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Neural Network Controller for Enhancement of Uninterruptible Power Supply Inverter

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***Abstract*: Uninterruptible Power Supplies (UPS) are emergency power sources, which have widespread applications in critical equipments, such as computers, automated process controllers and hospital instruments. With 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 conventional methods employ multi-loop control strategies to perform same task. In conventional methods more inputs cannot be given to the controller, though it accounts for better performance under nonlinear conditions, it will increase the complexity of the system. Whereas a neural network controller can accommodate more inputs and learn from data.**

Neural Networks (NNs) have been employed in many applications in recent years. A neural network is an interconnection of a number of artificial neurons that simulate a biological brain system. It has the ability to approximate nonlinear functions and can achieve higher degree of fault tolerance. NNs have been successfully introduced into power electronics circuits and application of NNs for harmonic elimination of Pulse Width Modulation (PWM) inverters, where a NN replaced a large and memory demanding look-up table to generate the switching angles of a PWM inverter for a given modulation index. This paper aims to study the behavior of UPS inverter under nonlinear loading condition. A neural network based controller is designed and tested for performance enhancement.

Index Terms- Neural networks, Pulse width modulation, Uninterruptible Power Supply.

I. INTRODUCTION

UPS provide electric power for critical functions and equipment when the quality of the normal supply, i.e. utility power is not adequate or fails entirely. With the rapid growth in the utilization of data processing systems, life care medical equipment, alarm systems and safety lighting, the demand for quality uninterruptible power is increasing.

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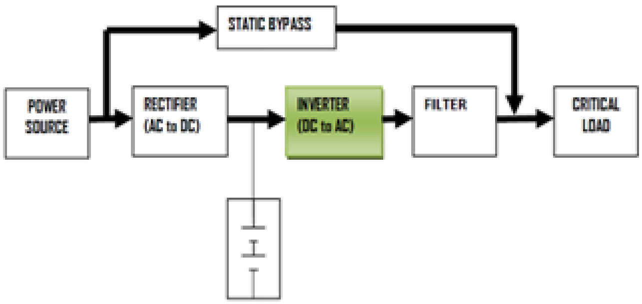

Fig. 1 Block diagram of conventional UPS system

Further, with the widespread application of high efficiency static power converter devices, many electrical loads are nonlinear, including the above-mentioned critical loads and generate harmonics. Therefore, additional harmonic filtering techniques must be applied in order to maintain a high quality Sinusoidal UPS inverter output voltage. One way of achieving “clean” sinusoidal load voltage is by using a sinusoidal pulse width modulation (SPWM) scheme. In this technique, the load voltage is compared with a reference sinusoidal voltage waveform and the difference in amplitude is used to control the modulating signal in the control circuit of the power inverter. A more advanced technique employs a programmed optimum PWM scheme that is based on the harmonic elimination technique. These schemes have been shown to perform well with linear loads. However, with nonlinear loads the PWM scheme does not guarantee low distortion of the load voltage. A typical UPS consists of a rectifier supplied battery bank for energy storage and a static inverter-filter system to convert a dc voltage to a sinusoidal ac output as shown in Fig.1. The inverter is typically operated with a pulse-width modulation (PWM) strategy under feedback control to realize the desired output waveform. UPS systems can be off-line, where the load is connected directly to the utility under normal operation and emergency power is supplied by the UPS. In the on-line configuration, the UPS powers the load continuously.

A. Challenges of UPS

In real time applications the UPSs have to face the following challenges:

- Should be capable of producing high quality sinusoidal output that is, the Total Harmonic Distortion (THD) in the output signal should be minimized.
- Should have good steady state and transient responses.
- Should be capable of maintaining quality output both under linear and non-linear loading conditions.

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B. Existing Control Strategies

In UPS to eliminate harmonics a real-time feedback control scheme using dead-beat control was proposed by A. Kawamura in the year 1986[15]. This technique employs the capacitor voltage and its derivative in a control algorithm to calculate the duration of the ON/OFF states of the inverter switching devices such that the capacitor voltage is exactly equal to the reference voltage at the next sampling time. Although this technique has been implemented for single- and three-phase applications, it has the following drawbacks:

- It is complex to implement
- It is sensitive to parameter variations
- Its control algorithm requires the estimation of the load parameters.

In order to achieve a control scheme that overcomes the above disadvantages, a current regulated control scheme for dc/ac applications was proposed in 1990 by N.R.Jargari. In this technique, the current in the filter capacitor is used as the feedback variable in a two-switch inverter circuit topology to achieve a sinusoidal capacitor current. An outer voltage control loop is also incorporated for load voltage regulation and compensation for imperfections in the implementation of the current control loop.

