Adaptive Fuzzy Control for Uninterruptible Pow‹ Supply with Three-Phase PWM Inverter

Feng-Yih Hsu[1] and Li-Chen Fu[1,2]

Dept. of Electrical Engineering[1]
Dept. of Computer Science & Information Engineering[2]
National Taiwan University, Taipei, Taiwan, R.O.C.

Abstract

The major problems of uninterruptible power supply (UPS) with three pha PWM inverter arise from unknown nonlinear loading to and phase couplings the inverters. In this paper, an adaptive fuzzy control is proposed to solve the problems. The control objective is to track the desired sine waveform regardless the versatile nonlinear loading, whose bound can be represented by a fuzzy rule-ba: The algorithm embedded in the proposed architecture can automatically update t fuzzy control rules and, consequently, drive the tracking errors to a designated neig borhood of zero.

I Introduction

To provide the reliable uninterruptible power supply (UPS) for the use of cor puters or factory automation systems has become more and more important. T most common configuration of a UPS system consists of a dc source, a dc-ac inverte and an inductance-capacitance (L-C) filter. To establish a clean and reliable UP the waveform of the output voltage of the UPS system can only contain low tot harmonic distortion (THD) and can only have little variation even in the face varied nonlinear load. To achive the above characteristics, a well designed controll is needed in a UPS system to compensate for the different system characteristi resulting from the various (nonlinear) loads to and phase couplings of the inverter A straightforward approach to improve the performance is to use a feedforwa compensator to cancel the dynamics of the unknown load. Dead beat control h: been proposed for the simple linear system load [1]-[4]. For a complex or ill-define load model, repetitive control can assure high performance in the steady-state co dition but results in poor transient response because of the long period to learn proper control law [5]. On the other hand, the conventional control in an analo UPS is to raise the control gain properly to robustify the stability as well as th performance for unknown load [6]. An alternative, however, exists which is to us an intellignet control methdology to suitably adjust the control gain in a responsi

0-7803-3687-9/96

y so as to compensate for the variation of characteristics due to load change. llowing this stream of thought, in this paper, an adaptive fuzzy control for a UPS stem is proposed to achieve the aforementioned control goal.

Problem Formulation

A UPS system equipped with a three-phase PWM inverter is depicted in Figure which consists of an L-C filter at the inverter output, IGBT's to play as switching vices, a dc capacitor filter at the inverter input, and an unknown load at the L-C ter output. The variables v_{r1}, v_{r2} and v_{r3}, are the PWM modulation signals ich are the inputs to the PWM modulator in the figure, whereas the variables v_{i1}, v_{i2} and v_{i3}, are the inverter outputs satisfying the following equality:

$$v_i = \frac{E_d}{2} v_r - v_h, \tag{1}$$

ere $v_i = [v_{i1}, v_{i2}, v_{i3}]^T$, $v_r = [v_{r1}, v_{r2}, v_{r3}]^T$, $v_h = [v_{h1}, v_{h2}, v_{h3}]^T$ which denotes e voltage-drop vector at the on-state of IGBT, and E_d is the dc voltage of the verter. From Fig. 1, the mathematic model of the UPS system can be formulated follows:

$$\begin{aligned} C_p \dot{v}_c &= i_c = i_i - i_L & (2) \\ L_s \dot{i}_i &= v_i - v_c - v_N & (3) \end{aligned}$$

here $v_c = [v_{c1}, v_{c2}, v_{c3}]^T$ is the vector of output voltages, $v_N = [v_n, v_n, v_n]^T$ with $v_n = \frac{1}{3}(v_{i1} + v_{i2} + v_{i3})$ being the neutral voltage, $i_c = [i_{c1}, i_{c2}, i_{c3}]^T$ is the vector of e capacitor currents, $i_i = [i_{i1}, i_{i2}, i_{i3}]^T$ is the vector of the inverter currents, and $i_L = [i_{L1}, i_{L2}, i_{L3}]^T$ is the vector of the load currents. By differentiating equation), we can get the following equation:

$$\ddot{v}_c = \frac{1}{C_p} \dot{i}_c = \frac{1}{C_p} (\dot{i}_i - \dot{i}_L) = \frac{1}{C_p L_s} (v_i - v_c - v_N) - \frac{1}{C_p} \dot{i}_L \tag{4}$$

o substitute equation (1) into equation (4), we can then obtain the dynamic equaon of the UPS system as follows:

$$\ddot{v}_c = \frac{1}{C_p L_s} (\frac{E_d}{2} v_r - v_h - v_c - v_N - L_s \dot{i}_L) \tag{5}$$

