side must be suppressed as much as possible, but q_S^* should be as small as possible to maximise the transmitting efficiency of electric energy in the power system and minimise the voltage variation.

3 Levelling control based on fuzzy logic

3.1 Conditions for levelling the load power fluctuation

The following three conditions are introduced to define the levelling of the active power and the energy of the SMES.

Condition 1: The active power on the source side should be levelled sufficiently.

Condition 2: The released or absorbed energy of the SMES must be decided so that the energy stored in the SMES is maintained between the minimum value $W_{max}/4$ and the maximum value W_{max}. The set point of the energy stored in the SMES is set to $5W_{max}/8$, which is the mean value of the stored energy.

Condition 3: The SMES must be able to release or absorb the electric power in accordance with the power demand p_C^* and q_C^*. These conditions can be written in the form of production rules as follows:

Production rule 1:
IF the change of the predicted active power on the source side is large,
THEN the change of the active power demand on the source side must be reduced.

Production rule 2:
IF the energy stored in the SMES is larger (smaller) than the set point,
THEN the released energy must be larger (smaller) or the absorbed energy smaller (larger).

Production rule 3:
IF the predicted active power on the source side approaches the upper limit of the energy that the SMES can release or absorb,
THEN the energy to be released and absorbed from the SMES must be reduced.

The state variable in production rule 1 is denoted by

$$x_1 = p_S^*(t: t - \Delta t) - p_S^*(t - \Delta t: t - 2\Delta t) \quad (4)$$

The state variable in production rule 2 is denoted by:

$$x_2 = \frac{w(t) - 5W_{max}/8}{5W_{max}/8} \quad (5)$$

where $w(t) = Li_{sc}(t)^2/2$.

The state variable of production rule 3 is denoted by

$$x_3 = \frac{\sqrt{[2(p_C^{*2} + q_C^{*2})]}}{3E} \quad (6)$$

3.2 Decision of power demand based on Lukasiewicz logic

The power demand for levelling the fluctuating load power is derived by means of approximate reasoning based on Lukasiewicz logic. The membership functions μ_{P1} and μ_{N1} of the fuzzy sets P_1 and P_2 for the left-hand side of production rule 1 are denoted by:

$$\mu_{P1}(x_1) = \tan^{-1}(a_1 x_1)/\pi + 0.5 \quad (7)$$

$$\mu_{N1}(x_1) = \tan^{-1}(-a_1 x_1)/\pi + 0.5 \quad (8)$$

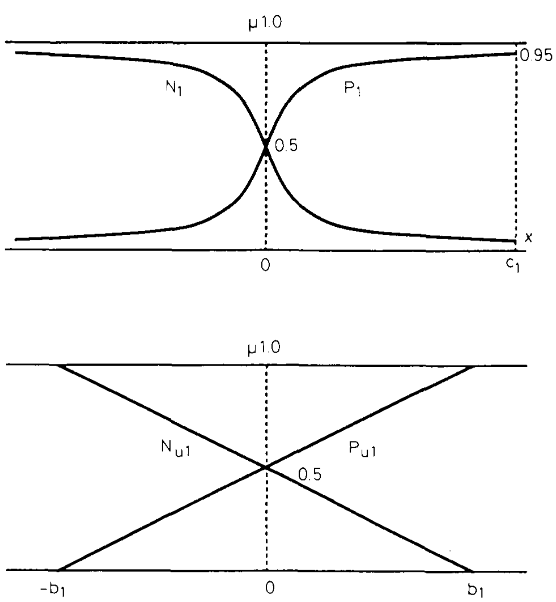

Fig. 3 *Membership function*

where μ_{P1} is 0.95 for $x_1 = c_1$. Then, the membership functions μ_{Pu1} and μ_{Nu1} of the fuzzy sets P_{u1} and P_{u2} for the right-hand side of production rule 1 are denoted by:

$$\mu_{Pu1}(u_k) = u_k/(2b_1) + 0.5 \quad (9)$$

$$\mu_{Nu1}(u_k) = -u_k/(2b_1) + 0.5 \quad (10)$$

Fig. 3 shows the membership function for eqns. 7–10.

