

Analogue Implementation of a Neural Network Controller for UPS Inverter Applications

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Abstract—An analogue neural-network controller for UPS inverter applications is presented. The proposed neural-network controller is trained off-line using patterns obtained from a simulated controller, which had an idealized load-current-reference. Simulation results show that the proposed neural-network controller can achieve low total harmonic distortion under nonlinear loading condition and good dynamic responses under transient loading condition. To verify the performance of the proposed NN controller, a hardware inverter with an analogue neural network (NN) controller (using mainly operational amplifiers and resistors) is built. Additionally, for comparison purposes, a PI controller with optimized parameters is built. Experimental results confirm the simulation results and show the superior performance of the NN controller especially under rectifier-type loading condition. Implementing the analogue neural-network controller using programmable integrated circuits is also discussed.

Index Terms—Neural network control, UPS inverter.

I. INTRODUCTION

UNINTERRUPTIBLE power supplies (UPSs) are emergency power sources, which have widespread applications in critical equipments, such as computers, automated process controllers, and hospital instruments. With the rapid growth in the use of high-efficiency power converters, more and more electrical loads are nonlinear and generate harmonics. It is a big challenge for a UPS to maintain a high-quality sinusoidal output voltage under a nonlinear loading condition.

The block diagram of a typical UPS inverter is shown in Fig. 1. A multiple-feedback-loop control scheme can be utilized to achieve good dynamic response and low total harmonic distortion (THD) [1], [2]. Such a scheme is essentially developed from linear system theory. When the loads are nonlinear, the performance degrades. Recently, a number of digital feedback control schemes have also been developed for PWM inverters [3]–[5]. Although the performances of these schemes are good, the complicated algorithms and the heavy computational demands make the implementations difficult.

Neural networks (NNs) have been employed in many applications in recent years. An NN is an interconnection of a number

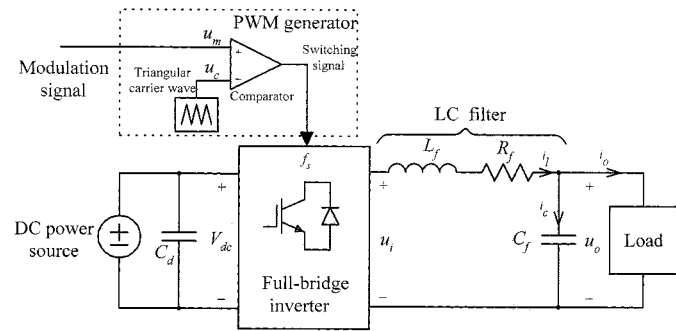


Fig. 1. UPS inverter.

of artificial neurons that simulates a biological brain system. It has the ability to approximate an arbitrary function mapping and can achieve a higher degree of fault tolerance [6]. NNs have been successfully introduced into power electronics circuits [7]. In the control of dc–ac inverters, NNs have been used in the current control of inverters for ac motor drives [8], [9], where the NN receives a phase-current error and generates a PWM signal to drive the inverter switches. References [10], [11] presented an application of NNs for the harmonic elimination of PWM inverters, where an NN replaced a large and memory-demanding look-up table to generate the switching angles of a PWM inverter for a given modulation index.

When an NN is used in system control, the NN can be trained either on-line or off-line. In on-line training, since the weights and biases of the NN are adaptively modified during the control process, it has better adaptability to a nonlinear operating condition. The most popular training algorithm for a feedforward NN is back propagation. It is attractive because it is stable, robust, and efficient. However, the back propagation algorithm involves a great deal of multiplication and derivation. If implemented in software, it needs a very fast digital processor. If implemented in hardware, it results in a rather complex circuitry [12]. Possible alternatives of the back propagation method are perturbation-based algorithms, such as weight perturbation [13], chain-rule perturbation [14] or random weight change [15]. In these algorithms, the weights are perturbed and the gradients are evaluated from the errors generated (instead of calculating the derivatives). They are feasible for analogue VLSI implementation [16]. However, in real-time control of the UPS inverter, there are no desired outputs to be presented to the NN since we have no prior knowledge about the loading condition. An NN emulator can be employed to identify the inverter behavior in order to

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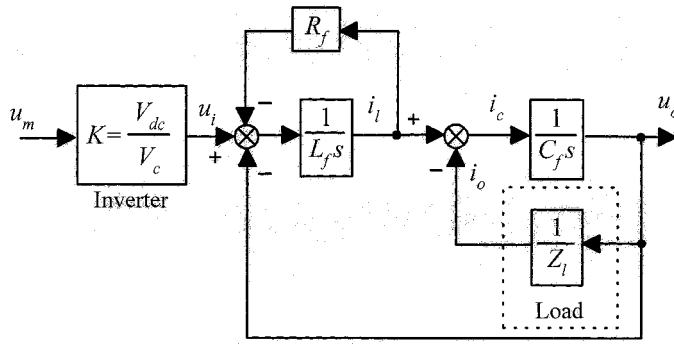


Fig. 2. Linear model of UPS inverter.

determine the output error of the NN controller [17], but this NN emulator also needs to be pre-trained with data obtained from simulations or experiments.

Off-line training of an NN requires a large number of example patterns. These patterns may be obtained through simulations. Although the weights and biases are fixed during the control process, the NN is a nonlinear system that has much better robustness than a linear system. Moreover, the forward calculation of the NN involves only addition, multiplication, and sigmoidal-function waveshaping that can be implemented with simple and low-cost analogue hardware. The fast-response and low-cost implementation of the off-line trained NN are suitable for UPS inverter applications.

