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Fuzzy Power Factor Control Systems

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Abstract

A method for obtaining the power energy with high quality is to keep the power factor for a load as close to unity as feasible. In this paper, we present a new method to improve the power factor for a load. The proposed method uses fuzzy control techniques in order to determine how many parallel capacitors are to be connected to the load for the correction of the power factor.

Key Words : power factor control, fuzzy control, phase advance capacitors

I. Introduction

A method for economical and effective use of power energy in a consumer is power factor control using phase advance capacitors for improving the power factor for the customer's load. Improving the power factor corresponds to decreasing the electric power rate. Hence, the need of improving the power factor in the consumer that contains low power factor loads such as induction motor, electric furnace, electric welding machine, is more and more increasing. Generally, the merits of using the phase advance capacitor banks are the decrease of the electric power rate, the prevention of power voltage drop, the margin of the power transformer capacity, and the decreasing of copper loss in the power transformer. The merits of the power company are the reduction of the distribution loss, high efficiency operation, and the rational driving of electric equipments. However, the phase advance capacitor may produce a contrary effect to the consumer when a light load is connected. Therefore, the automatic on/off control for the phase advance capacitors is necessary. The effect of automatic control for the advance capacitors, is to keep the proper power factor for the load, is to decrease the electric power rate, and is to prevent over-voltage in the light load[1].

The paper is organized into 5 sections. Section 2 introduces the basic concepts for the power factor and power factor control. In Section 3, the theoretical aspects of power factor control are discussed in the view point of stochastic diffrential equation. In Section 4, we describe the proposed fuzzy control scheme for power factor control, Section 5 is conclusions.

II. The Brief Review of Power factor Control

The power factor is defined as the ratio of average power to apparent power as follows:

$$Power\ factor = \frac{P}{VI} = \cos\theta \tag{1}$$

where P is the average power absorbed by consumers and VI is the apparent power which is provided by power companies.

The power factor is actually observed as a certain value below a unity value 1. Since the customer's load is inductive in most cases, parallel capacitors which is connected to a load are used for compensating the low power factor in order to keep the power factor of the load as close to unity as feasible. There are many inductive and capacitive components in the load, The power factor can be controlled by opening and closing a specific capacitor with appropriate control law.

III. Theoretical Aspects of Power Factor Control

The power factor for a load varies from time to time. Thus, the power factor can be defined as a random variable X_t depending on time. We define a function describing the trend of the power factor as $a(t, X_t) \in L^2_T$, where L^2_T is mean The power factor for a load varies from time to time. Thus, the power factor can be defined as a random variable X_t depending on time. We define a function describing the trend of the power factor as $a(t, X_t) \in L^2_T$, where L^2_T is mean squared Lebesgue measurable space for $t \in [0, T]$. In addition, we define a indeterministic term of the power factor depending on the variation of the reactance and the conductance as $b(t, X_t) \in L^2_T$. Then, we can obtain the following stochastic differential equation representing the variation of the power factor for a Wiener process $\{W_t : F_t\}$ defined on filtration F_t[2][3]:

$$dX_t = a(t, X_t)dt + b(t, X_t)dW_t \tag{2}$$

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Figure 1 shows the one-day trend of the power factor for a real load. Assuming that the control effect $J(X_t, \frac{\partial X_t}{\partial t})$ is added to a random variable X_t, we can obtain a new random variable Y_t defined on incremental σ-algebra filtration F_t as follows:

$$Y_t = U(X_t, \tfrac{\partial X_t}{\partial t}) = X_t + J(X_t, \tfrac{\partial X_t}{\partial t}) \tag{3}$$

Hence, the dynamic equation of power factor control including the control effect $J(X_t, \frac{\partial X_t}{\partial t})$ is as follows :

$$dY_t = \{\frac{\partial U}{\partial t}(x,\dot{x}) + LU(x,\dot{x})\} + b(t,X_t) + (1+\frac{\partial J}{\partial x}(x,\dot{x}))dW_t \tag{4}$$

where

$$L = a(t,X_t)\frac{\partial}{\partial x} + \frac{1}{2}b(t,X_t)^2\frac{\partial^2}{\partial x^2} \tag{5}$$

