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POWER FACTOR CORRECTION OF SYNCHRONOUS MOTOR USING FUZZY LOGIC

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Abstract

Application of fuzzy logic theory in power factor correction of a synchronous motor is investigated in this paper. The power factor measured at the input terminals of a synchronous motor is adjusted to a required value using a fuzzy logic controller (FLC). If the measured power factor is different than the required reference value an error signal is generated. This error signal is evaluated by FLC to obtain a control signal for the synchronous motor excitation circuit since the power factor of a synchronous motor can be controlled and held at a desired value by adjusting the excitation current. Therefore it seem, to be more economic than other methods for some special applications.

I. Introduction

One of the important problems of today's energy utilization is the use of generated electrical energy efficiently. If the energy is not utilized properly, large voltage variations occur in transmission and distribution (T&D) systems resulting in low utilization efficiency for users. Therefore, operating power factor of T&D systems must be corrected. Since the reason of low power factor operation of T&D systems is the reactive power requirements of loads, this problem should be eliminated at load terminals. Thus, the required reactive power is supplied from another source, usually compensating capacitors, at load terminals and the reactive power loading of T&D systems is reduced [1]. The control of reactive power flow and voltage magnitude in high voltage alternating current (HVAC) systems has become an important task. Regarding the voltage and power variations in industry and distribution systems the design of new and special compensation systems has emerged [2]. Reactive power required by the loads is generated using dynamic or static phase shifters [1]. Nowadays, static capacitors, reactors and thyristor technology are frequently used in HVAC systems [3].

Although, over the years the static Volt Ampere Reactive (VAR.) systems have been used to control the voltage fluctuations caused by over-loading, they are also used in a different way to reduce the voltage variations [4]. In this paper, the reactive power control of an industrial plant having synchronous motors is studied. Therefore, the operating power factor of each synchronous motor is controlled separately to reduce the reactive power extracted from the supply system. Classical mathematical approaches used in system modeling may not be applicable to the systems with unknown states and models [5]. However, fuzzy logic theory can be used to establish a relationship between input and output of the systems that are very complex to be modeled mathematically. Fuzzy logic uses linguistic expressions to define system variations and adjusts system input to obtain a desired output with IF-THEN-ELSE procedure [6]. Due to its flexible usage, fuzzy logic has found a large application area including power systems [7,8]. In this paper, a fuzzy logic based controller is designed to operate synchronous motors at desired power factor levels.

2. Mathematical Model Of The Synchronous Motor

Using the dq-axis transient model equations of synchronous machines, the following steady-state equations are obtained [9].

$$(1)\qquad \begin{bmatrix} V_d^s \\ V_q^s \\ V_f^r \end{bmatrix} = \begin{bmatrix} R_1 & -\omega_1 L_q & 0 \\ \omega_1 L_d & R_1 & \omega_1 M_f \\ 0 & 0 & R_f \end{bmatrix} \begin{bmatrix} i_d^s \\ i_q^s \\ i_f^r \end{bmatrix}$$

Where $\omega_1 = \omega_m$ is the synchronous speed in rad/s.

Three-phase voltages and currents of a synchronous motor for balanced operation can be written as:

$$V_{a,b,c}(t) = \sqrt{2}.V.Sin[\omega_1 t - (m-1)(2\pi/3)] \qquad (2)$$

$$i_{a,b,c}(t) = \sqrt{2}.I.Sin[\omega_1 t - \phi_1 - (m-1)(2\pi/3)] \qquad m = 1,2,3 .... \qquad (3)$$

Where V and I are the RMS values of voltages and currents, respectively. ϕ_1 is the phase angle between voltage and current. Besides, the torque of a synchronous motor can be expressed, as follows, using the dq-axis transient model equations [9].

$$T_e = p[(L_d - L_q)\, i_d^s\, i_q^s + M_f\, i_q^s\, i_f^r] \qquad (4)$$

For steady-state operation motor equations can be written in terms of dq variables as

$$V_d^s = -\sqrt{3}\ V\ Sin\delta \qquad (5)$$

$$V_q^s = \sqrt{3}\ V\ Cos\delta \qquad (6)$$

$$i_d^s = -\sqrt{3}\ I\ Sin(\delta + \phi_1) \qquad (7)$$

$$i_q^s = \sqrt{3}\ I\ Cos(\delta + \phi_1) \qquad (8)$$

Where δ is the initial load angle. From equations above.