Simulations of an NN controller with off-line training for PWM inverter were reported in [18]. The NN learned the control law through simulations off-line. The inputs of the NN were time, present output voltage, and last sampled output voltage. The limited information might not be enough to ensure a sinusoidal output voltage under various loading conditions. Moreover, only computer simulation results were reported in [18].

In this paper, we propose an analogue NN controller with off-line training for UPS inverter applications. Example patterns are obtained from a simulated controller, which has an idealized load-current-reference. A selected feedforward NN is trained to model this controller using back propagation algorithm. After training, the NN is used to control the inverter on-line. Simulation results show that the proposed NN controller can achieve low THD under nonlinear loading condition and good dynamic response under transient loading condition. To further verify the performance of the proposed NN controller, a hardware inverter with an analogue NN controller is built (using mainly operational amplifiers and resistors). Additionally, for comparison purposes, a PI controller with optimized parameters is built. Experiment results confirm the simulation results and show the superior performance of the proposed NN controller especially under rectifier-type loading condition. A discussion about the programmable integrated-circuit implementation of the proposed analogue NN controller will also be given.

II. PROPOSED NN CONTROLLER

Fig. 2 shows a linear model of an inverter, in which the PWM inverter is modeled as a proportional block with a gain K 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 u_c as shown in Fig. 1.)

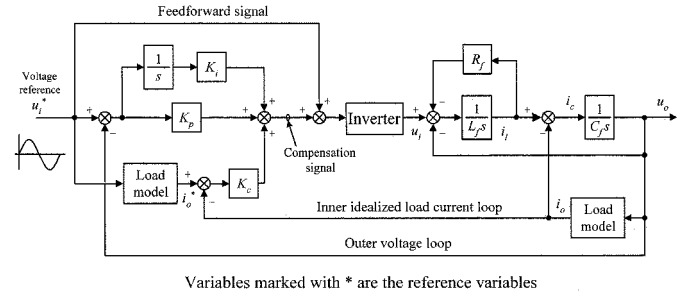
Fig. 3. Controller with idealized load-current-reference i_o^* for obtaining example patterns.

TABLE I
INVERTER PARAMETERS

Parameter	Value	Unit
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	μ H
Inductor Resistance, R_f	0.2	Ω
Filter Capacitor, C_f	30	μ F

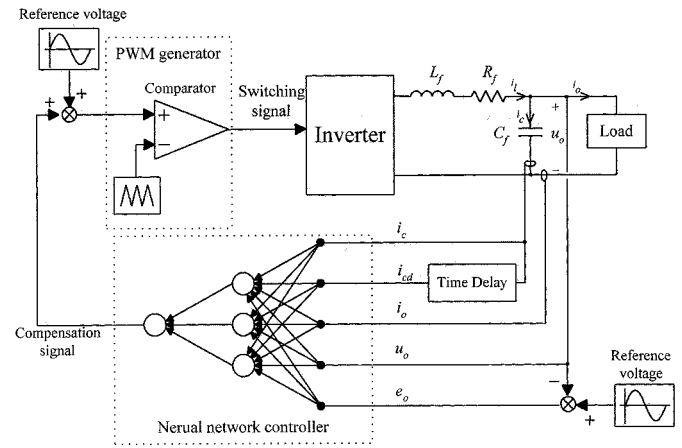


Fig. 4. Proposed NN control scheme for a UPS inverter.

A multifeedback-loop control scheme can give good performance under a certain linear loading condition [1], [2]. Such a scheme senses the current in the capacitor (or inductor) of the LC filter and uses the sensed signal to control an inner feedback loop. An outer voltage feedback loop is incorporated to ensure a sinusoidal output voltage. Owing to the introduction of the inner current feedback loop, the output impedance of the inverter is reduced and the dynamic stiffness is enhanced. However, a uniform performance cannot be obtained under extreme loading condition, and THD increases significantly when a nonlinear load is used.

We propose an NN controller for UPS inverters to reduce the output voltage distortion under nonlinear loading condition. Off-line training is adopted to ensure that the inverter will have a fast transient response and a low cost.