Since, $\frac{\partial U}{\partial t}(x,\dot{x}) = 0$, equation (4) can be rewritten as follows:

$$dY_t = LU(x,\dot{x})dt + b(t,X_t)\cdot(1+\frac{\partial J}{\partial x}(x,\dot{x}))dW_t$$
$$Y_t = Y_{t_0} + \int_{t_0}^{t} LU(x,\dot{x})ds + \int_{t_0}^{t} b(s,X_s)\cdot(1+\frac{\partial J}{\partial x}(x,\dot{x}))dW_s \tag{6}$$

In addition,

$$\frac{\partial U}{\partial t}(x,\dot{x}) = \frac{\partial J}{\partial x}(x,\dot{x})$$
$$\frac{\partial^2 U}{\partial t^2}(x,\dot{x}) = \frac{\partial^2 J}{\partial x^2}(x,\dot{x}) \tag{7}$$

If $J(x, \dot{x})$ satisfies the following bounded variation condition

$$\exists B_1, B_2 \in R[0,\infty)\ s.t.\ |\frac{\partial J}{\partial x}(x,\dot{x})| \le B_1\ and\ |\frac{\partial J}{\partial x}(x,\dot{x})| \le B_2 \tag{8}$$

, then the following inequality is satisfied:

$$|LU(x,\dot{x})| \le |a(t,X_t)||\frac{\partial U}{\partial t}(x,\dot{x})| + \frac{1}{2}|b(t,X_t)^2||\frac{\partial^2 U}{\partial t^2}(x,\dot{x})|$$
$$= |a(t,X_t)||1 \pm B_1| + \frac{1}{2}|b(t,X_t)^2|B_2 \tag{9}$$

In order to discuss the solution Y_t of the stochastic differential equation (6), which is affected by the control input, we assume that the following condition holds[2][3].

Assumption 1 (Measurability)

For $(t, x) \in [t_0, T] \times R$,

$$a(t,X_t) \in L_T^2$$
$$b(t,X_t) \in L_T^2$$

Assumption 2 (Global Lipschitz Condition)

For all $(t, x) \in [t_0, T]$ and $x, y \in R$, there exists $K > 0$ such that

$$|a(t,x) - a(t,y)| \le K|x-y|$$
$$|b(t,x) - b(t,y)| \le K|x-y|$$

Assumption 3 (Initial Value Bound)

X_{t_0} is F_{t_0} measurable, and $E(|X_{t_0}|) < \infty$

Assumption 4 (Linear Growth Bound)

For all $t \in [t_0, T]$ and $x, y \in R$, there exists $K > 0$ such that

$$|a(t,x)|^2 \le K^2|1+|x|^2|$$
$$|b(t,x)|^2 \le K|1+|x|^2|$$

Assumption 1~4 hold, we obtain the following inequality:

$$\begin{aligned}
&E(|Y_t|^2) \\
&\le 3E(|Y_{t_0}|^2) + 3E(|\int_{t_0}^{t} LU(x,\dot{x})ds|^2) + 3E(|\int b(s,X_s)\cdot(1+\frac{\partial J}{\partial x}(x,\dot{x}))dW_s|^2) \\
&\le 3E(|Y_{t_0}|^2) + 3(T-t_0)\int_{t_0}^{t} E(|LU(x,\dot{x})|^2)ds + 3\int E(|b(s,X_s)\cdot(1+\frac{\partial J}{\partial x}(x,\dot{x}))|^2)dW_s \\
&\le 3E(|Y_{t_0}|^2) + 6(T-t_0)\int_{t_0}^{t} E(|a(s,X_s)(1\pm B_1)|^2) + \frac{1}{2}B_2^2 E(|b(s,X_s)^2|^2)ds \\
&+3\int_{t_0}^{t} E\cdot(|b(s,X_s)\cdot(1\pm B_1)|^2)dW_s \\
&\le 3E(|Y_{t_0}|^2) + 6(T-t_0)\cdot|1\pm B_1|^2\int_{t_0}^{t} E(|a(s,X_s)|^2)ds + \frac{1}{2}B_2^2\int_{t_0}^{t} E(|b(s,X_s)^2|^2)ds \\
&+3|1\pm B_1|^2\int_{t_0}^{t} E(|b(s,X_s)|^2)dW_s \\
&\le 3E(|Y_{t_0}|^2) + 6(T-t_0)\cdot|1\pm B_1|^2 K^2\int_{t_0}^{t} E(1+|X_s|^2)ds + \frac{1}{2}B_2^2K^4\int_{t_0}^{t} E(1+|X_s|^2)^2 ds \\
&+3|1\pm B_1|^2 K^2\int_{t_0}^{t} E(1+|X_s|^2)dW_s
\end{aligned} \tag{10}$$

