DESIGN AND IMPLEMENTATION OF A NEURAL-NETWORK-CONTROLLED UPS INVERTER

Xiao Sun*, Dehong Xu**, Frank H.F. Leung*, Yousheng Wang** and Yim-Shu Lee*

* Department of Electronic and Information Engineering
The Hong Kong Polytechnic University
Hung Hom, Kowloon, HONG KONG

** Department of Electrical Engineering
Zhejiang University
Hangzhou 310027, P.R. CHINA

ABSTRACT: **A low-cost analog neural network control scheme for the inverters of Uninterruptible Power Supplies (UPS) is proposed to achieve low total harmonics distortion (THD) output voltage and good dynamic response. Such a scheme is based on learning control law from representative example patterns obtained from two simulation models. One is a multiple-feedback-loop controller for linear loads, and the other is a novel idealized load-current-feedback controller specially designed for nonlinear loads. Example patterns for various loading conditions are used in the off-line training of a selected neural network. When the training is completed, the neural network is used to control the UPS inverter on-line. A simple analog hardware is built to implement the proposed neural network controller, an optimized PI controller is built as well. Experimental results show that the proposed neural-network-controlled inverter achieves lower THD and better dynamic responses than the PI-controlled inverter does.**

I. INTRODUCTION

Uninterruptible power supplies (UPS) should provide a sinusoidal voltage to its customers with constant magnitude. However, voltage distortion arises when nonlinear loads involve, e.g., diode rectifiers, which draw non-sinusoidal current when fed with a sinusoidal voltage. As growing utilization of nonlinear power electronics loads, it is becoming more difficult and significant to design a suitable controller for UPS inverter, the core of UPS, to maintain a sinusoidal voltage especially for the cases of nonlinear loads.

Some multiple-feedback-loop control strategies for the UPS inverter were proposed in [1][2]. Such schemes sense the current in the capacitor (or inductor) of the LC filter to form an inner current feedback loop incorporating with an outer voltage feedback loop. Owing to the introduction of the inner current feedback loop, the output impedance of the inverter is decreased and the dynamic stiffness enhanced. The controlled inverter can produce a satisfactory sinusoidal output voltage within a certain load range. However, such schemes are based on linear control theory. A uniform performance cannot be obtained under extreme loading conditions, and THD increases significantly when there is a nonlinear load.

In recent years, artificial neural networks (ANNs) have received considerable attention and their applications are now being actively explored. ANNs are computing architectures that consist of massively parallel interconnections of simple neural processor. They have the ability to approximate an arbitrary nonlinear mapping [3]. ANNs have already been introduced into various control and signal processing applications in power electronics and drives [4][5]. In the control of DC-AC inverters, ANNs have been employed in the current control of inverters for AC motor drives [6]-[8]. References [9][10] presented an ANN application in the harmonic elimination of PWM converters where the ANN replaced a large and memory-demanding look-up table to generate the switching angles of a PWM converter for a given modulation index. ANN was also utilized in control of the UPS inverter [11]. In this method, the ANN is trained off-line, and the trained network can be employed for on-line control. The inputs of the ANN are time, present output voltage and last sampled output voltage. However, the ANN may not have enough information to ensure a sinusoidal output voltage for the extreme loading conditions.

This paper proposes a low-cost analog ANN control scheme for UPS inverters. First, simulation models are built using MATLAB and SMULINK to obtain adequate example patterns. Then, a selected ANN is trained off-line with the database comprising all example patterns. When the training is completed, this ANN is used to control the inverter on-line. A simple analog hardware is built to implement the proposed ANN controller, a optimized PI controller is built as well. Experimental results show that the proposed ANN controlled inverter achieves lower THD and better dynamic responses than the PI controlled inverter does.

This project was supported by The Hong Kong Polytechnic University and Zhejiang University.