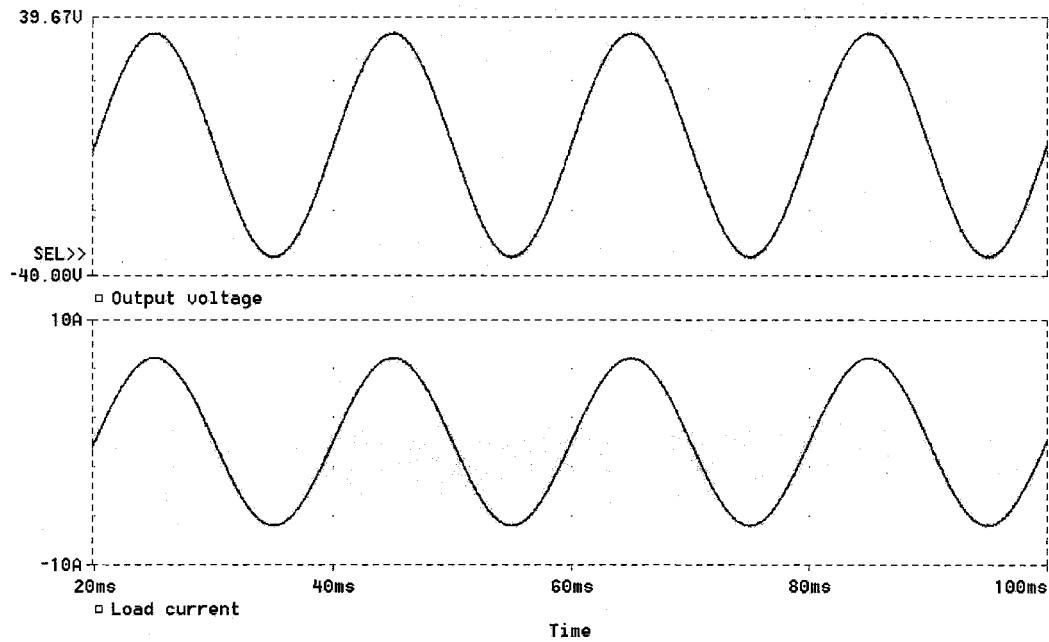


Fig. 5. Simulation result of the steady-state response of the proposed NN controlled UPS inverter for a full resistive load (5 Ω).

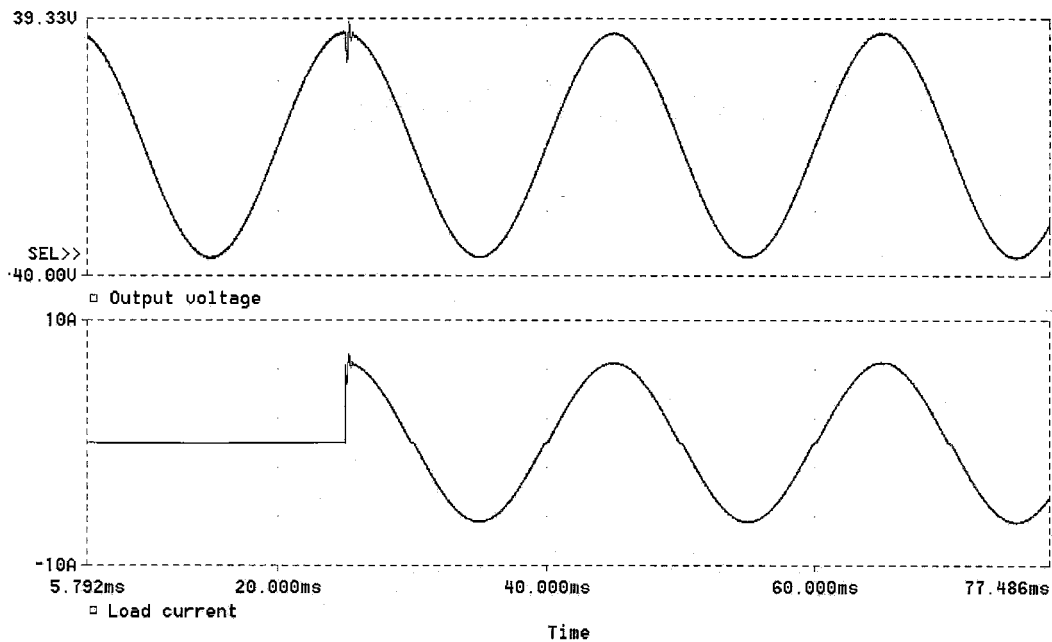


Fig. 6. Simulation result of the transient response of the proposed NN controlled UPS inverter when the load changes from no load to full load.

In order to obtain good example patterns for NN off-line training, we need a simulation model that can perform well not only under linear loading condition, but also under nonlinear loading condition. The problem with the nonlinear load is that it draws nonsinusoidal current with rather high spike, so that the output voltage is distorted. If the load current can be predicted, we can design a controller to enable the output current to keep track of this predicted current. Starting with the multi-feedback-loop control scheme introduced in [1], [2], we change the inner capacitor (or inductor) current loop to a load current loop, as shown in Fig. 3. A sinusoidal voltage reference is fed to the load model to generate an idealized load-current-reference, i_o^* . The error between this current reference, i_o^* , and actual load current, i_o , is used as the input of the controller. An outer

voltage loop is employed to achieve output voltage regulation. This model is easy to build and to simulate. Its performance is good not only under linear loading condition but also under nonlinear loading condition.

We build such a controller with an idealized load-current-reference using software tools MATLAB [19]. The PWM inverter is described by the following equation in MATLAB:

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

where V_{dc} is the voltage of dc source, 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 (as shown in Fig. 1).

