A Comparative Study and Implementation of Controller for UPQC in Single-Phase to Three-Phase System

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***Abstract*—This paper presents comparative study and implementation of Unified Power Quality Conditioner (UPQC) to eliminate harmonics and reactive power compensation in a single-phase to three-phase converter system. The proposed configuration solves typical problems encountered in remote rural area applications, where only a single-phase supply is available and there is a demand for three-phase supply. The universal active power filter is a power line conditioner. It consists of a combination of series type and shunt type active power filter topologies. The series active power filters are used to minimize voltage harmonic distortion and sag/swell compensation of the input voltage. The shunt active filters used are to minimize current harmonics and compensate reactive power of the system, resulting in effective power factor improvement. In this scheme, a three phase line interactive uninterruptible power supply system also is used. A suitable control approach is used to minimize the voltage and current harmonics simultaneously. The simulation model of Universal Active Power Filter, for single phase to three phase system was developed using MATLAB -simulink with PI and Neural Network controller. The results in terms of THD are compared for PI and Neural Network controller and the prototype model is developed using dsPIC30F4011 controller, for the one which provides better results in comparison. The effectiveness of the proposed system is validated from the experimental results.**

Keywords—Unified Power Quality Conditioner (UPQC), Total harmonic distortion (THD), reactive power compensation, PI controller, Neural Networks controller.

I. INTRODUCTION

Power quality is an important problem due to a large number of power electronic components is used in the electric power system. Nonlinear loads such as diode rectifiers, adjustable speed drives and arc furnaces cause problems of current harmonics and voltage distortion in power system. These results in many problems, such as low power factor and increased power losses in the transmission and distribution systems. It also causes many power quality problems in the system. There are many equipment to improve the power quality (PQ) such as Uninterruptible Power Supply (UPS), line voltage regulators, transient suppressors, Active Filters, a hybrid filter [1] -[5]. etc.,

Active power filters are used in shunt, series and a combination of shunt and series connection forms to compensate the voltage and current based distortions. The active power filter plays a vital role to improve the power quality in the power system. The combination of shunt and series active power filter is called as Unified Power Quality Conditioner (UPQC) is mostly used to enhance the power quality.

UPQC is an important component to minimize the power quality problems. The universal active power filter that has a series connected single phase converter and a shunt connected three phase PWM converter. These two converters share the same DC bus and the same rules are followed to connect them into two lines. The basic function of UPQC in utility application is to provide the reactive power compensation, eliminate the line current harmonics, voltage harmonics and balance the line voltage. To provide uninterruptable supply, a battery bank is connected parallel to the DC bus capacitor. Due to certain operating constraint, shunt or series active power filters can compensate only specific power quality problems. Shunt active filters are used to eliminate current harmonics, compensate the reactive power and current unbalance. Series active filters are used to eliminate the voltage harmonics and balance the voltage on the source side [6].

The proposed Unified Power Quality Conditioner consists of shunt and series active power filters as shown in Fig1. . Shunt active power filters are connected parallel to the line. Series active power filters are connected before the load in series with the AC mains, through a coupling transformer. It eliminates voltage harmonics and also regulates and balances the terminal voltage of the load or line. A simple P-I (proportional-integral) controller is used to regulate the DC bus voltage to derive the reference supply current peak value in phase with supply voltage. The PWM control technique is used to generate the gating signals for the switching devices of the APF (Active Power Filter). Detection and compensation of distortions are very important control functions of an active power filter. Many techniques have been developed, such as p–q theory, synchronous d– q reference frame, synchronous detection, proportional-integral (PI) controller, adaptive detection, and selective detection used to develop compensation algorithm.