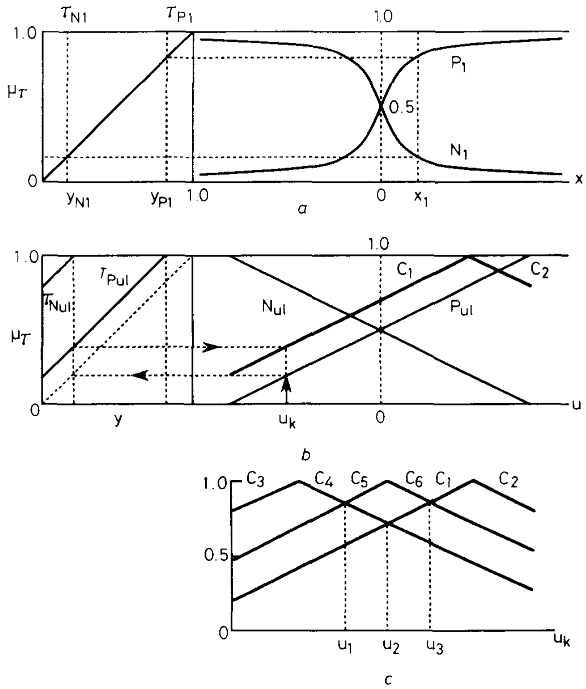

Fig. 4 *Approximate reasoning based on Lukasiewicz logic*

Next, we explain the method of the approximate reasoning based on Lukasiewicz logic shown in Fig. 4. Provided that the truth value of each rule is true, the fuzzy truth values $\mu_{\tau P1}$ and $\mu_{\tau N1}$ of the left-hand side are expressed by

$$\mu_{\tau P1}(y) = \delta(y - y_{P1}) \quad (11)$$

$$\mu_{\tau N1}(y) = \delta(y - y_{N1}) \quad (12)$$

where $y_{P1} = \mu_{P1}(x_1)$ and $y_{N1} = \mu_{N1}(x_1)$. The fuzzy truth of the right-hand side is derived in the next expressions from the fuzzy truth of the left-hand side and the fuzzy modus ponents.

$$\mu_{\tau Pu1}(y) = y + (1 - y_{P1}) \quad (13)$$

$$\mu_{\tau Nu1}(y) = y + (1 - y_{N1}) \quad (14)$$

The fuzzy sets obtained from production rules 1 and 2 are represented by C_1 and C_2; the membership functions μ_{C1} and μ_{C2} of the fuzzy set of the manipulated value are then gained from the expressions:

$$\mu_{C1}(u_k) = \mu_{\tau Pu1}(\mu_{Pu1}(u_k)) \quad (15)$$

$$\mu_{C2}(u_k) = \mu_{\tau Nu1}(\mu_{Nu1}(u_k)) \quad (16)$$

Substituting eqns. 7–10, 13 and 14 into eqns. 15 and 16, we obtain:

$$\mu_{C1}(u_k) = u_k/(2b_1) - \tan^{-1}(a_1 x_1) + 1 \quad (17)$$

$$\mu_{C2}(u_k) = -u_k/(2b_1) - \tan^{-1}(-a_1 x_1) + 1 \quad (18)$$

where μ_{C1} and μ_{C2} are limited within the range 0.0–1.0. In the same manner as above, the membership functions for production rules 2 and 3 are obtained from

$$\mu_{C3}(u_k) = u_k/(2b_2) - \tan^{-1}(a_2 x_2) + 1 \quad (19)$$

$$\mu_{C4}(u_k) = -u_k/(2b_2) - \tan^{-1}(-a_2 x_2) + 1 \quad (20)$$

$$\mu_{C5}(u_k) = u_k/(2b_3) - \tan^{-1}(a_3 x_3) + 1 \quad (21)$$

$$\mu_{C6}(u_k) = -u_k/(2b_3) - \tan^{-1}(-a_3 x_3) + 1 \quad (22)$$

The defuzzificated value u is the medium value from the points of the intersection of each membership function as shown in Fig. 4*c*.

$$u = \text{medium } (u_1, u_2, u_3) \quad (23)$$

Then, the power demand is decided by using the obtained defuzzificated value in the expression

$$p_s^*(t + \Delta t: t) = p_s^*(t: t - \Delta t) + u/100 \quad (24)$$

Although the active and reactive powers are obtained from the instantaneous values of current and voltage waveforms, the power demands obtained from eqn. 24 are the values obtained from the sustained wave by selecting the proper values of Δt and the coefficients in fuzzy logic.