However, the mean squared value of the solution X_t of the stochastic differential equation which is not affected by the control input is as follows:

$$\begin{aligned}
&E(|X_t|^2) \\
&\le 3E(|X_{t_0}|^2) + 3E(|\int_{t_0}^{t} a(s,X_s)ds|^2) + 3E(|\int_{t_0}^{t} b(s,X_s)dW_s|^2) \\
&\le 3E(|X_{t_0}|^2) + 3(T-t_0)E(\int_{t_0}^{t} |a(s,X_s)|^2 ds) + 3E(|\int_{t_0}^{t} b(s,X_s)dW_s|^2) \\
&\le 3E(|X_{t_0}|^2) + 3(T-t_0+1)\cdot K^2\cdot E(\int_{t_0}^{t} (1+|X_s|)^2)ds
\end{aligned} \tag{11}$$

By the inductive hypothesis from the equation (11) we can obtain the following:

$$\sup_{t_0 \le t \le T} E(|X_t|) \le C_0 < \infty \tag{12}$$

Consequently, the result of equation (10) is as follows:

$$\begin{aligned}
&E(|Y_t|^2) \\
&\le 3E(|Y_{t_0}|^2) + 6(T-t_0)^2\cdot|1\pm B_1|^2 K^2(1+C_0^2) + 3(T-t_0)^2 K^4 B_2^2(1\vee C_0^2) \\
&+|1\pm B_1|^2\cdot K^2(T-t_0)\cdot(1+C_0^2) \\
&= 3E(|Y_{t_0}|^2) + 3(T-t_0)\cdot K^2\{2(T-t_0)|1\pm B_1|^2(1+C_0^2) + K^2B_2^2(1\vee C_0^2) + |1\pm B_1|^2(1+C_0^2)\}
\end{aligned} \tag{13}$$

In equation (13), since B_1 and B_2 are arbitrarily chosen parameters, and the right side is the product of B_1 and B_2, we can control Y_t to reach within the desired region in the sense of mean square.

IV. Fuzzy Power Factor Control

In Section 3, we observed that the power factor has indeterministic terms. Furthermore, since the power factor is controlled by opening and closing lead capacitors, the control input can be described mathematically as a linear combination of unit step functions as follows:

$$J(X_t) = \sum_{k=1}^{n} C_k \cdot \{u(X_t - r_k^C) - u(X_t - r_k^O)\} \tag{14}$$

where C_k is the compensated power factor as the k-th lead capacitor is closed, r_k^C is the reference power factor for closing the k-th lead capacitor, r_k^O is the reference power factor for opening the k-th lead capacitor and $u(x)$ is a unit step function represents $u(x)=1$ for $x \geq 0$, and $u(x)=0$ for $x < 0$. In the stochastic differential equation for the dynamics of the power factor control, if the control $J(X_t)$ has the form in equation (14), then the 1st order differential and 2nd order differential are Delta-Dirac and doublet function, respectively. Consequently, the pathwise continuity property may be broken. In this case, opening and closing actions of the capacitors are so frequent that bring out the stress of the power system.

However, if the control $J(X_t)$ has nonlinear function (for example, hysterisis property) such that the discontinuity in the control $J(X_t)$ can be diminished sufficiently, then the stress of the power system can be minimized.