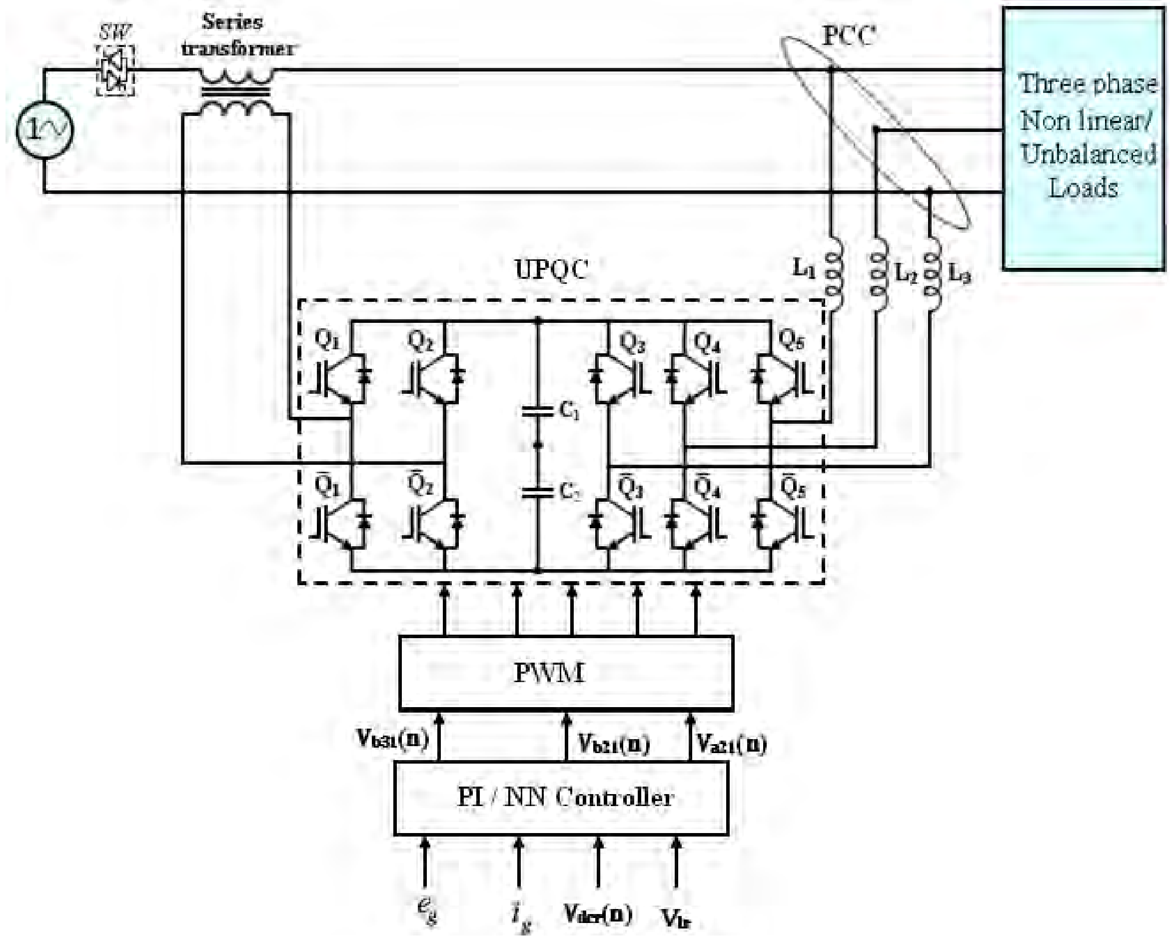


Fig. 1 Schematic diagram for proposed system

The proposed system compensates current harmonics by imposing a sinusoidal current to the grid in phase with the grid voltage [7] -[11].

This paper presents the topology used and the whole scheme of operation of the unified power quality conditioner for different controllers with comparative study. At the end results of the implemented prototype are presented.

2. SYSTEM DESCRIPTION

Fig.1. Shows the proposed unified power quality conditioner configuration. It consists of series and shunt active power filter topology. The series active power filter is connected to the supply main through the inductor L_1, L_2 and a coupling transformer. These inductors are used to give linear input to the series active power filter. The shunt active power filter is connected parallel to the load through the inductors $L_{3,}$ $L_{4,}$ and L_5.

These Inductors are used to inject the required current, whenever the current harmonics are present in the system. The grid voltage and grid current are represented as e_g and i_g. The DC link voltage is V_c and the DC link capacitor are C_1 and C_2. Three phase load currents are i_{l1},i_{l2} and i_{l3} and V_l is the load voltage. The series active power filter voltage is V_{a21} and the shunt active power filter voltage is V_{b31}.To implement the UPS system, added a static switch (*sw*) is used to provide the disconnection between the UPS system and the grid power supply. The UPS protects the critical loads when an occasional interruption of the incoming power occurs [12].

3. DESIGN OF DC-LINK CAPACITOR AND INDUCTOR

The DC side capacitor serves two main purposes: (i) it maintains a DC voltage with small ripples in steady state, and (ii) serve as an energy storage component to supply real power difference between source and load during the transient period. In steady state, real power supplied by the source should be equal to the real power demand of the load and a small power to compensate the losses in the active filter. Thus, the DC-link capacitor voltage can be maintained at a reference value. However, when the load condition varies, the real power balance between the source and the load will be disturbed. This real power difference will be compensated by this DC-link capacitor.