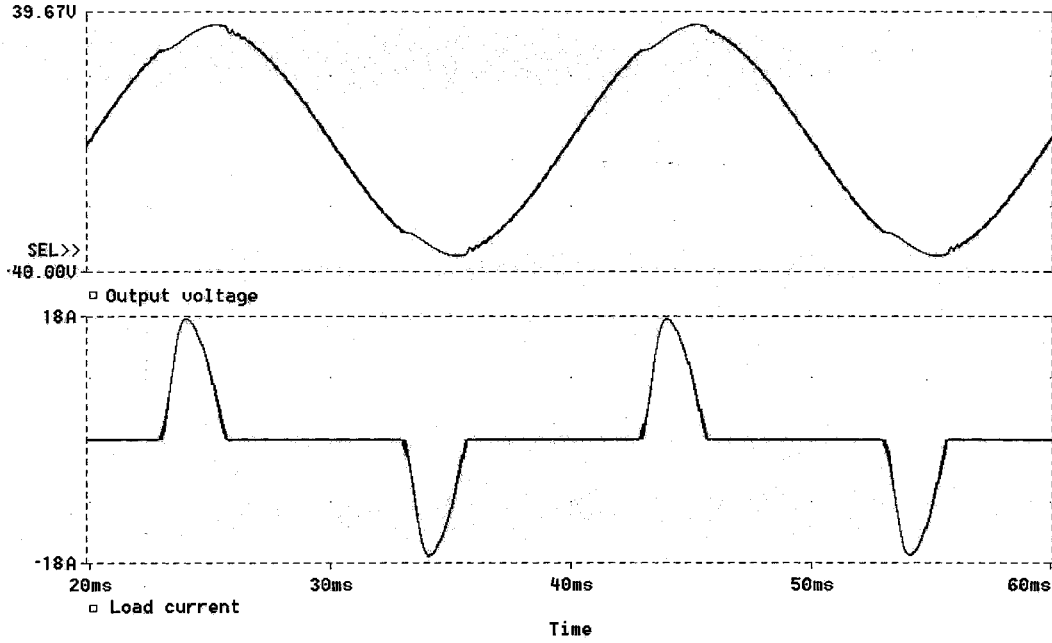


Fig. 7. Simulation result of the proposed NN controlled UPS inverter for a full-wave diode bridge rectifier load ($3200 \mu\text{F}$ 10Ω).

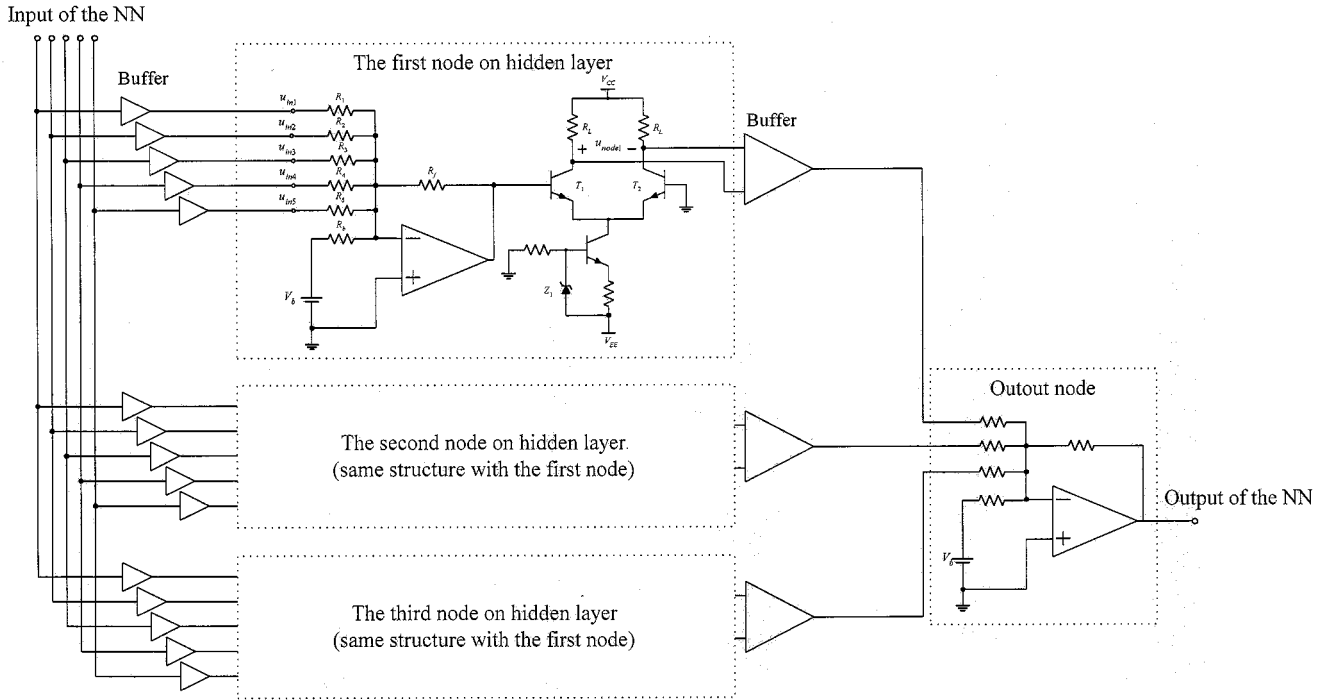


Fig. 8. Analogue implementation of the proposed NN controller.

The load model in Fig. 3 can be of any type. Resistive, inductive, or capacitive load can be easily constructed in MATLAB. A nonlinear load, such as a full-wave diode bridge rectifier, can also be built in MATLAB. We can describe a diode using

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

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

It should be noted that a fixed set of controller parameters (K_p , K_i , and K_c) is not good for every loading condition. Each loading condition has a set of optimal parameters, which can be

determined from simulation that produce an output voltage with a low THD and a small enough steady-state error. The output voltage, load current, and capacitor current of the inverter are collected as the inputs to the NN. The compensation signal (as marked in the middle of Fig. 3), instead of the whole modulation signal, is collected as the desired output of the NN. By using this compensation signal as the desired output of the NN, more effective learning and better control performance can be achieved.