$$V\ Sin\delta = R_1\ I\ Sin(\delta + \phi_1) + \omega_1\ L_q\ I\ Cos(\delta + \phi_1) \qquad (9)$$

$$V\ Cos\delta = R_1\ I\ Cos(\delta + \phi_1) - \omega_1\ L_q\ I\ Sin(\delta + \phi_1) + \omega_1\ M_f\ I_f^r / \sqrt{3} \qquad (10)$$

are obtained. These last two equations are the characteristic equations of a synchronous motor at steady-state. With balanced phase voltages the following equations can be derived from equations (7) and (10).

$$I_d^s = \sqrt{3}[(\ V\ Cos\delta - V_o)\ \omega_1\ L_q - R_1\ V\ Sin\delta] / [\omega^2\ L_d\ L_q + R_1^2] \qquad (11)$$

$$I_q^s = \sqrt{3}[(\ V\ Cos\delta - V_o)\ R_1 + \omega_1\ L_d\ V\ Sin\delta] / [\omega^2\ L_d\ L_q + R_1^2] \qquad (12)$$

Where

$$V_o = (1/\sqrt{3})(\omega_1\ M_f\ I_f^r)$$

Similarly, power factor angle ϕ_1 and phase current I can be obtained as

$$\tan(\delta + \phi_1) = I_d^s / I_q^s \qquad (13)$$

$$I = \sqrt{\frac{(I_d^s)^2 + (I_q^s)^2}{3}} \qquad (14)$$

If R_1 is ignored and torque equation is rewritten, then

$$T_e = (3p/\omega_1)[(V_o\ V\ Sin\delta)/(\omega_1\ L_d) + (1/2)\ V^2[(\omega_1\ L_q)^{-1} - (\omega_1\ L_d)^{-1}]Sin2\delta] \qquad (15)$$

is obtained, where p: is the number of the poles.

If the reactive power is written for $R_1 = 0$, the following equation is obtained.

$$Q = -3[(V_o\ V\ Cos\delta)/(\omega_1\ L_d) - V^2/(\omega_1\ L_d) - V^2[(\omega_1\ L_q)^{-1} - (\omega_1\ L_d)^{-1}]\ Sin2\delta] \qquad (16)$$

similarly, the total active power is written as:

$$P = 3\ V\ I\ Cos\phi_1 = \omega\ T_e \qquad (17)$$

3. Design Of The Fuzzy Logic Controller

The main purpose of this study is to design a fuzzy logic based controller to control the power factor of a synchronous motor. The principle scheme of the system to be controlled is shown in Figure 1. In this scheme, the operating power factor of the synchronous motor is measured and compared with a reference power factor value in order to obtain an error signal that is evaluated by the FLC to yield a control signal. This control signal is then used to control the excitation current of the motor by adjusting the output voltage of a dc chopper. The motor is assumed to be running at its synchronous speed during all these procedures.

The control signal to the dc chopper is used to determine the chopper conducting period or chopper duty cycle, which may vary between 0 and 1. The dc voltage applied to the motor excitation circuit is adjusted depending on the value of the chopper duty cycle.

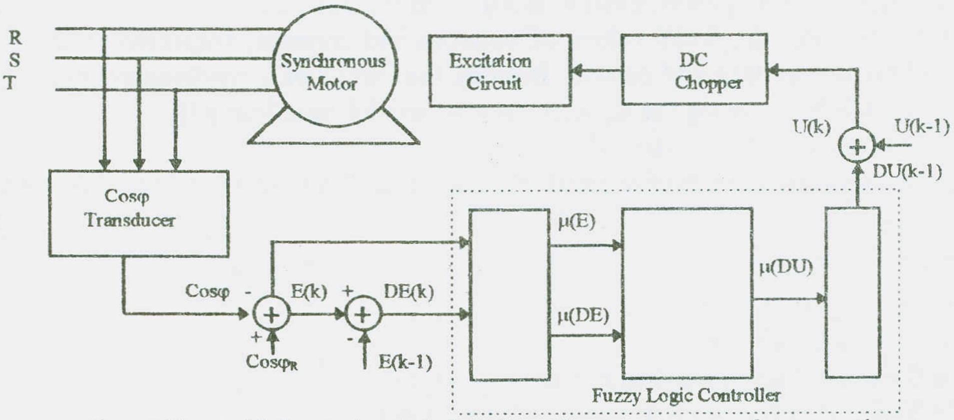


Figure 1. The principle fuzzy logic control scheme for synchronous motor power factor correction