0-7803-5735-3/99/$10.00 ©1999 IEEE

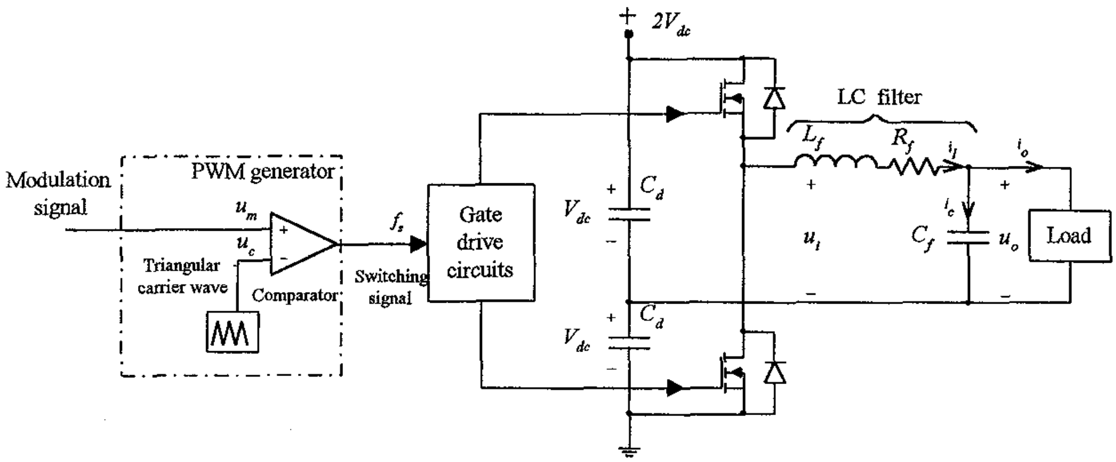


Fig.1. Single-phase UPS inverter system

II. Diagram of UPS Inverter and Linear Model

Fig. 1 shows the circuit diagram of a single-phase half-bridge voltage source UPS inverter, followed by a LC filter. PWM generator and gate drive circuits are also illustrated. R_f represents the resistance of the filter inductor. The effective series resistance (ESR) of the filter capacitor is ignored since it only has a small effect within the frequency range concerned.

Because the switching frequency f_s (here is 20KHz) is several orders higher than the fundamental frequency of the AC output, the dynamics of the PWM inverter can be ignored. Thus, the UPS inverter can be modeled as a simple proportional gain block. Fig.2 shows a linear model of the inverter system (PWM inverter plus the output filter and the load), in which the proportional gain of the inverter, K, is equal to V_{dc}/V_c (V_{dc} is the voltage of the DC power source and V_c is the peak voltage of the triangular carrier wave).

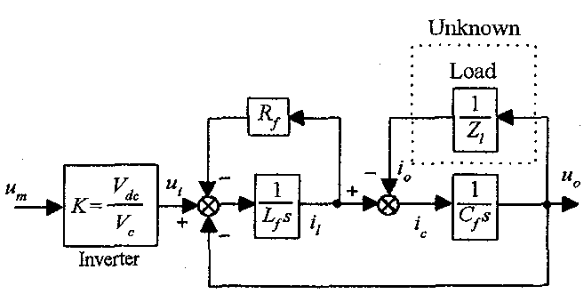


Fig.2. Linear model of UPS inverter

III. Obtaining Example Patterns and Training the Neural Network

Fig. 3 shows the structure of a feedforward multi-layer neural network that has one hidden layer. This kind of ANN will also be used in this paper. The circles represent neurons. The transfer function of nodes is sigmoid in the hidden layer, and linear in the output layer. Training algorithm is chosen as back propagation. The back propagation algorithm is most commonly used for the training of feedforward neural networks. It updates the network weights and biases in the direction that the performance function, usually the sum of square errors, decreases most rapidly. The training is usually done by an off-line computer simulation program using a large number of example patterns. The example patterns can be obtained from analysis, simulation or directly from experiments if the model is totally unknown.

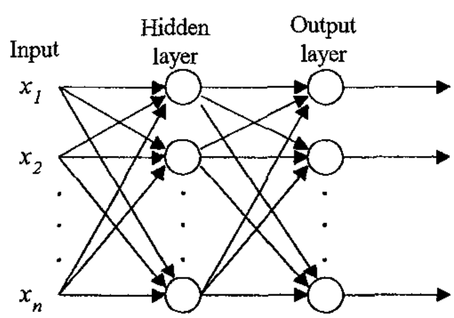


Fig.3. Structure of a two layer feedforward neural network

The proposed ANN control scheme for UPS inverter is to present a large number of example patterns obtained under various loading conditions to an ANN, and train the ANN properly to represent the control law. Two controllers,