The off-line training of an NN needs a large database that contains input-output relationships. In the case of UPS inverters, the database should include the input-output patterns under all possible loading conditions. We classify the loading condition into

two types, linear and nonlinear. The linear loads are further separated into resistive, capacitive, and inductive categories. The nonlinear loads are full-wave bridge rectifiers followed by a capacitor filter and a resistor load, in which we further classify them according to different output power ratings, different power factors, and different current crest factors. A new example pattern is obtained each time the load model is changed. The pattern database contains hundreds of patterns, in which two-thirds are for linear loading condition, and the other one-third is for nonlinear loading condition.

In the selection of an NN for the inverter, we believe the NN should be as simple as possible (with fewer inputs and fewer hidden nodes) so as to speed up the control process and to reduce the controller cost. The training of the NN is automated by a computer program that presents a randomly selected example pattern from the pattern database to the NN a large number of times (approximately one thousand and five hundred times). During each time, the weights and biases of the NN are updated using the back propagation algorithm to make the mean square error between the desired output and the actual output of the NN less than a predefined value.

The following is a summary of the design steps for the proposed NN controller for UPS inverter applications.

- 1) Build the simulated controller with the idealized load-current-reference for the inverter, as shown in Fig. 3.
- 2) For each of the loading conditions, tune the parameters of the controller to the optimal values. Then collect the output voltage, load current, and capacitor current as the inputs of the NN, and the compensation signal as the desired output of the NN. These patterns form a pattern database for the training of the NN.
- 3) Select an NN structure that is simple and yet sufficient to model the simulated controller based on the pattern database.
- 4) Train the NN using software tools (e.g., MATLAB with Neural Network Toolbox).

III. SIMULATION RESULTS, ANALOGUE HARDWARE IMPLEMENTATION, AND EXPERIMENTAL RESULTS

To verify the ideas described above, we have designed an NN controller for a UPS inverter, whose parameters are listed in Table I.

For the purpose of obtaining training data, a simulated controller, as shown in Fig. 3, is built using MATLAB. Hundreds of example patterns are collected to form a pattern database for linear and nonlinear loads. Fig. 4 shows the complete inverter arrangement. The NN controller has a 5-3-1 structure (five inputs, three nodes in a hidden layer and one output node). The nodes on the hidden layer have a sigmoid transfer function, and the output node has a linear transfer function. This NN structure is the result of many repeated trials. The structure is found to be simple but efficient. Its inputs are capacitor current, delayed capacitor current, load current, output voltage, and error voltage between the reference voltage and the output voltage. The delay time of the delayed capacitor current (i_{cd}) is one switching period. Such a time-delay is obtained from a simple R-C low-pass

filter. The training of the NN is done using the Neural Network toolbox of MATLAB.

A. Simulation Results

We simulate the proposed NN controller using PSpice, which has accurate models of switching components and diodes. The weights and biases from MATLAB simulations are put into the PSpice model. The steady-state and transient responses of the proposed NN controlled inverter are investigated.

The output voltage and load current waveforms of the inverter system for a full resistive load ($5\ \Omega$) are depicted in Fig. 5. The figure shows that the proposed NN controlled UPS inverter is capable of producing a good sinusoidal output voltage. Fig. 6 shows the simulation result of dynamic response when the load changes from no load to full load ($5\ \Omega$). The figure shows that the system exhibits fast dynamic response with little change in the output voltage, indicating that the proposed NN controller is capable of maintaining a “stiff” output voltage. Fig. 7 shows the output voltage and load current waveforms of the inverter for a nonlinear load consisting of a full-wave diode bridge rectifier followed by a $3200\ \mu\text{F}$ capacitor in parallel with a $10\ \Omega$ resistor. Note that although the load current has high spikes, the voltage waveform is distorted only slightly. The THD of the output voltage is found as

$$\begin{aligned} \% \text{THD} &= 100 \times \sqrt{\sum_{h \neq 1} \left(\frac{\text{hth harmonic component}}{\text{the fundamental component}} \right)^2} \\ &= 1.76\% \end{aligned} \quad (3)$$

B. Analogue Hardware Implementation

After off-line training is completed, the weights and biases will not be changed during the control process. Since the forward propagation of the NN involves just multiplication, addition, and sigmoid waveform shaping, a simple analogue circuit can be used to implement the proposed NN controller. To further verify the performance of the proposed NN controller, an experimental inverter system is built with the parameters listed in Table I. We design a simple analogue circuit to implement the proposed NN controller. Fig. 8 shows the schematic of the circuit, which is composed of mainly operational amplifiers and resistors. The nonlinear sigmoidal function is realized by a differential pair. The weights and the biases of neural network are represented by resistors. The output voltage of the first node in hidden layer u_{node1} can be described as:

$$u_{\text{node1}} = \text{Sigmoid} \left[- \left(\frac{R_f}{R_1} u_{\text{in1}} + \frac{R_f}{R_2} u_{\text{in2}} + \frac{R_f}{R_3} u_{\text{in3}} + \cdots + \frac{R_f}{R_b} u_b \right) \right] \quad (4)$$

where $\text{Sigmoid}(x) = (2/1 + e^{-2x}) - 1$.