The control goal is to let the output-voltage vector v_c track the desired sineave vector $v_c^* = [v_{c1}^*, v_{c2}^*, v_{c3}^*]^T = [v_{c1}^*(2\pi f_\omega t), v_{c1}^*(\frac{2\pi}{3} + 2\pi f_\omega t), v_{c1}^*(\frac{4\pi}{3} + 2\pi f_\omega t)]^T$, here f_ω is the frequency of the desired sine-wave voltage. Let the tracking error ector be denoted as $e_{v_c} = v_c^* - v_c = [e_{v_c 1}, e_{v_c 2}, e_{v_c 3}]^T$ and its time derivative as $\dot{e}_{v_c} = \dot{v}_c^* - \dot{v}_c = \dot{v}_c^* - \frac{1}{C_p} i_c$. Then, the error dynamics of the system can be derived s follows:

$$\ddot{e}_{v_c} = \ddot{v}_c^* + \frac{1}{C_p L_s} (v_c - \frac{E_d}{2} v_r + v_N + v_h + L_s \dot{i}_L) \tag{6}$$

Define the desired capacitor current vector $i_c^* = C_p \dot{v}_c^* = [i_{c1}^*, i_{c2}^*, i_{c3}^*]^T$, and defi a new vector, q, as $q = e_{i_c} + \lambda e_{v_c} = [q_1, q_2, q_3]^T$, where $e_{i_c} = i_c^* - i_c$ is the curre tracking error and λ is a positive constant. Then, a different error dynamic mo with respect to q can be derived as follows:

$$\begin{aligned}\dot{q} &= \dot{i}_c^* + \frac{\lambda}{C_p} e_{i_c} + \frac{1}{L_s}(v_c - \frac{E_d}{2} v_r + v_N + v_h) + \dot{i}_L \\ &= \dot{i}_c^* + \frac{\lambda}{C_p} q - (\frac{\lambda^2}{C_p} - \frac{1}{L_s}) v_c - \frac{1}{L_s}(\frac{E_d}{2} v_r - v_N - v_h) + \dot{i}_L\end{aligned}$$

Generally, the load is passive and the load current i_L will vary with resp to different loads. Hence, the j-th element of i_L here is assumed, without loss generality, as a time-varying nonlinear function, $i_{Lj} = g_j(v_{cj}, t)$. In turn, this le to an explicit expression of the time derivative of the load current, i_L, as:

$$\frac{di_{Lj}}{dt} = \frac{\partial g_j}{\partial v_{cj}} \dot{v}_{cj} + \frac{\partial g_j}{\partial t} = \frac{1}{C_p} \frac{\partial g_j}{\partial v_{cj}} i_{cj} + \frac{\partial g_j}{\partial t} = g_{fj} i_{cj} + g_{tj},$$

where $g_{fj} = \frac{\partial g_j}{\partial v_{cj}}$ and $g_{tj} = \frac{\partial g_j}{\partial t}$, respectively.

Assume that $|g_{tj}| \le \epsilon_t$, $|v_{hj}| \le \epsilon_h$, and $|g_{fj}| \le M_v \le \overline{M}_v$, for $j = 1, 2, 3$, wh $\overline{M}_v >> \epsilon_t + \frac{4\epsilon_h}{3L_s}$, ϵ_h and ϵ_t are some positive constants.

To remove the effect of v_n, let $v_{r1} + v_{r2} + v_{r3} = 0$ so that we can derive v_n $\frac{v_{i1}+v_{i2}+v_{i3}}{3} = \frac{-(v_{h1}+v_{h2}+v_{h3})}{3}$. Now, let the control law be designed as follows:

$$\begin{aligned}v_{r1} &= \frac{2L_s}{E_d}\left[\dot{i}_{c1}^* - (\frac{\lambda^2}{C_p} - \frac{1}{L_s}) v_{c1} + f(v_{c1}, q_1)\right] \\ &= \frac{2L_s}{E_d}\left[\dot{i}_{c1}^* - K_v v_{c1} + f(v_{c1}, q_1)\right] \\ v_{r2} &= \frac{2L_s}{E_d}\left[\dot{i}_{c2}^* - K_v v_{c2} + f(v_{c2}, q_2)\right] \qquad (\text{:} \\ v_{r3} &= -(v_{r1} + v_{r2}), \qquad (\text{:}\end{aligned}$$

where $K_v = \frac{\lambda^2}{C_p} - \frac{1}{L_s}$ is a constant gain, f is the proposed adaptive fuzzy controll