As shown in Figure 1, the FLC is separated by dotted lines from other parts of the scheme and it consists of three main stages.

Stage 1: Fuzzification

The crisp values of error, E and change in error, DE are converted to fuzzy values μ(E) and μ(DE), which represent the membership degrees of E and DE, respectively, in linguistic fuzzy subsets NL, NM, ..., PM, PL as shown in Figure 2.

The shapes of the fuzzy subsets is an important problem to be defined. These fuzzy subsets must be suitable for system response. Different fuzzy membership functions representing the fuzzy subsets can be used. The membership functions suited best for the system studied are given in Figure 2.(a) for E and in Figure 2.(b) for DE and DU.

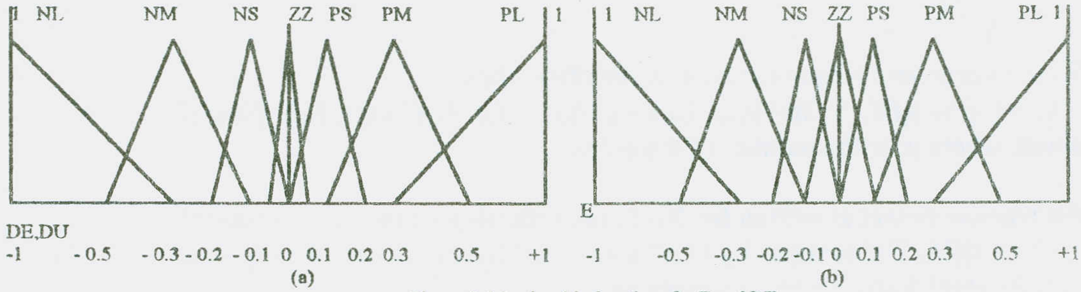


Figure 2. Membership functions for E and DE.

The following example shows how the crisp values of E and DE are converted to fuzzy numbers.

Let E and DE be 0,52 and -0,22 respectively. Then the following steps are performed in order.

1. Determine the linguistic fuzzy subsets in which E and DE have non-zero membership degrees. For the values given, the related fuzzy subsets are found to be PL for E and NM for DE.

2.The membership degrees of E and DE in the fuzzy subsets determined in step 1 are obtained. For the example given the membership values are obtained as $\mu_{PL}(E)=0{,}733$ and $\mu_{NM}(DE)=0{,}65$.

Stage 2: The Rule Decision Table

The rules are the second important stage in FLC design. They are obtained from the input-output relationship of the system to be controlled. The rule decision table used here is given in Table 1.

Table 1. Rule Decision Table

DE E	NL	NM	NS	ZZ	PS	PM	PL
NL	NM 1	NM 2	NS 3	NS 4	NS 5	NM 6	NM 7
NM	NM 8	NM 9	NS 10	NS 11	NS 12	NM 13	NM 14
NS	NM 15	NS 16	NS 17	ZZ 18	ZZ 19	NS 20	NM 21
ZZ	NL 22	NM 23	NS 24	ZZ 25	PS 26	PM 27	PL 28
PS	PM 29	PS 30	ZZ 31	ZZ 32	PS 33	PS 34	PM 35
PM	PM 36	PM 37	PS 38	PS 39	PS 40	PM 41	PM 42
PL	PM 43	PM 44	PS 45	PS 46	PS 47	PM 48	PM 49

This rule decision table includes the linguistic control actions depending on the linguistic definition of error and change in error. For example;

IF E is PL and DE is NM Then DU is PM

This is the implementation of one rule (rule 44) using the values of E and DE given in example of Stage 1. The other rules are also implemented similarly. With the above IF...THEN expression, the linguistic fuzzy subsets in which the change DU, in control signal has non-zero membership degree are determined.