It is very difficult that we determine such a nonlinear control function, which satisfy the above property. Consequently, we introduce a fuzzy logic control (FLC) concept to get around the demerits due to the discontinuity of the control $J(X_t)$. When we design a power factor controller using the FLC, each fuzzy set in the power factor controller can be made with C^∞ functions. If we choose the power factor X_t and the difference $\Delta_t X_t$ of X_t in unit time as the input variables of the FLC and C^∞ class functions as the output variable, then the power factor control can be obtained:

$$J(X_t, \Delta_t X_t) = \sum_{k=1}^{n} C_k \cdot u(F_t(X_t, \Delta_t X_t) - r_k) \tag{15}$$

where $F_t(X_t, \Delta_t X_t)$ is the output of the FLC whose input values are X_t and $\Delta_t X_t$, and r_k is the threshold value for closing lead capacitors. Furthermore, the 1st order and 2nd order differential of control $J(X_t)$ are as follows:

$$\begin{aligned} \frac{\partial J(X_t, \Delta_t X_t)}{\partial X_t} &= \sum_{k=1}^{n} C_k \cdot \delta(F_t(X_t, \Delta_t X_t) - r_k) \frac{\partial F_t(X_t, \Delta_t X_t)}{\partial X_t} \\ \frac{\partial^2 J(X_t, \Delta_t X_t)}{\partial X_t^2} &= \sum_{k=1}^{n} C_k \cdot \delta(F_t(X_t, \Delta_t X_t) - r_k) \cdot \left(\frac{\partial F_t(X_t, \Delta_t X_t)}{\partial X_t} \right)^2 \\ &\quad + C_k \cdot \delta(F_t(X_t, \Delta_t X_t) - r_k) \frac{\partial^2 F_t(X_t, \Delta_t X_t)}{\partial X_t^2} \end{aligned} \tag{16}$$

The hypothesis of equation (16) represents that the demerits due to discontinuous control inputs can be diminished by the 1st order and 2nd order differential of control $J(X_t)$.

V. Experimental Results

The input-output fuzzy variables for the power factor control are denoted as PF and DPF which represent the power factor X_t and the difference of the power factor $\Delta_t X_t$, respectively. The name of the output fuzzy variable is ON/OFF. The membership functions of the fuzzy sets are described using the following Gaussian function:

$$\exp(-(x-m)^2 / 2\sigma^2) \tag{17}$$

Figure 2, Figure 3, and Figure 4 show the fuzzy sets of PF, DPF and ON/OFF, respectively. Table 1 and Table 2 represent the details of the fuzzy sets of PF and DPF, respectively. Table 3 is the details of the fuzzy sets of the output fuzzy variable. In addition, the fuzzy rules for the proposed fuzzy power factor controller are described in Table 4. Experimental data for the original uncontrolled power factor was given as a sinusoidal signal $0.8+0.15\sin(7.59\,t)$ with white noise. The power of white noise is 0.075.

Figure 5 shows the original power factor corrected by the proposed fuzzy controller. The experimental results shows that the proposed FLC power factor control system can stabilize the power factor within 0.9~1.0.

VI. Conclusions

We presented a power factor controller using FLC in this paper. The analysis of the stochastic differential equation reveals that the proposed method can diminish the demerits of the target system caused by the discontinuity in the conventional power factor control. The experimental results shows that the control performance of the proposed control system is so sufficient as to adjust the original power factor varying from 0.7 to 1.0 to the desired power factor between 0.9 and 1.0.

Table 1 The details of the fuzzy sets of the input variable PF

Fuzzy Set Name	Meaning	σ	M
SN	Large Lag PF	0.4	0.0
N	Lag PF	0.3	0.5
Z	PF = 1.0	0.1	1.0
P	Lead PF	0.4	1.5

Table 2 The details of the fuzzy sets of the input variable DPF

Fuzzy Set Name	Meaning	σ	M
DN	Minus PF Variation	0.4	-1.0
DZ	No PF Variation	0.4	0.0
DP	Plus PF Variation	0.4	1.0

Table 3 The details of the fuzzy sets of the output variable ON/OFF

Fuzzy Set Name	Meaning	σ	M
OFF	Open Capacitor	0.6	-1.0
Maintain	Maintain	0.2	0.0
ON	Close Capacitor	0.6	1.0