III Adaptive Fuzzy Control

Let $f(v_{ck}, q_k)$ be rewritten as follows:

$$f(v_{ck}, q_k) = K_q q_k + (|i_{ck}| + \epsilon) \tau_f(v_{ck}, q_k), \qquad (\text{:}$$

where ϵ is a small constant satisfying $\epsilon \ge \frac{(\epsilon_t + \frac{4\epsilon_h}{3L_s})}{M_v(v_{ck})}$ for $k = 1, 2$ and $\tau_f(v_{ck}, q_k)$ the key adaptive fuzzy function. To simplify the notations, let $u = [u_1, u_2]^T$ w $u_1 = v_{ck}$, $u_2 = q_k$, and $w = \tau_f(v_{ck}, q_k)$, where v_{ck} and q_k are the k-th elements v_c and q, respectively.

s a general description of the fuzzy knowledge representation [10], a fuzzy rule consists of a collection of fuzzy *If-then* rules. Let u denote as an input fuzzy or in the discourse universe U_u and $L = \{L_j^1, \cdots, L_j^{\alpha_j}, \cdots, L_j^{l_j}\}$ as a family izzy sets associated with the membership functions $\mu_{L_j^{\alpha_j}}$ (see Fig. 2) corrending to the variable u, $j = 1, 2$, where $L_j^{\alpha_j}$ is obviously a fuzzy set in L_j. In tion, the centers of the family of fuzzy sets, L_j, are grouped into a set as $\overline{u}_j = \cdots, \overline{u}_j^{\alpha_j}, \cdots, \overline{u}_j^{l_j}\}$, where $\overline{u}_j^{\alpha_j}$ is a center satisfying $\overline{u}_j^1 < \cdots < \overline{u}_j^{\alpha_j} < \cdots < \overline{u}_j^{l_j}$) see Fig. 2). Let L and $\overline{u}$ be both defined as product sets, $L = \prod_{j=1}^{2} L_j$ and of $\prod_{j=1}^{2} \overline{u}_j$, respectively, consisting of the families of fuzzy sets L_j and the sets of ers $\overline{u}_j$, $j = 1, 2$. Then, an example of the i-th fuzzy rule is expressed as follows:

$$R[i]: \text{If} \quad u \quad \text{is} \quad L^{\alpha(i)}, \quad \text{then} \quad w \quad \text{is} \quad Q^{\beta(i)}, \tag{13}$$

re $L^{\alpha(i)} \in L$, $\alpha_{(i)} = \alpha_{1(i)} \times \alpha_{2(i)}$ is a product index associated with the i-th rule, $\tau_f(u)$ is denoted as an output fuzzy variable. Let $Q = \{Q^1, \cdots, Q^\beta, \cdots, Q^r\}$ denoted as a family of fuzzy sets associated with the membership functions corresponding to the output variable w_Υ with Q^β being a fuzzy set in the ily Q and $Q^{\beta(i)} \in Q$ with $\beta_{(i)}$ being an integer index associated with the i-ule. Furthermore, let the sets of centers of the family of fuzzy sets, Q, be oted as $\overline{w} = \{\overline{w}^1, \cdots, \overline{w}^\beta, \cdots, \overline{w}^r\}$, where $\overline{w}^\beta$ is a center of the fuzzy set satisfying $< \cdots < \overline{w}^\beta < \cdots < \overline{w}^r$. Generally speaking, w can be expressed as follows: be ritten as:

$$w = \tau_f = \sum_{i=1}^{\Upsilon} \overline{w}^{\beta(i)} \xi_i(u) = \Theta^T \xi(u), \tag{14}$$

re $\Theta = [\overline{w}^{\beta(1)}, \cdots, \overline{w}^{\beta(\Upsilon)}]^T$ is regarded as a parameter vector and $\xi = [\xi_1, \cdots,$ ^{T} as a regressive vector.