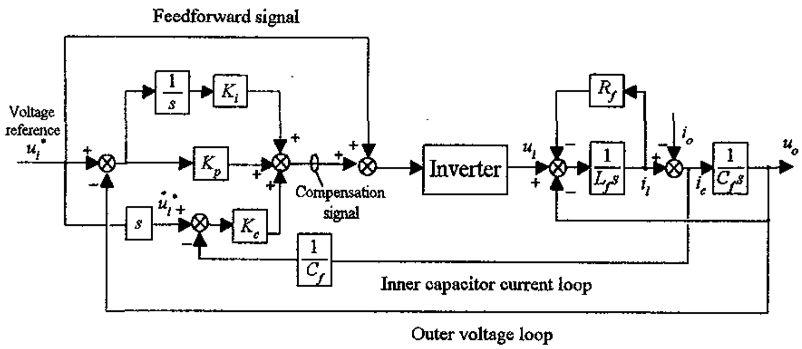


Fig.4. Multiple-feedback-loop control scheme to obtain example patterns under linear loading conditions

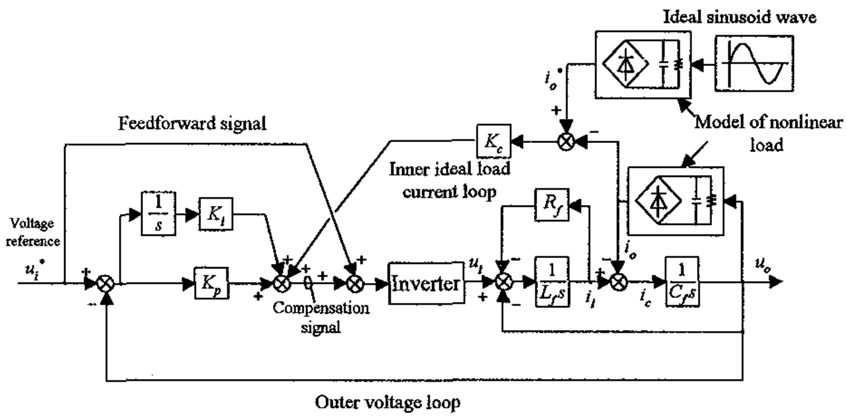


Fig.5. Idealized load-current feedback control scheme to obtain example patterns under nonlinear loading conditions

one for linear loads, the other for nonlinear loads, are built using MATLAB and SIMULINK.

A. Obtaining Example Patterns under Linear Loading Conditions

Under linear loading conditions (resistive, capacitive, or inductive), a multiple-feedback-loop control scheme can give good performance [1][2]. The control scheme for linear loads is shown in Fig.4. Different from the strategy proposed in [1][2], there is a feedforward signal from the reference voltage (shown at the top of Fig.4), which is found to have advantages of reducing steady-state error and providing a high tracking accuracy to the reference. Although it may cause large overshoot in the dynamic response, the drawback can be overcome by optimizing the parameters of the voltage feedback loop. The modulation signal to the PWM generator consists of two components, one is a sinusoidal feedforward signal, and the other is a compensation signal (as marked in the middle of Fig.4) produced by feedback loops. In this way, the ANN can be trained to generate only the compensation signal as its desired output. This will result in a more effective training and a better control performance.

We describe the full-bridge inverter using the following equation in MATLAB and SIMULINK:

$$u_i = \begin{cases} V_{dc} & (u_m \geq u_c) \\ -V_{dc} & (u_m < u_c) \end{cases} \tag{1}$$

where u_m is the instantaneous voltage of the modulating signal and u_c is the instantaneous voltage of the triangular carrier wave in the PWM.

It should be noted that a fixed set of parameter cannot be good for all kinds of linear loads. Each load is associated with a set of optimal parameters. We design the parameters for each load using frequency-domain analysis to ensure enough stability margin and small steady-state error, and fine-tune the parameters in the simulations. The compensation signal as shown in Fig.4 is collected as the desired output of the ANN. The output voltage and output currents (including load current and capacitor current) of the inverter are collected as the inputs to the ANN. Dozens of example patterns are obtained from the simulation results under different loading conditions and controller parameters.