Here it should be noted that analogue circuits have limited precision. It is therefore essential to assess how closely the analogue circuit can approximate the NN. The largest deviation between the analogue implementation and the NN is introduced by the inaccurate weights represented by resistors. In order to study the effect of inaccurate weights, the following experiment is performed:

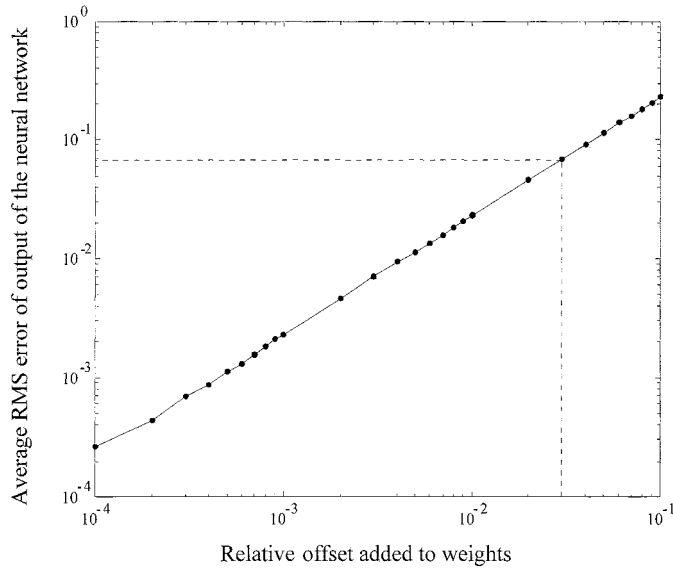


Fig. 9. Effect of limited precision in the weights.

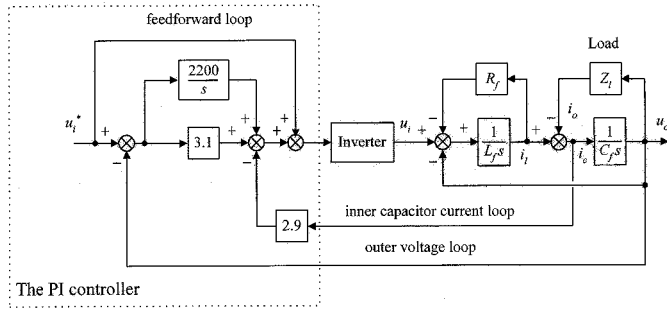


Fig. 10. Analogue PI controller for comparison purposes.

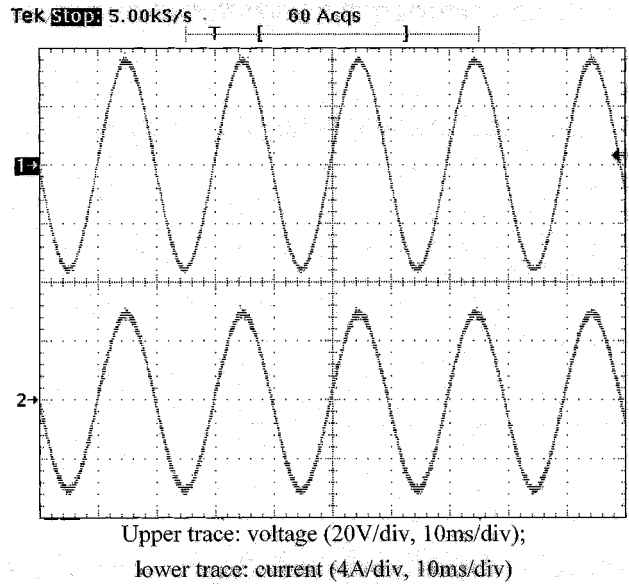
- 1) A network is well-trained with the pattern database. The accurate values of the required weights are stored.
- 2) Randomly-varying offsets are added to the accurate weights to perturb the NN.
- 3) The root mean square (RMS) error between the output of the original NN and the output of the perturbed NN is evaluated.
- 4) The procedure is repeated 50 times for each level of relative offset with different inputs and the RMS error is averaged over the 50 runs.

Fig. 9 shows the average RMS error as a function of the relative offset. The error increases with the relative offset almost linearly. With 3% relative offset of the weights, which can be achievable in most analogue circuitry, the RMS error of output is about 6.6%. Such an error is tolerable in the control system of a UPS inverter.

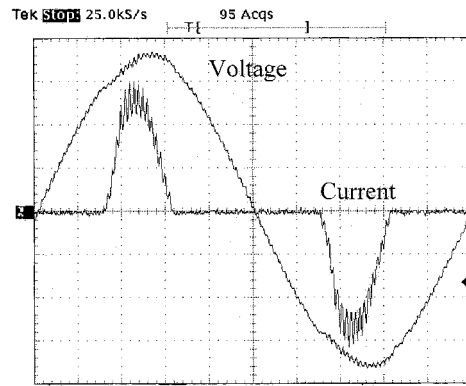
C. Experimental Results

An experimental hardware of the NN controlled inverter, as shown in Fig. 4, has been built. For the purpose of comparison, an inverter with a PI controller has also been built. The structure of the PI controller is shown in Fig. 10. The parameters of the PI controller have been optimized for a resistive full-loading condition using frequency domain design techniques.