3.3 Modification of power demand

When the power control cannot be put into practice because of the limits of the energy stored in the SMES and the current flowing into the SMES, the power demand derived from eqn. 24 must be modified so that the modified power demand exists in the controllable area as shown in Fig. 5.

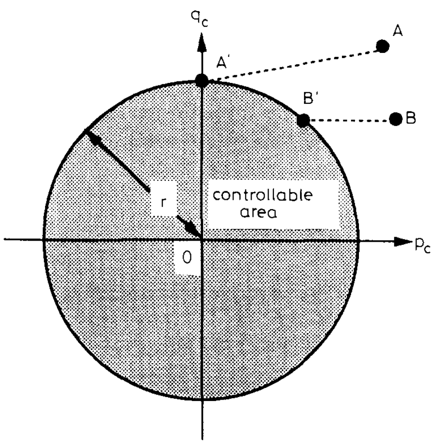

Fig. 5 *Modification of power demand*

Compensation of the reactive power occurs before the levelling of the active power. Therefore, the power demand indicated at the point A is modified to be that at the point A', and the power demand at the point B is modified to be that at the point B'.

The power demand must be modified if the SMES current is below the lowest limit ($I_{max}/2$):

$$p_c^{*\prime} = \begin{cases} 0 & (p_c^* > 0) \\ p_c^* & (p_c^* < 0) \end{cases} \quad (25)$$

$$q_c^{*\prime} = q_c^*$$

Similarly, it must be modified if the SMES current is above the upper limit (I_{max}):

$$p_c^{*\prime} = \begin{cases} p_c^* & (p_c^* > 0) \\ 0 & (p_c^* < 0) \end{cases} \quad (26)$$

$$q_c^{*\prime} = q_c^*$$

4 Simulation

4.1 Estimation method of power levelling

The results of the proposed power control are evaluated by the variance:

$$v = \sum_{n=1}^{1000} \{M_s'(n) - p_s(n)\}^2/1000 \quad (27)$$

In this simulation, the simulation time is 700 s, and the number of data in the simulation is 1000. As the variance v becomes smaller, the active power on the source side follows well after the sustained component.

4.2 Discussion on coefficient in fuzzy logic

The coefficients in the membership functions b_1, b_2, b_3, c_1, c_2 and c_3 must be decided for the good levelling. In SMES with a small current rating, power control becomes impossible despite the provisions of production rule 3, in which the power demand is modified, and power levelling cannot be achieved. Thus, we set the coefficients b_2 and c_2 so that power control is in the controllable area and good levelling of power fluctuation is obtained. Then b_1, b_3, c_1 and c_3 are set to unity.

To level the fluctuation of power in the sustained wave, the sampling period of active and reactive power Δt must be smaller compared with the period of the sustained wave. p_S follows the fringe wave when Δt is selected to be too small, and so Δt is 0.5 s for the load power fluctuation in Fig. 1 [2].

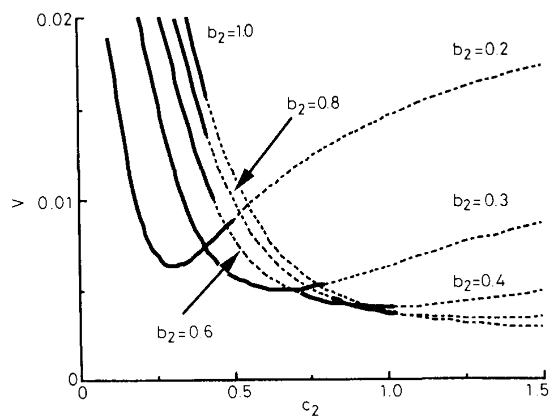

Fig. 6 *Variance for b_2 and c_2*

Fig. 6 shows the variance of the levelled power to the sustained component for the coefficients b_2 and c_3. In this figure, the solid line indicates the controllable area and the broken line indicates the uncontrollable area when the current rating of the SMES becomes smaller. These coefficients must be selected so that the variance v is small. Then the coefficients b_2 and c_3 are 0.8 and 1.0, respectively.