Although the technique results in a sinusoidal capacitor current, the power circuit configuration and the switching scheme used to implement the technique produce a load voltage that is sinusoidal with a dc offset. For UPS applications, the presence of the dc voltage offset is unacceptable.

In the year 1996, Naser M. Abdel-Rahim proposed multiple feedback loop control strategy for Single-phase voltage-source UPS inverters which overcomes the drawbacks in the above mentioned technique [10]. A multiple-feedback-loop control scheme can be utilized to achieve good dynamic response and low total harmonic distortion (THD). 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. Although the performance schemes are good, the complicated algorithms and the heavy computational demands make the implantation difficult.

C. Neural Networks

Neural networks (NNs) have been employed in many applications in recent years. An NN is an interconnection of a number 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 [13]. NNs have been successfully introduced into power electronics circuits [12]. In the control of dc–ac inverters, NNs have been used in the current control of inverters for ac motor drives [7], [9], where the NN receives a phase-current error and generates a PWM signal to drive the inverter switches. References [6], [5] 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 feed-forward 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 [11]. Possible alternatives of the back propagation method are perturbation-based algorithms, such as weight perturbation [4], chain-rule perturbation [8] or random weight change [3]. 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 [2]. However, in real-time control of the UPS inverter, there are no desired outputs to be presented to the NN since no prior knowledge about the loading condition. An NN emulator can be employed to identify the inverter behavior in order to determine the output error of the NN controller [1], 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 wave shaping 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 [3]. 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 [3]. The advantages of NN controller are the adaptive nature by which it intelligently modifies its output for different loading conditions.

D. Objective Of The Research

This research work aims to improve the behavior of UPS inverter under nonlinear loading conditions. A neural network based controller was designed, trained and tested for performance enhancement.

II. Inverter Control Methodology

The harmonic reduction in UPS system is reduced conventionally mainly through two basic topologies. They are:

- filter inductor current sensing and
- filter capacitor current sensing.

In the both topologies the current loop (capacitor current or inductor current) is inner feedback loop and the outer loop is voltage feedback loop.

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A. *Mathematical Analysis*

Classical control transfer function analysis is commonly used in engineering investigations to provide insights into the expected steady-state and dynamic performance of a system. In this section, transfer functions for the various feedback control schemes illustrated (inductor current feedback and capacitor current feedback schemes) are used to compare their anticipated performance characteristics, before proceeding to detailed simulation and experimental investigations.

With the filter capacitor current feedback scheme, the output filtered voltage transfer function is (1), shown in the diagram below, where

$$G_{PI}(s) = K_P + \frac{K_i}{s} \qquad (1)$$

$G_{PI}(s)$ is transfer function of PI compensator

$$v_0 = \frac{G_{PI}(s)}{s^2 L_f C_f + s R_f C_f + s C_f G_{PI}(s) + G_{PI}(s)} v_0^* - \frac{R_f + s L_f}{s^2 L_f C_f + s R_f C_f + s C_f G_{PI}(s) + G_{PI}(s)} i_L \qquad (2)$$

Equation (2) shows that the output voltage depends on both the reference voltage (first term) and the load current (second term). The second term of (2) is commonly referred as the system output impedance and its inverse is referred as the system dynamic stiffness (defined as the magnitude of load current needed to produce a unit deviation in output voltage). Ideally, the output voltage should exactly track its 50 Hz reference with unity gain and negligible phase offset, while rejecting any load current influence. The load current can therefore be viewed as a disturbance input, with a target that the transfer gain from the load current to the output voltage should be zero at the fundamental as well as at harmonic frequencies.

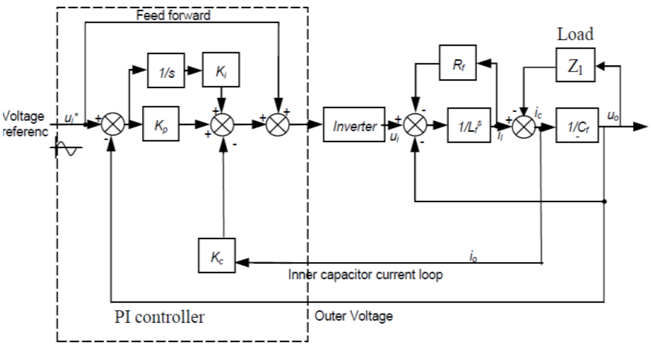

Fig.2 Schematic diagram of capacitor current feedback strategy.