Then the crisp DU values corresponding to the maximum degree points of these fuzzy subsets are stored to be used in the next step along with the membership degrees. For the example given, the linguistic fuzzy subsets from rule 44 is found to be PM: Positive Medium which has a maximum degree point at DU=0,3. This is the crisp value of DU that is stored to be used in the next step. The IF...THEN algorithm gives the fuzzy subsets where DU has non-zero membership degrees. However, this algorithm does not give any information about the values of the membership degrees. Therefore, besides IF...THEN linguistic expressions, the following Boolean algebra is used to obtain the membership grades of DU.

$$\mu_{PM}(DU) = \min[\mu_{PL}(E)\,,\ \mu_{NM}(DE)]$$

For the example given above, rule 44 yields the membership degree of DU in PM as $\mu_{PM}(DU) = 0{,}65$. The same procedure is repeated for all active rules to obtain non-zero membership grades of DU in corresponding fuzzy subsets. These non-zero membership degrees of DU are then stored to be used in the next step. It should be noted that only the rule 44 is active for the example given.

Stage 3: Defuzzification

As shown in Figure 1, there are two inputs to dufuzzification stage. These are μ(DU) membership degrees of DU in fuzzy subsets defined in Figure 2.(b), and the crisp values of DU corresponding to the maximum membership degree points of fuzzy subsets in which DU has a non-zero membership degree. These two inputs are evaluated in defuzzification stage to obtain the final value of the control signal change. Usually two algorithms known as maximum of maxima, (MOM) and center of area (COA) are used in defuzzification. COA is used here and the final crisp value of the change in control signal is obtained for the kth sample as

$$DU(k) = \frac{\sum_{i=1}^{n} \mu_{DU}(i)\, DU(i)}{\sum_{i=1}^{n} \mu_{DU}(i)} \tag{18}$$

Where n = 49 for the rule table used. For the example given the crisp value of DU(ı) is determined as

$DU(k) = [\,0 + (0{,}6)(0{,}3) + 0\,] \,/\, (\,0 + 0{,}6 + 0\,) = 0{,}3.$

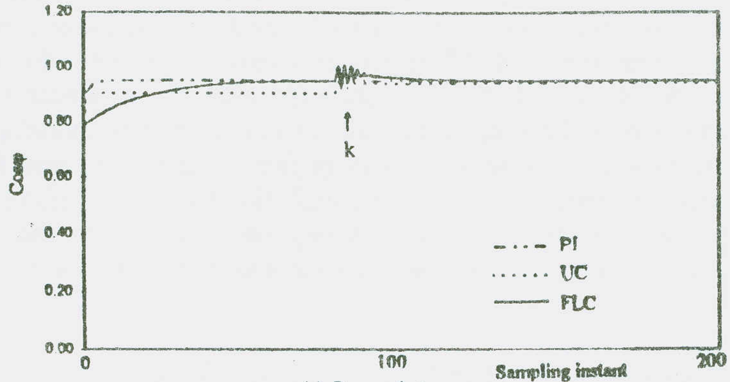
The final control signal is then obtained by adding this change to the previous control signal U(k-1) as