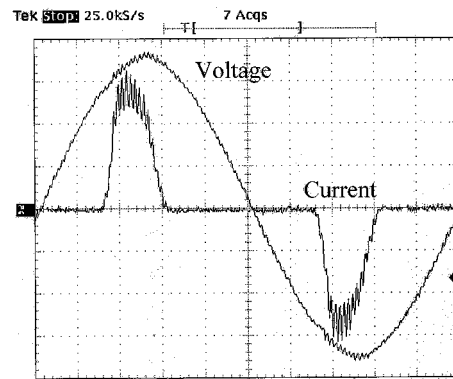
Fig. 11 shows the experimental steady-state output voltage and load current of the NN controlled UPS inverter for a full



bFig. 11. Experimental steady-state waveform of the NN controlled UPS inverter for a full resistive load (5 Ω).



(a)



(b)

Fig. 12. Experimental result for a full-wave diode bridge rectifier load (3200 μF 10 Ω): (a) PI controlled UPS inverter and (b) proposed NN controlled UPS inverter.

resistive load. Fig. 12 compares the output voltage and load current waveforms of the NN controlled inverter with those of the PI controlled inverter for a full-wave bridge-rectifier load, whose output is connected directly to a 3200 μF capacitor in parallel with a 10 Ω resistor. The figure shows that the output voltage of the NN controlled inverter has lower distortion than

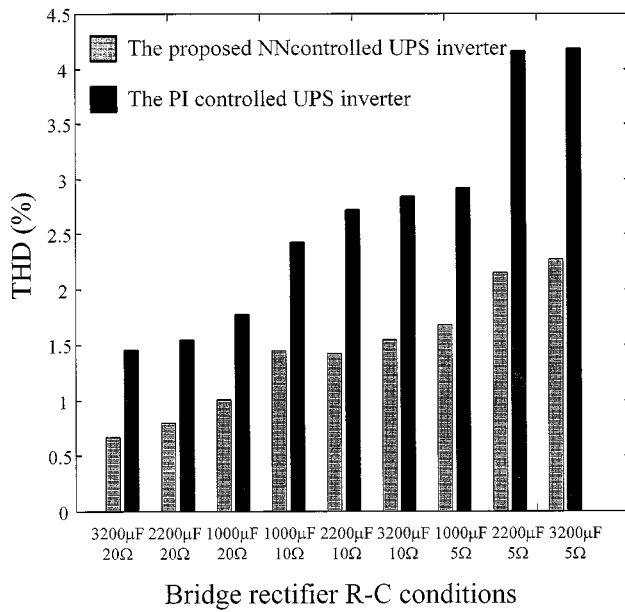


Fig. 13. Comparison of the THD of the output voltage under different rectifier-type loads.

that of the PI controlled inverter. Fig. 13 compares the THD of the output voltage of the NN controlled inverter with that of the PI controlled inverter under different rectifier-type loads. It is found that the NN controller significantly outperforms the PI controller. Fig. 14 shows the output voltage and load current waveforms for a step change of load from no load to 5 Ω resistive load. Compared with the PI controller, the NN controller achieves a smaller overshoot in the output voltage. The NN controller also has an improved dynamic response.

In the NN controller, the input-output mapping of the NN is stored in the pattern database, which includes many cases of rectifier-type loads. The NN learns the control laws from this database. Therefore, the NN takes care of the characteristics of these rectifier-type loads. It is for this reason that the NN controller can achieve lower distortion in the output voltage than the PI controller.

The experimental results given above confirm that the proposed NN controller can be easily realized by analogue circuit. The NN controller is capable of maintaining good steady-state and dynamic responses, and has significant improvement in reducing the THD of the output voltage under nonlinear loading condition. It is very suitable for applications where the load introduces periodic distortions.

IV. IMPLEMENTATION OF THE PROPOSED NN CONTROLLER USING PROGRAMMABLE INTEGRATED CIRCUITS

For the analogue NN controller described in Section III, if the weights and biases of the network have to be changed, the corresponding resistors have to be replaced. This brings in inconvenience in the fabrication of the controller circuit. We therefore suggest a mixed analogue/digital circuit, which can be implemented in IC (integrated circuit) form, to implement the weighting and biasing functions. Fig. 15 shows the block diagram of the proposed integrated circuit, which consists

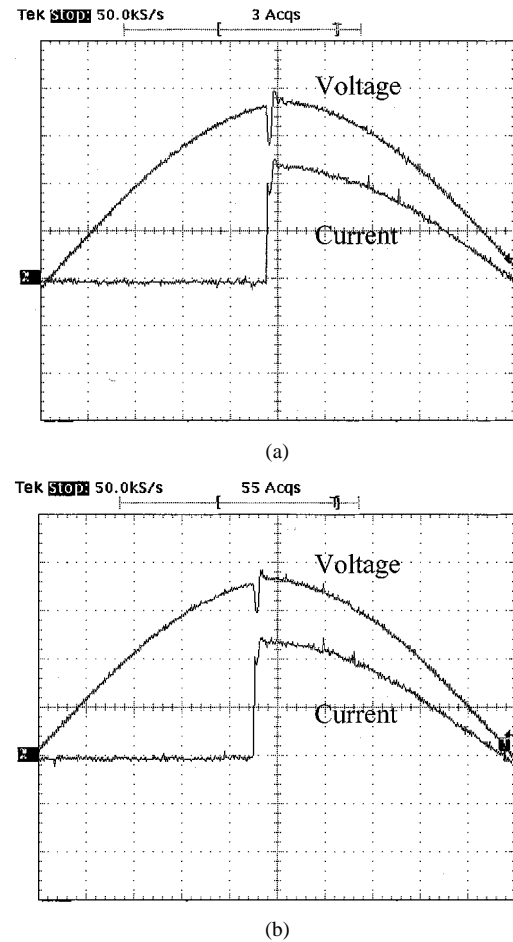


Fig. 14. Experimental results with a step-change of load from no load to 5 Ω : (a) PI controlled UPS inverter and (b) proposed NN controlled UPS inverter.