To minimize distortion in the output voltage caused by load current harmonics, two fine-tuning approaches are possible. The first obvious approach is to reduce the filter inductance, which lessens the significance of the second term in (2). There is however a lower limit to which the inductance can be reduced due to the consequential increase in ripple current drawn from the inverter. The second approach is to selectively compensate for individual harmonics through the use of a discrete Fourier transform (DFT), or multiple synchronous d-q or resonant compensators at each of the selected harmonic frequencies, as reported in [13] and [16], respectively.

B. *Design of Conventional (PI) Controller*

If the mathematical model of the plant can be derived, then it is possible to apply various design techniques for determining parameters of the controller that will meet transient. The PI controller can designed using Ziegler-Nichols Method for tuning the parameters.

In this method, we first set $T_r = \infty$ and $T_d = 0$. Using the proportional control action only , increase K_p from 0 to a critical value K_{cr} at which the output first exhibits sustained oscillations.(If the output does not exhibit sustained oscillations for whatever value K_p may take, then this method does not apply.) Thus critical gain K_{cr} and the corresponding period P_{cr} are experimentally determined. Ziegler and Nichols suggested that we set the values of the parameters K_p, T_i and T_d according to the formula shown in Table.I.

If the system has a known mathematical model (such as transfer function), then we can use the root-locus method to find the critical gain K_{cr} and the frequency of the sustained oscillations ω_{cr}, where $2\Pi/\ \omega_{cr}=P_{cr}$. These values can be found from the crossing points of the root-locus branches with the jω axis. This is another method of obtaining values of K_{cr} and P_{cr} from Routh's stability criterion. Since, we know the characteristic equation of the plant. The parameters K_{cr} and P_{cr} from Routh's stability criterion are given below:

Time period Pcr= 555.36 μ sec

Critical gain at which sustained are produced=Kcr= 6.7

Table I. Ziegler-Nichols Tuning Rule Based on Critical Gain K_{cr} and Critical Period P_{cr} (second Method).

Type of Controller	K_p	T_i	T_d
P	0.5 K_{cr}	∞	0
PI	0.45 K_{cr}	$\frac{1}{2} Pcr$	0
PID	0.6 K_{cr}	0.5 P_{cr}	0.125 P_{cr}

The proportional and integral constants are found from the formula table shown above and their values are given following:

$Kp=0.45xK_{cr}=3.015$

$Ti=½*P_{cr}= 462.5$ μ sec

$Ki=1/T_i= 2162.162$

However the values of K_p and K_i obtained from Ziegler-Nichols method are not the exact values, we need to fine tune the parameters practically to obtain the exact values to meet required transient and steady state performances of the system. The values so obtained are K_p=2.9 and K_i=2200 for this plant.

The PI controller can be build as following block diagram in simulink (MATLAB) to obtain the performance of the conventional controller.

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C. Neural Network Controller

As we observed from previous chapter that the conventional controller's performance is good for linear loading conditions of UPS inverter, but its performance deteriorates with non-linear loading. The problem with non-linear load is that it draws non-sinusoidal current with rather high spike, so that the output voltage is distorted. If the load can be predicted, we can design a controller to enable the output current to keep track of this predicted current. To improve the performance of the conventional controller if we try to increase the number of feedback loops and trying to keep track of load current then the complexity of the circuit increases and hence the cost. Therefore we need a controller which can accommodate more number of feed-back inputs with less complexity and low cost.

This research work proposes NN controller for UPS inverters to reduce the output voltage distortion under nonlinear loading condition. Since, the Neural Networks has better non-linear functional approximation capability and it can accommodate any number of inputs with much less complexity it is used here.

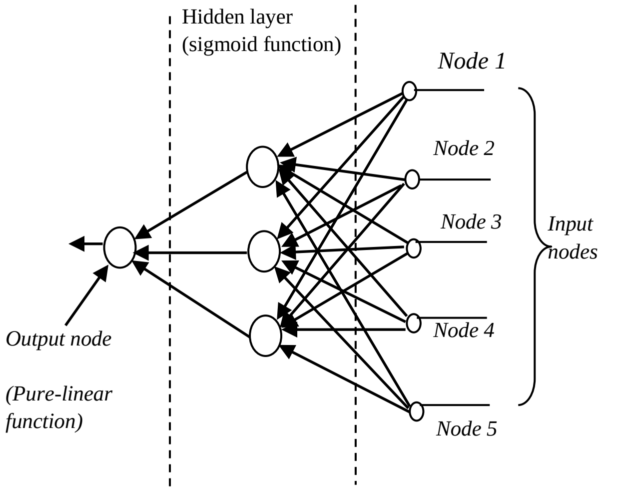

Fig.3 Structure of Neural Network controller (5-3-1)