Though w has been defined previously, there still exits the problem is how to ermine the optimal w in terms of appropriate choice of the parameters of Θ. To en this difficulty, for a neighborhood of $u_2 = 0$ we define a new variable

$$u_{2\Delta} = q_{k\Delta} \quad = \quad \begin{cases} u_2 - \bar{a}, & \text{as } u_2 < \bar{a}; \\ u_2 - \bar{b}, & \text{as } u_2 > \bar{b}; \\ 0, & \text{otherwise.} \end{cases} \tag{15}$$

that $\dot{u}_{2\Delta} = \dot{u}_2$, as $u_{2\Delta} \neq 0$ where $\bar{a}$, $\bar{b}$ are some constant satisfying $\bar{a} \leq \overline{u}_2^{\alpha_2^0} <$ $\overline{u}_2^{\alpha_2^0+1} \leq \bar{b}$, where the index α_2^0 indicates that two contiguous center points, $\overline{u}_2^{\alpha_2^0}$ l $\overline{u}_2^{\alpha_2^0+1}$, are in the neighborhood of zero. Let ϕ represent the deadzone range, , $\phi = [\bar{a}\,\bar{b}]$. Based on this new variable definition, we can define the optimal ameter vector as follows:

$$\Theta^* \quad = \quad arg\ min[sup_{u \in U_\Delta} \Theta^T \xi(u) sgn(u_2) \geq M_v(u_1)] \tag{16}$$

ere $U_\Delta = U_u \backslash \phi$. After the optimal vector Θ_k^* is sought, we thus redesign $i_{ck}, q_k)$ as

$$f_k(u) = (|i_{ck}| + \epsilon)\left\{d_k(u)\tau_f(u) + \left[1 - d_k(u)\right]\overline{M}_v sgn(q_k)\right\} + K_q q_k, k = 1, 2 \tag{17}$$

where $u = [v_{ck}, q_k]^T$, $d = [d_1, d_2]^T$ and its k-th element d_k is expressed as

$$d_k(u) = \begin{cases} 1, & \text{as } u \in U_\Delta; \\ 0, & \text{otherwise.} \end{cases},$$

Besides, the update laws are given as follows :

$$\dot{\Theta} = r|i_{ck}|q_{k\Delta}\xi(u) \quad \text{as} \quad u \in U_\Delta \qquad ($$

for some $r > 0$. The following theorem states the condition under which the abc mentioned adaptive fuzzy control law will yield satisfactory result.

Theorem 1 *If the control law and the update law are given as in equations* (9 (11), (14), (17) *and* (18), *then the tracking errors will asymptotically converge t neighborhood of zero.*

IV Simulation Results

Consider a nonlinear load as a triac-connected resistor, whose resistor is giver 50Ω and with firing angles α as 36° and 72°. Various coefficients of the UPS mo are $C_p = 75\mu F$, $L_s = 0.5mH$, $v_h = [2, 2, 2]$, $E_d = 400$, and the desired sine-w output voltage is given as $v_{cd}^* = [156sin(120\pi t), 156sin(\frac{2\pi}{3} + 120\pi t), 156sin(\frac{4\pi}{3}$ $120\pi t)]^T$. The triangular form and sup-min operator are selected as members functions and compositional operators, respectively. The total number of the rı of the fuzzy controller, $\Upsilon = l_1 \times l_2 = 5 \times 5 = 25$, and the initial parameter vec of fuzzy-rule base, Θ, is set to zero. The sampling time of control servo is given $50\mu s$ in the outer loop, and the inner loop is to simulate the dynamic equation w fixed step size $0.1\mu sec$. Fig. 3 shows the results of simulation results for firing an 36°. At the beginning, sinice initial parameter vector is set to zero, which appe to use only the PD controller to compensate for the uncertainties in the first per of sine wave, the tracking error is quickly driven toward zero after the first peri

V Conclusions

In the paper, we had proposed a novel fuzzy controller for a UPS system w three-phase PWM inverter. It can update fuzzy control rules to compensate for unknown nonlinear load and drive the tracking error of the output voltages to designated neighborhood of zero. The simulation results showed that the propop fuzzy control scheme posseses a rapid converging feature. Besides, a dexterous of fuzzy mathematics made the seeming complicated control be a scheme with pealing computing efficiency.