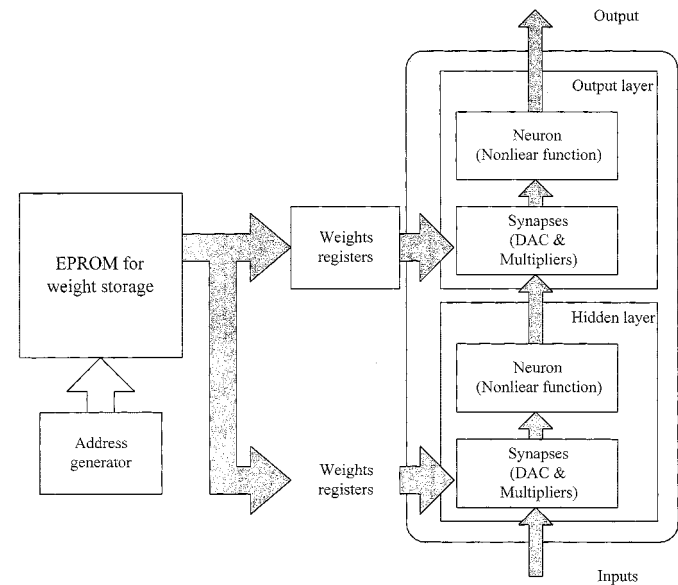


Fig. 15. Block diagram of the integrated circuit implementation of the proposed NN controller.

of three parts: EPROM (for weight storage), synapses, and neurons. The following is a brief description of the functions of the building blocks of the proposed circuits shown in Fig. 15.

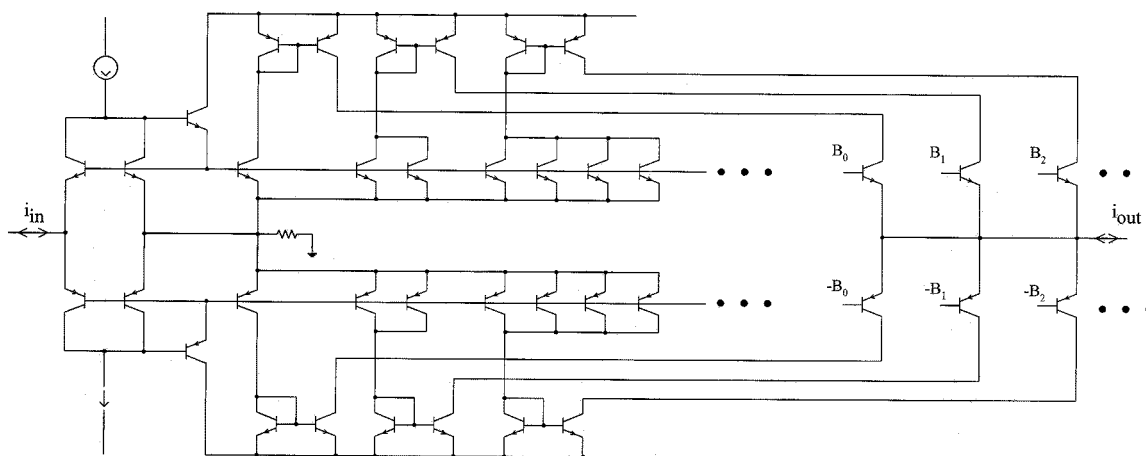


Fig. 16. Circuit of a synapse.

A. EPROM

The EPROM is used to store (digitally) the values of the weights and biases. The values stored in EPROM can be programmed. From Fig. 9, we have found that a five-bit resolution is already adequate. The maximum quantization error is 3%. Thus a weight register needs only six bits each. (The extra bit is for the sign.)

B. Synapses

A synapse receives a digital weighting signal from the EPROM and uses it to programme the weighting coefficient of the input. In order to perform this function, we suggest the circuit shown in Fig. 16. The input current, i_{in} , which may come from the inputs of the NN or the output of node of last layer, is used as the reference of a current mirror. The output current, i_{out} , is the product of the input current and the stored weight. This circuit functions as a D/A converter and a multiplier.

C. Neurons

A differential pair is used to perform the sigmoidal-function waveshaping, similar to the one shown in Fig. 8.

This proposed programmable controller employs only resistors and transistors. So it can be easily implemented using integrated circuits. Such a scheme has the feature of fast computation and low cost, which can meet the requirement of real-time controller for power converters.

V. CONCLUSION

An analogue NN controller for UPS inverter has been presented in this paper. Training patterns for the NN controller are obtained from a simulated controller with an idealized load-current-reference. After training, the NN can be used to control the UPS inverter on-line. Simulation results show that the proposed NN controller can achieve low THD under nonlinear loading condition and good dynamic response under transient loading condition. We implement the proposed NN controller using a simple analogue circuit. A PI controller with optimized parameters is also built for comparison purposes. Experimental results

confirm the simulation results and show the superior performance of the proposed NN controller, especially under rectifier-type loading condition. The proposed NN controller is particularly suitable for nonlinear load that introduces periodic distortion. The implementation of the proposed analogue NN controller using programmable integrated circuits has also been discussed.

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