D. Training the Neural Network Controller

Off-line training is adopted to ensure that the inverter will have a fast transient response and a low cost. This project proposes a 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. The schematic diagram shown in the figure below is built in the simulink (MATLAB) and simulated to obtain example patterns. The load model in the figure shown below is either linear load such as pure resistive or combination of resistor and capacitor or combination of resistor and inductor or combination of all the three. Non-linear loads such as full-wave diode bridge rectifier feeding capacitor and resistor in parallel. All these load models can be easily constructed using software tools MATLAB.

It should be noted that a fixed set of controller parameters (Kp,Ki and Kc) is not good for every loading condition. Each loading condition has a set of optimal parameters, which can be determined from simulation that produces 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. 4), 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 sampling frequency at which the inputs and output of the Neural Network are collected for this project is 100 KHz. The example patterns are collected for each loading condition (both linear and non-linear loading conditions).

Once the example patterns are collected, a selected feed forward NN is trained to model this controller using back propagation algorithm. The network is trained up to a mean square error of 0.000469 and then the corresponding weights and biases are used to simulate neural network controller. Gradual reduction in mean square error as the training progresses is shown in the Fig 6.

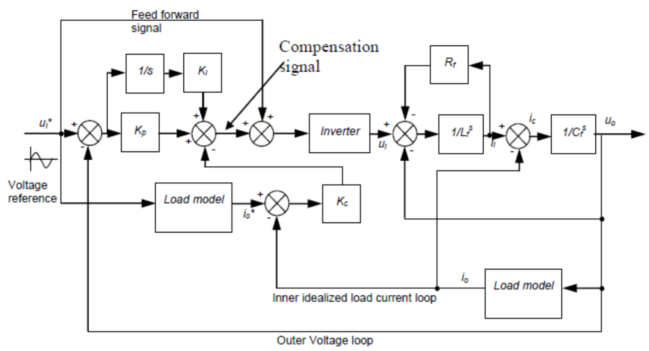

Fig.4.Controller with idealized load-current-reference i_o^* for obtaining example patterns

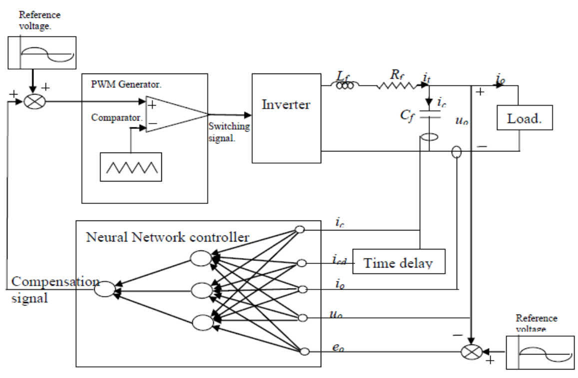

Fig.5. Proposed Neural Network controller scheme for a UPS inverter

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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. Simulation results show the superior performance of the proposed NN controller especially under rectifier-type loading condition.

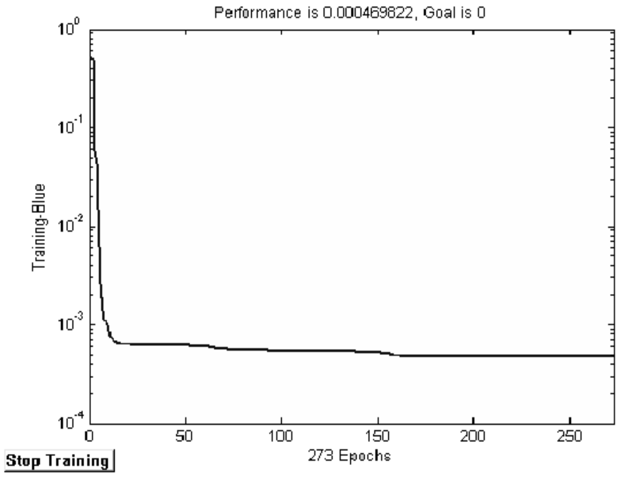

Fig.6. Graph showing the gradual reduction of error during the training of NN.