When the converter provides only reactive current, the minimum capacitance value of the DC link may be calculated from maximum DC-voltage ripple constraint, originated by the switching frequency. For proper operation of active filters, at every time the voltage of the DC capacitor voltage value must be 1.5 times the maximum voltage of the line [13]. The design value of the capacitor is given by

$$C = \frac{\sqrt{2} i_{c,ripple}}{2 f_{ch} \Delta v_{c\max}} \quad (1)$$

Where, $i_{c,ripple}$ is the rms current in the capacitor, f_{ch} is the switching frequency, and $\Delta v_{c\,max}$ the DC - link allowable ripple voltage of dc-link.

The design of the inductors is an important matter in the shunt active power filter, because this type of filter must have source current characteristics. The design of inductors affects the DC bus voltage and the THD value of the grid current. As a matter of fact, an increase in the value of this inductor will increase the DC bus voltage and also decrease the THD value of the voltage. Then decrease in the inductor value, will decrease the DC-link voltage while increasing the THD value.

4. PRINCIPLE OF OPERATION

In the existing techniques, series active power filter circuit configuration is based on a three phase PWM voltage source inverter or single phase PWM voltage source inverter connected in series with the power lines through three numbers of single-phase coupling transformers or a single phase coupling transformer. For different types of applications, the three-phase PWM-voltage-source converters can be changed by three single phase PWM inverters. In this proposed system, series active power filter circuit is based on single phase PWM- voltage source inverter connected in series with the power line through a single phase coupling transformer. Current harmonic and voltage compensation are achieved by generating the appropriate voltage waveforms with the single phase PWM voltage source inverter, which are replicated in the power system through a coupling transformer.

Series active power filters are used to eliminate voltage harmonics generated by non-linear loads, voltage unbalances and voltage sags / swells at the load terminals by using the PI controller scheme. The high impedance enforced by the series active power filter is formed by generating a voltage of the same frequency that the current harmonic component that is desired to be eliminated. By compensating the fundamental frequency magnitude positive, negative and zero sequence voltage components of the power distribution systems voltage regulation or voltage unbalances can be corrected. In this system, the series active power filter injects a voltage component in series with the supply voltage and therefore can be observed as a controlled voltage source, compensating the load side voltage regulation, and unbalance voltage. The Voltage injection of random phase with respect to the load current implies active power transfer capabilities which increases the rating of the series active power filter.

Shunt active power filters are used to minimize the current harmonics by injecting equal-but-opposite magnitude harmonic compensation current. In this case, the shunt active power filter operates as a current source inverter. It injects the harmonic components generated by the load but phase shifted by 120 degrees. As a result, components of harmonic currents contained in the load current are cancelled by the effect of the shunt active filter, and source current remains sinusoidal one and in phase with the respective phase voltage. Shunt active power filters are normally implemented with PWM voltage-source inverters. In this variety of applications, the PWM-Voltage source inverter operates as a current-controlled voltage-source [14].

The control scheme of a shunt active power filter should calculate the current reference waveform for each phase of the inverter, to maintain constant DC voltage, and generate the inverted gating signals. The current reference circuit produces the reference currents essential to minimize the load current harmonics and compensate the reactive power, and also tries to maintain constant the DC voltages across the capacitors C_1 and C_2. Also, the compensation effectiveness of an active power filter depends on its ability to follow with a minimum error and time delay the reference signal calculated to compensate the distorted load current. Last of all, the DC voltage control unit must keep the total DC bus voltage constant and equal to a given reference value. The DC voltage control is attained by adjusting the small amount of real power absorbed by the inverter. This small magnitude of real power is adjusted by changing the amplitude of the fundamental component of the reference current [15], [16].

5. PROPOSED CONTROL SCHEME

This paper presents the comparative study of controller for Universal Active Power Filter in single-phase to three-phase system. In this proposed system PI and Neural Networks controller is implemented and its performance is analyzed.

5.1. PI Controller

Fig.2. shows the block diagram of the proposed PI controller. The capacitor DC-link voltage Vc is adjusted to a reference value by using the PI controller. This controller provides the amplitude of the reference current I_{gr}. For the harmonic and reactive power control, the instantaneous reference current i_{gr} must be synchronized with voltage e_g. This is obtained via PLL block; this block indicates the instantaneous phase δ of voltage e_g and generates the current i_{gr} from I_{gr} and δ indicated by PI block.