B. Obtaining Example Patterns under Nonlinear Loading Conditions

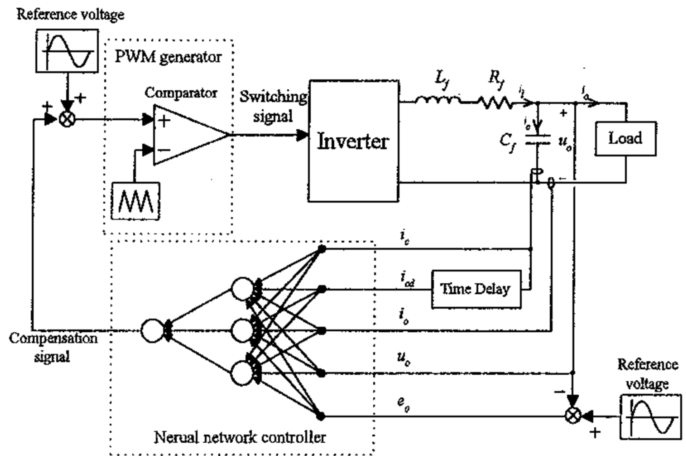


Fig.6. Proposed neural network control scheme for UPS inverter

Many electrical loads nowadays are nonlinear. It is therefore essential to maintain the performance of a UPS inverter under nonlinear loading conditions. The nonlinear load in this paper is chosen to be a full-wave diode bridge rectifier with an output filter. The input current of the nonlinear load, namely the output current of the inverter, is usually non-sinusoidal with a rather large $di/_{dt}$. The multiple-feedback-loop control scheme used for the linear loading conditions cannot perform satisfactorily. Thus, we should find another control scheme especially for nonlinear loads to obtain example patterns.

If the load current of the inverter can be predicted, we can design a controller to keep track of the output current. Following the control scheme used for the linear loading conditions, we change the inner capacitor-current loop to a load-current loop (as shown in Fig. 5), where a sinusoidal voltage is fed to a model of nonlinear load to obtain a load-current reference. The actual load current is compared with this reference, and the error signal is used as the controller input. Although such scheme is impossible to implement practically, we can perform simulations to obtain example patterns for training the ANN.

A model of such an idealized load-current feedback control scheme is built using MATLAB and SIMULINK. The PWM full-bridge inverter is modeled in the way as mentioned in the last subsection. The core of modeling a full-wave diode bridge rectifier in MATLAB and SIMULINK is the model of the power diode. We describe a diode using the following equation:

$$i_d = \begin{cases} 0 & u_d < 0.7 \\ (u_d - 0.7)/0.1 & u_d \geq 0.7 \end{cases} \qquad (2)$$

where u_d is the instantaneous forward voltage across the diode and i_d is the instantaneous forward current in diode.

The parameters of controller are determined from simulations to produce an output voltage with a low THD and a small enough steady-state error. Similar to the linear loads, dozens of example patterns are obtained under different rectifier with various output filter capacitors and load resistors.

C. Structure of the proposed ANN controller

All the example patterns obtained from simulation are put together to form a database that contains the information about the control law of the inverter. A proper ANN is then used to learn the control law. The network should be as simple as possible to reduce the calculation time of the ANN. Fig.6 shows the proposed ANN controlled inverter. The ANN is of a 5-3-1 structure (five inputs, three nodes in hidden layer and one output). The inputs are the capacitor current, delayed capacitor current, the load current, the output voltage, and the error between the reference voltage and the output voltage. The delay time of the delayed capacitor current (i_{cd}) is the switching period. Such a time delay is obtained from a low-pass filter. This ANN structure is the result of many repeated trials. To obtain a trained ANN that can perform well for both linear and nonlinear loads, it is found from many trials that the pattern database should consist of about two-third of patterns for linear loads and about one-third of patterns for nonlinear loads.

The training of the neural network is done off-line using MATLAB with Neural Network Toolbox. The Levenberg-Marquardt algorithm is used in the training, which has a fast convergence rate. The ANN is trained repeatedly with randomly selected example pattern from the pattern database. After the training is completed, the weights and biases are downloaded to the ANN controller to control the inverter on-line.

IV. EXPERIMENT

After on-line training is done, the weights and biases will never be changed during the control process, and the forward propagation just involves multiplications, additions and sigmoid functions. Therefore, a simple analog circuit is utilized to implement the proposed ANN controller. Fig.7

shows an analog resistor — operational amplifier implementation of a neuron. The multiplication and addition is realized by some resistors and an operational amplifier. The sigmoid function is realized by a differential pair (inside the dashed line).