E. Summary of design steps for NN controller

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

- Build the simulated controller with the idealized load current-reference for the inverter, as shown in Fig. 4.
- 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.
- Select an NN structure that is simple and yet sufficient to model the simulated controller based on the pattern database.
- Train the NN using software tools (e.g., MATLAB with Neural Network Toolbox).

III. RESULT AND ANALYSIS

We have simulated the proposed NN controller using MATLAB, which has accurate models of switching components and diodes. The weights and biases from MATLAB simulations are put into the simulink 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 (5Ω) are depicted. The results shows that the proposed NN controlled UPS inverter are capable of producing a good sinusoidal output voltage. Fig. 11 shows the simulation result of dynamic response when the load changes from no load to full load (5Ω). 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 3200µF capacitor in parallel with a 10 Ω 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 to be improved.

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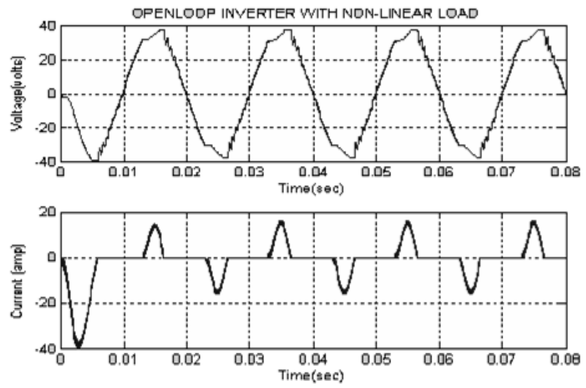

Fig.7 Output Voltage and Current waveforms of UPS inverter with open loop feeding non-linear load.

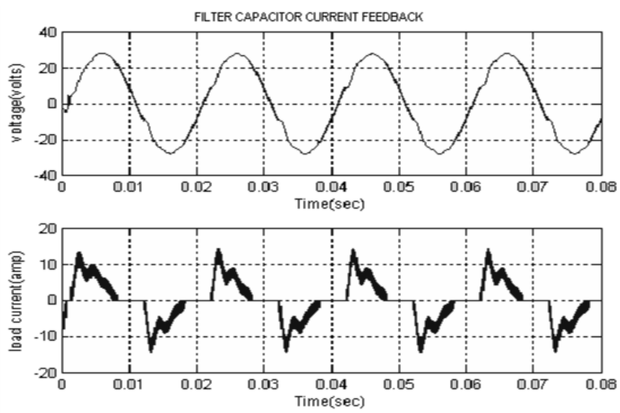

Fig.8 Output Voltage and Current waveforms of UPS inverter with conventional controller feeding non-linear load

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Fig. 8 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 3200μF capacitor in parallel with a 10 Ω 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 to be improved.

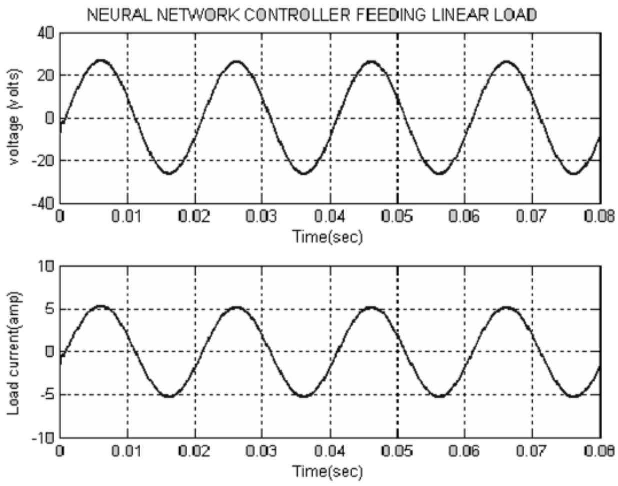

Fig.9. Output Voltage and Current waveforms of UPS inverter with conventional controller feeding non-linear load.