References

[1] Youichi Ito and Shoichi Kawauchi, "Microprocessor-Based Robust Digital Control for UPS with Three-Phase P Inverter", *IEEE, Trans. on Power Electronics, vol. 10, no. 2, pp. 196-204, 1995*

[2] T. Yokoyama and Atsuo Kawamura, " Disturbance Observe Based Fully Digital Controlled PWM Inverter for C Operation", *IEEE, Trans. on Power Electronics, vol. 9, no. 5, pp. 473-480, 1994*

[3] K. Gokhale, A. Kawamura, and R. G. Hoft, "Dead Beat Microprocessor Control of PWM Inverter for Sinus Output Waveform Synthesis", *IEEE, Trans. on Industry Applications, vol. 23, no. 5, pp. 901-910, 1987*

T. Kawabata, T. Miyashita and Y. Yamamoto, "Dead Beat Control of Three Phase PWM Inverter", *IEEE, Trans. on Power Electronics, vol. 5, no. 1, pp. 21-28, 1990*

T. Haneyoshi and A. Kawamura, "Waveform Compensation of PWM Inverter with Cyclic Fluctuating Loads", *IEEE, Trans. on Industry Applications, vol. 24, no. 4, pp. 582-589, 1988*

M. J. Ryan and R. D. Lorens, " A High Performance Sine Wave Inverter Controller with Capacitor Current Feedback and BACK-EMF Decoupling", *IEEE PESC, pp. 507-513, 1995*

M. A. Boost and P. D. Ziogas, "Towards a Zero-Output Impedance UPS system", *IEEE, Trans. on Industry Applications, vol. 25, no. 3, pp. 408-418, 1989*

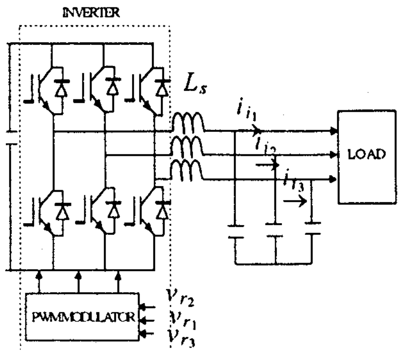
L. D. Salvador, "A Multilevel Systolic Approach for Fuzzy Inference Hardware", *IEEE Micro, pp. 61-71, October, 1995*

T. Miki and T. Yamakawa "Fuzzy Inference on an Analog Fuzzy Chip", *IEEE Micro, pp. 8-18, August, 1995*

L. X. Wang, "Stable Adaptive Fuzzy Control of Nonlinear Systems", *IEEE, Conf. on Decision and Control, 1992*

J-J E. Slotine and W. Li, *Applied Nonlinear Control*, Englewood Cliffs, NJ: Prentice Hall, pp. 278-284, 1991.

S. Sastry and M. Bodson, *Adaptive Control: Stability, Convergence, and Robustness*, Prentice Hall, 1989.



ure 1. UPS with a three-phase PWM inverter

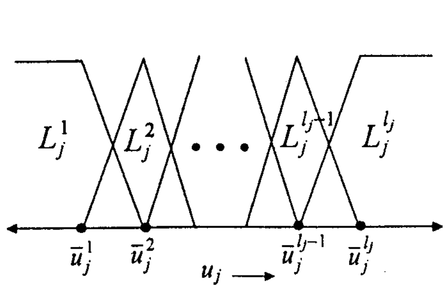


Figure 2. The environment of fuzzy variable u_j

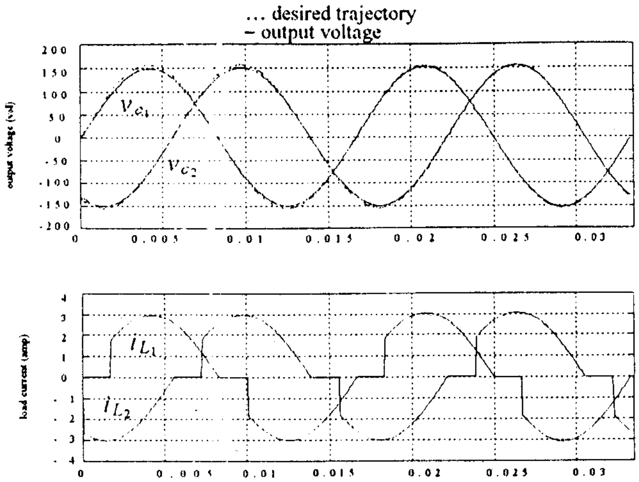


Figure 3. The simulation results