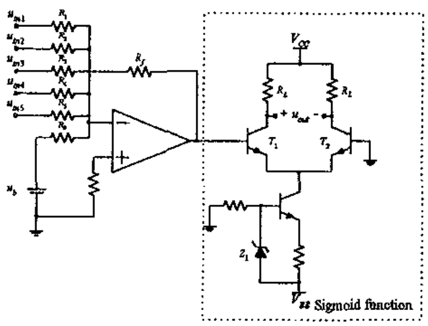


Fig.7. An analog circuit realization of a neuron

The relation between u_{out} and u_{in} can be described by:

$$u_{out} = Sigmoid[-(\frac{R_f}{R_1}u_{in1} + \frac{R_f}{R_2}u_{in2} + \frac{R_f}{R_3}u_{in3} + \ldots + \frac{R_f}{R_b}u_b)]$$

where: $Sigmoid(x) = \dfrac{2}{1+e^{-2x}} - 1$ (3)

The weights and the biases of neural network are represented by the resistor values R_1, R_2, R_3, ..., R_b. The proposed ANN controller can be simply implemented.

Table 1 Inverter Parameters

Parameter	Value	Units
Switching frequency, f_s	20	KHz
DC source voltage, V_{dc}	48	V
Rated Output Voltage	25	V_{rms}
Rated Output Frequency	50	Hz
Rated Output Current	5	A_{rms}
Rated output impedance	5	Ω
Filter Inductor, L_f	250	μH
Inductor Resistance, R_f	0.2	Ω
Filter Capacitor, C_f	30	μF

A UPS inverter system was implemented in the laboratory, whose parameters are listed in Table 1. To verify the performance of the proposed neural network controller, an analog PI controller was built as well. The PI controller was depicted in Fig.4 with optimal parameters, K_p=3.1, K_i=2200 and K_c=2.9.

Fig. 8 shows the waveform of the steady-state response for full resistive load. The figure shows that the proposed ANN controlled UPS inverter is capable of producing a sinusoidal output voltage.

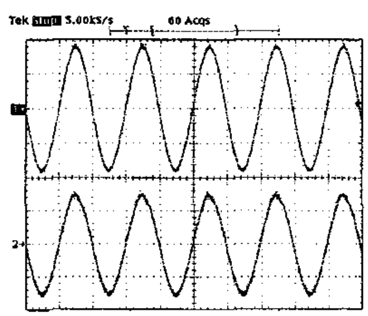
Fig. 9 shows the comparison of the output voltage and current of ANN controlled and the PI controlled inverters under a full-wave diode bridge rectifier load, whose output is connected to a 3200μF capacitor in parallel with a 5Ω resistor. The figure shows that the output voltage of the ANN-controlled inverter has less distortion than that of the PI controlled inverter has. Fig.10 shows the comparisons of the THD of the output voltage using the two controllers under bridge rectifier loads feeding with different R-C values. It shows that the proposed ANN controller can decrease the THD of the output voltage by 0.8~2.0% than that using the PI controller.

Fig.11 shows the output voltage and the current waveforms with a step change of load from no load to full resistive load. Compared with the performance of the PI controller, the ANN controller improved the dynamic response especially for large load variation.

These experimental results confirm that the circuit (of which each neuron has the structure shown in Fig.7) can simply realize the proposed ANN controller. IN addition, the proposed ANN controller maintains good steady-state and dynamic response, and effectively decreases the THD of the output voltage under nonlinear loading conditions.

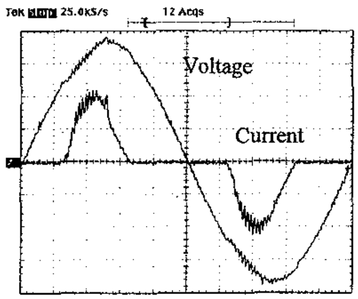
V. Conclusions

A neural network control scheme for UPS inverter has been presented in this paper. First, the methods for obtaining the example patterns are introduced. Two simulation models are built to obtain example patterns for linear and nonlinear loads respectively. One is a multiple-feedback-loop controller for linear loads; and the other is an idealized load-current feedback controller specially designed for nonlinear loads. Then a neural network is selected to train using example patterns so as to formulate the control law. The proposed neural network controller is implemented using a simple analog circuit. Experimental results confirm that the circuit can function the proposed ANN controller. By comparisons with a traditional PI controller, it is shown that the proposed neural network controlled UPS inverter has good steady-state and transient responses, and can decrease the THD under nonlinear loading conditions.