$$U(k) = U(k-1) + DU(k) \tag{19}$$

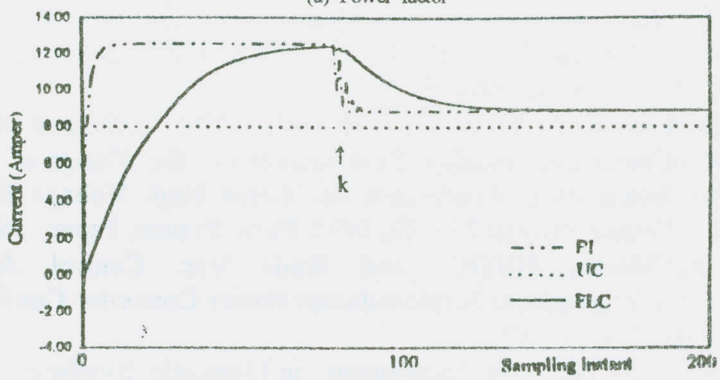
4. Results

The simulated performance of the proposed approach for power factor correction of synchronous motors is shown for two cases in Figures 3 and 4 . The effects of the load torque variations on the power factor are studied in both cases. Hence, the load torque is suddenly increased at kth sampling instant and the performances of PI and FL controllers are compared. Figure 3 shows the results for case I in which the reference power factor is less than 0,96. As shown, the classical PI controller gives better performance with a shorter settling duration. The results for the reference power factor values over 0,96 are given in case II. FL controller yields better outputs in this case. As seen in Figure 4 the results of PI controller have fluctuations around the reference. This results show that FL controller gives better results for power factors higher than 0,96 as the PI controller seems to be better bellow 0,96. The performance of FL controller may be increased by using more suitable membership functions and rule table. This study is just to show that the FL controller can be used in this sort of application. Therefore fine tuning is recommended for better results.

Case I.



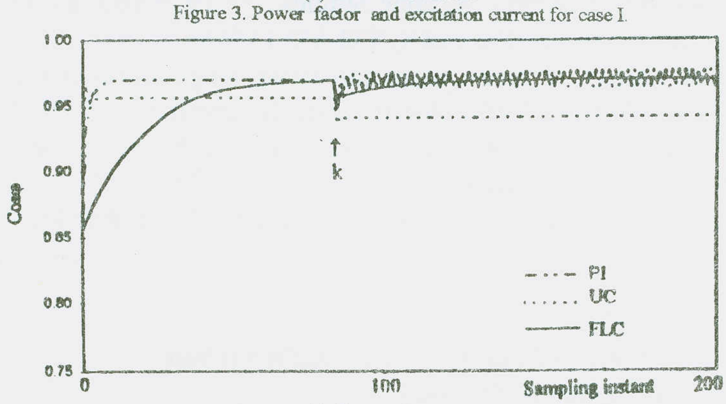
(a) Power factor



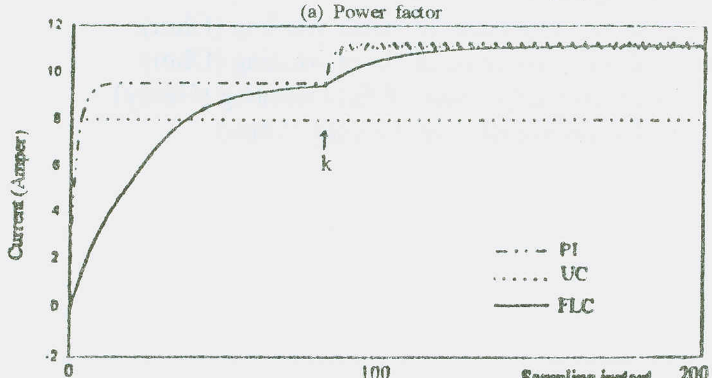
(b) Excitation current

Figure 3. Power factor and excitation current for case I.

Case II.



(a) Power factor



(b) Excitation current

Figure 4. Power factor and excitation current for case II.

5. Conclusions

Application of fuzzy logic in synchronous motor power factor correction problem has been studied in the paper. As shown in results, fuzzy logic controller can give results as good as a PI controller. Although PI controller seems to be better FL controller gives better performance for uncontrolled (UC) system disturbances. However, the designer of a fuzzy logic controller must have sufficient information on the relationship between input and output of the system. Therefore this information must be acquired from an expert. Since compensating capacitances are not required, the proposed method becomes more economical than the systems with compensating units. However the number of the machines should be limited to an optimum number. Otherwise economical considerations may be reversed.

6.References

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7. Appendix

Parameters of the synchronous motor

R1=0,213.	Total resistance of stator winding (Ohm).
Nk=2.	Number of the poles.
Xq=8,5.	q-axis reactance of stator winding (Ohm).
Xd=21,4.	d-axis reactance of stator winding (Ohm).
Mf=0,01.	Mutual inductance of field winding (Henry).
Rf=50.	Resistance of field winding (Ohm).