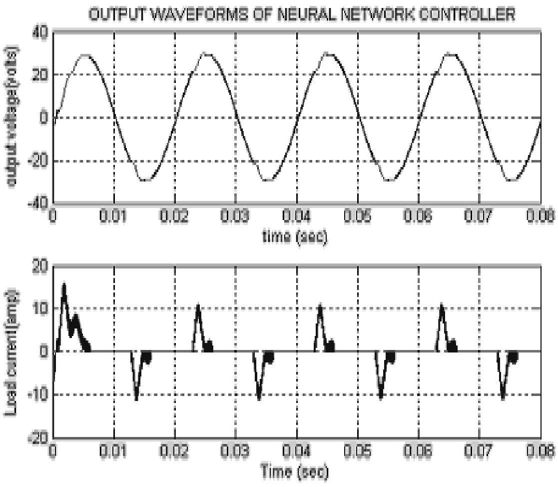

Fig.10 Output Voltage and Current waveforms of UPS inverter with Neural Network controller feeding non-linear load

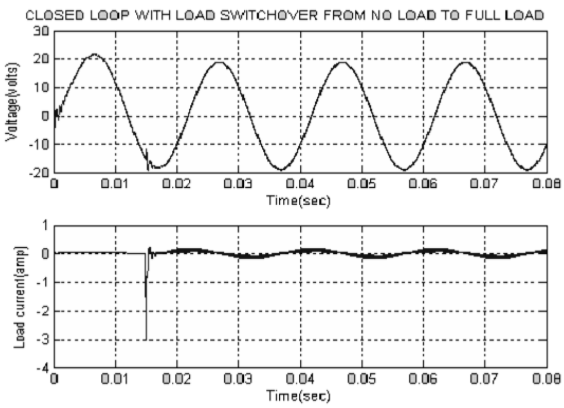

Fig.11 Current over shoot with load Switch over from no load to full load.

The following figure shows the comparison of percentage Total Harmonic Distortions of Conventional controllers that is Capacitor current feedback scheme and inductor current feedback scheme.

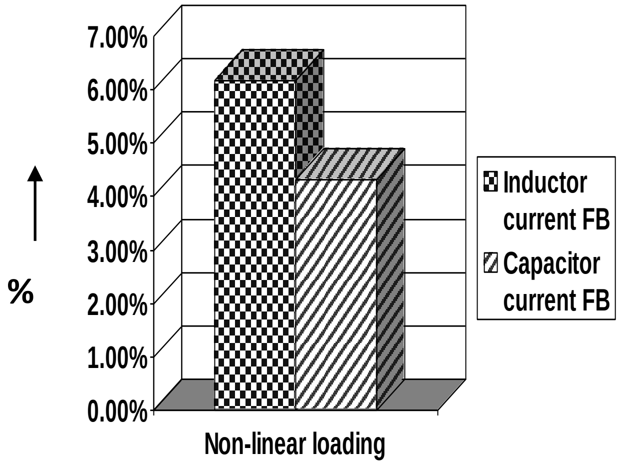

Fig.12. Comparison of Total Harmonic Distortion (THD) for Multi-loop control

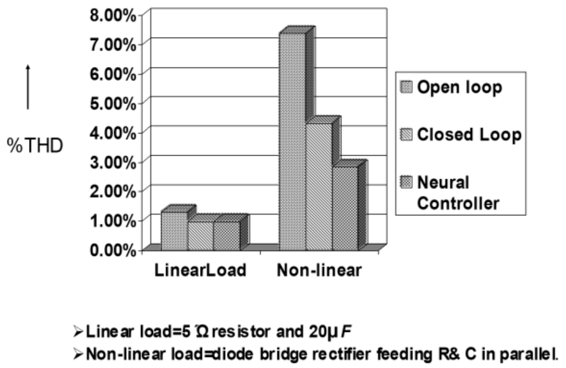

Fig:13 Comparison of Total Harmonic Distortion (THD).

Table. II Comparison of %THD of all the schemes

	Linear load	Non-linear load
Open loop inverter	1.32%	7.39%
Conventional controller	0.98%	4.31%
NN controller	0.98%	2.86%

IV. CONCLUSION

A simulation study of the conventional (PI) and neural based controller was done. The Neural Network controller is designed and its performance has been validated. Based on the results, the following conclusions can be made.

- Among multi-loop control strategies the Filter capacitor current feed back loop performs superior to that of Filter inductor current feedback loop and hence, it is chosen for comparison purposes with Neural Network controller.

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- The conventional controller performs well for linear loading conditions however; its performance deteriorates for non-linear loading conditions. That is the total harmonic distortion (THD) increases for non-linear loading conditions.
- Neural based controller gives a superior performance under linear as well as non-linear loading conditions when compared with conventional controller.
- Especially under non-linear loading conditions the reduction in THD (improvement in quality of output) is reduced from 4.31% to 2.86% by the Neural Network controller.

A. Future Work

The hardware implementation of the UPS and the proposed Neural Network controller can be made and tested for its superior performance.

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