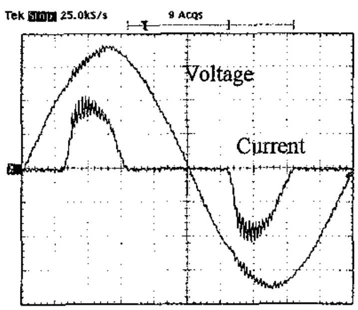


Upper trace: voltage (20V/div, 10ms/div);
lower trace: current (4A/div, 10ms/div)

Fig.8. Experimental result of the steady-state response of the proposed ANN controlled UPS inverter for full load (5Ω)



(a) Voltage (10V/div, 2ms/div) Current (10A/div, 2ms/div)



(b) Voltage (10V/div, 2ms/div) Current (10A/div, 2ms/div)

Fig.9. Experimental result for a full-wave diode bridge rectifier load (3200μF 5Ω) of (a) The PI controlled UPS inverter; (b) The proposed ANN controlled UPS inverter

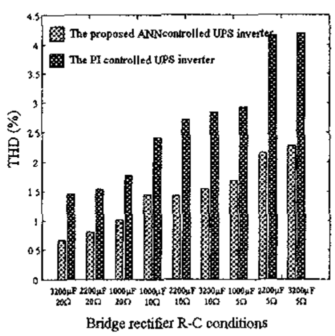
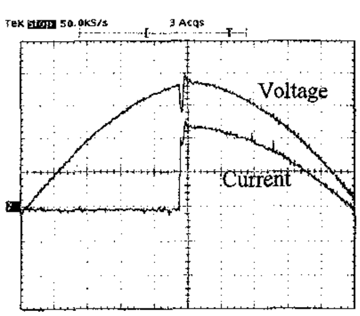
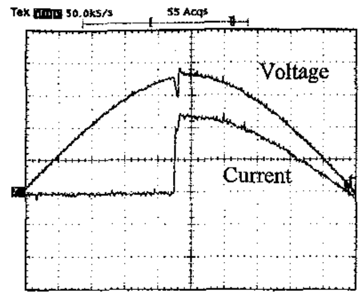


Fig.10. The THD of the output voltage for bridge rectifier loads feeding with different R-C values



(a) Voltage (10V/div, 1ms/div) Current (2.5A/div, 1ms/div)



(b) Voltage (10V/div, 1ms/div) Current (2.5A/div, 1ms/div)

Fig.11. Experimental results with a step-change of load from no load to 5Ω of (a). The PI controlled UPS inverter; (b). The proposed ANN controlled UPS inverter

References

[1] N. M. Abdel-Rahim and J. E. Quaicoe, "Analysis and design of a multiple feedback loop control strategy for single-phase voltage-source UPS inverters", *IEEE Trans. Power Electronics*, vol.11, no.4, pp.532-541, 1996

[2] M. J. Ryan, W. E. Brumsickle, and R. D. Lorenz, "Control topology options for single-phase UPS inverter", *IEEE Trans. Ind. Applicat.*, vol.33, no.2, pp.493-501, 1997

[3] K. J. Hunt, D. Sbarbaro, R. Zbikowski and P. J. Gawthrop, "Neural networks for control system — a survey" *Automatica*, vol.28, no.6, pp.1083-1112, 1992

[4] B. K. Bose, "Expert system, fuzzy logic, and neural network applications in power electronics and motion control", *Proceeding of the IEEE*, vol.82, no.8, pp.1303-1323, 1994

[5] B. R. Lin, "Analysis of neural and fuzzy-power electronic control", *IEE Proc.- Sci. Meas. Technol.*, Vol.144, No.1, pp.25-33, 1997

[6] M. R. Buhl and R. D. Lorenz, "Design and implementation of neural networks for digital current regulation of inverter drives", in *IEEE/IAS Annu. Meet. Conf. Rec.*, pp415-423, 1991

[7] B. R. Lin and R. G. Hoft, "Power electronics inverter control with neural networks", in *IEEE-APEC Conf. Rec.*, pp.128-134, 1993

[8] M. P. Kazmierkowski and D. Sobczuk, "Improved neural network current regulator for VS-PWM inverters", in *IEEE-IECON'94, Conf. Rec.*, pp.1237-1241, 1994

[9] A. M. Trzynadlowski and S. Legowski, "Application of neural networks to the optimal control of three-phase voltage-controlled inverters", *IEEE Trans. Power Electronics*, vol.9, no.4, pp.397-404, 1994

[10] D. Daniolos, M. K. Darwish and P. Mehta, "Optimised PWM inverter control using artificial neural networks", *Electronics Letters*, vol.31, no.20, pp.1739-1740, 1995

[11] R. C. Hwang, T. J. Liang and J. W. Chen, "Neural networks controlled PWM inverter", *IEEE-INTELEC'97 Conf. Rec.*, pp.201-206, 1997