Table 4 The fuzzy rule for the proposed method

	SN	N	Z	P
DN	ON	ON	Maintain	Maintain
DZ	ON	ON	Maintain	Maintain
DP	ON	Maintain	OFF	OFF

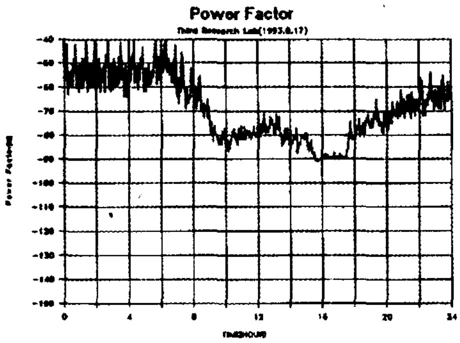

Figure 1 The one-day trends of power factor for a real load

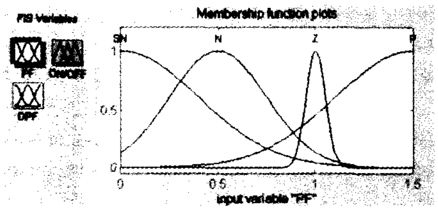

Figure 2 Fuzzy sets of PF

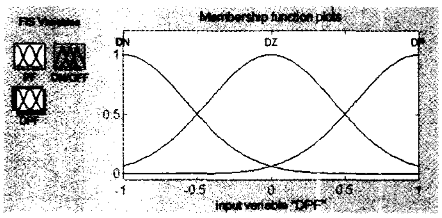

Figure 3 Fuzzy sets of DPF

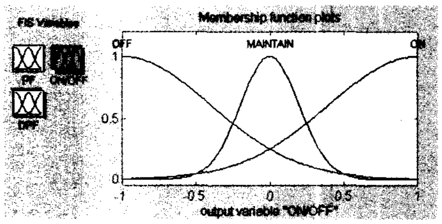

Figure 4 Fuzzy sets of ON/OFF

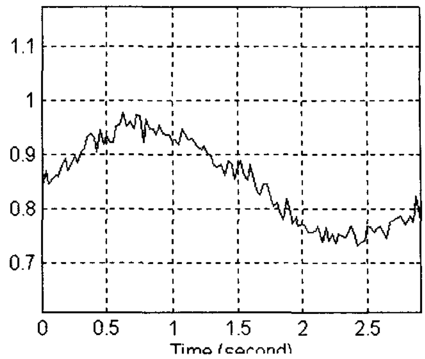

Figure 5 Uncontrolled power factor

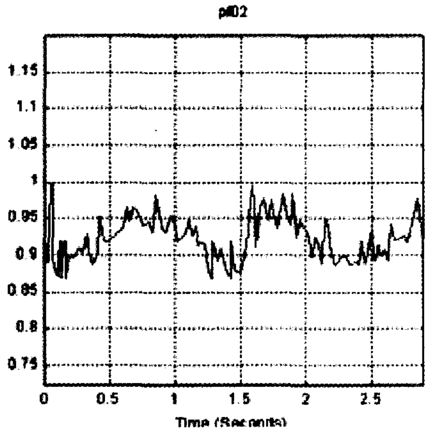

Figure 6 Power factor corrected by a conventional PF controller

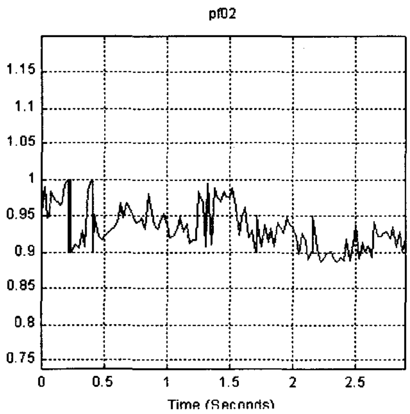

Figure 7 Power factor corrected by the proposed FLC

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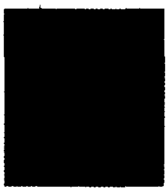

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