4.3 Simulation results

Fig. 7 shows the results of levelling the fluctuating load power. When $Q_E = 20$ p.u. and $Q_I = 4$ p.u., the active power is well levelled and the reactive power is compensated to be zero as shown in this Fig. 7*a*. When the energy capacity of the SMES is reduced (Fig. 7*b*, Q_E = 10 p.u. and Q_I = 4 p.u.), the active power is well levelled

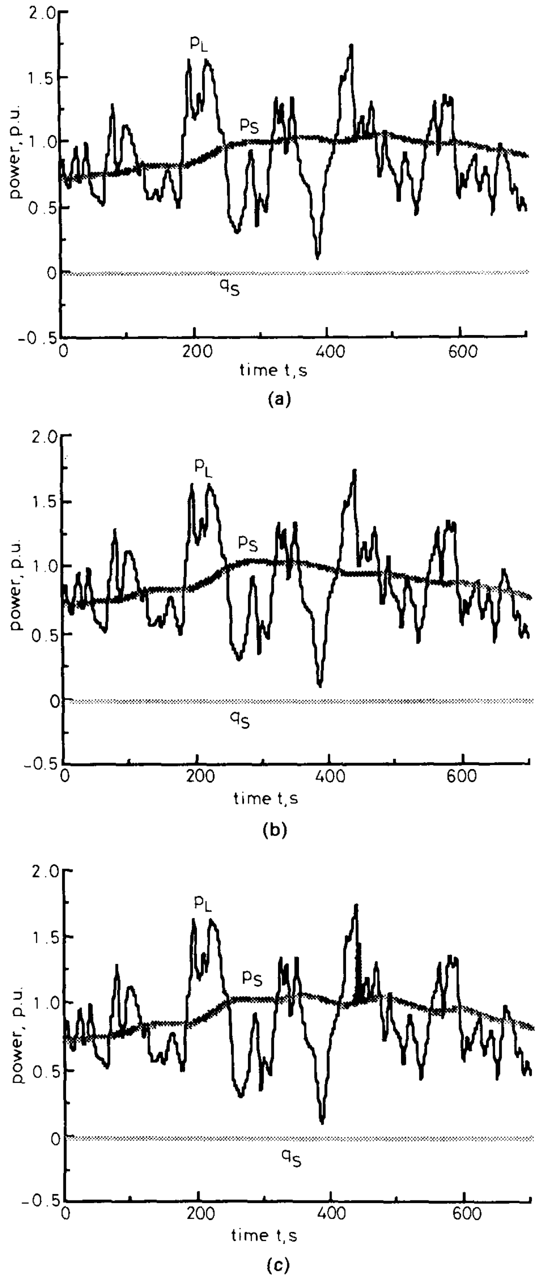

Fig. 7 *Control results of levelling load fluctuation*
a Case 1: Q_E = 20 p.u., Q_I = 4 p.u.
b Case 2: Q_E = 10 p.u., Q_I = 4 p.u.
c Case 3: Q_E = 20 p.u., Q_I = 3 p.u.

and the reactive power is compensated to be zero, as in Fig. 7*a*. However, there is a period when the active power cannot be levelled because of the reduced current capacity of the SMES (Fig. 7*c*, Q_E = 20 p.u. and Q_1 = 3 p.u.). In this period, the active power on the source side indicates the sudden change. However, the reactive power is compensated to be zero even in this period, which is caused by the lack of the energy stored in the SMES due to the small current capacity.

Table 1 shows the levelling results of the proposed method with those of other methods. The variance in the proposed method is smallest in cases 1 and, particularly, 3. The variance of the proposed method in case 2 is slightly larger than that of the control method of Reference 5. However, the levelling of the fluctuating load power can be achieved well, as shown in Fig. 7*b*. Thus, it is confirmed that the control method proposed in this paper is superior to the other control methods.

Table 1: Comparison of variance with other methods

	SMES rating		Variance		
	Q_E (p.u.)	Q_I (p.u.)	Proposed method	Literature [5]	Literature [2]
1:	20	4	0.0037	0.0047	0.0134
2:	10	4	0.0110	0.0101	0.0256
3:	20	3	0.0047	0.0132	0.0188

5 Conclusions

In this paper, an SMES control strategy for levelling the fluctuating load power based on Lukasiewicz logic is proposed. The control characteristics are discussed and compared with those of other control methods proposed by the authors. The variance in the proposed method in this paper is smaller than those obtained with the other control methods, confirming that the poposed method is superior to the others. This control system and technique is readily available for the energy saving and stabilisation of the power system.

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