The error in DC bus voltage at n^{th} sampling instant is given by,

$$V_{dce}(n) = V_{dcr}(n) - V_{dcr}(n) \qquad (2)$$

where, $V_{dcr(n)}$=Reference dc voltage ,$V_{dc(n)}$ = Dc link capacitor voltage

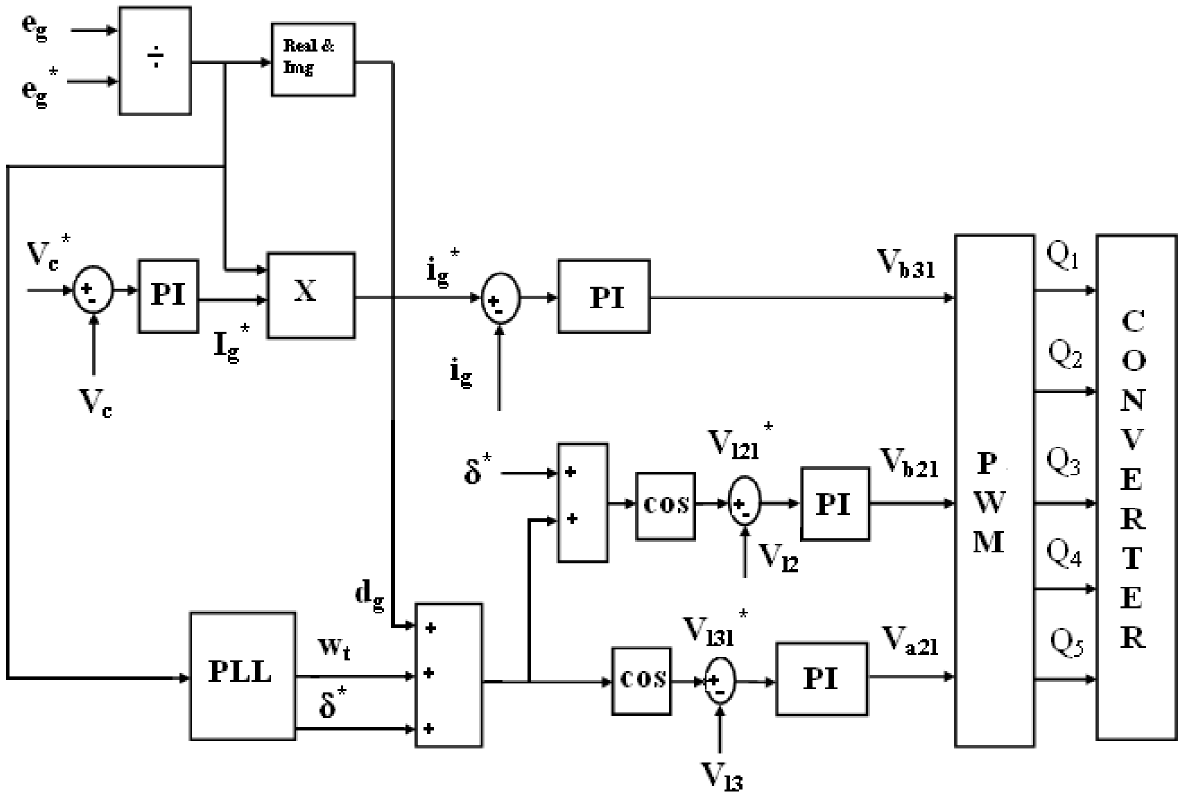


Fig.2 Block diagram of PI Controller scheme

The output of the PI controller for maintaining the DC bus voltage at the n^{th} sampling instant is given by,

$$i_g(n) = k_p\left(V_{dce}(n) - V_{dce}(n-1)\right) + k_i V_{dce}(n) + i_g(n-1) \qquad (3)$$

where, k_p and K_i – Proportional and integral gain

$V_{dce(n)}$ and $V_{dce(n-1)}$ – Voltage errors in n^{th} and $(n-1)^{th}$ instant

$i_g(n)$ – Reference current

The reference grid current is given by,

$$I_{gr}(n) = i_g(n) * e_g(n) \quad (4)$$

The error in grid current is given by,

$$I_{ge}(n) = I_{gr}(n) - I_g(n) \quad (5)$$

where, $I_{gr}(n)$ – Reference grid current , $I_g(n)$ – Grid current

The reference line voltages are given by,

$$V_{l21} = \sqrt{3}V_{lr}\cos(\omega t + dg + \delta_r + 60) \quad (6)$$

$$V_{l31} = \sqrt{3}V_{lr}\cos(\omega t + dg + \delta_r) \quad (7)$$

The error in line voltages are given by,

$$V_{l21e}(n) = V_{l21}(n) - V_b(n) \quad (8)$$

$$V_{l31e}(n) = V_{l31}(n) - V_c(n) \quad (9)$$

The reference voltages are given by,

$$V_{b31}(n) = k_p\left(I_{ge}(n) - I_{ge}(n-1)\right) + k_i I_{ge}(n) + V_{b31}(n-1) \quad (10)$$

$$V_{b21}(n) = k_p\left(V_{l21e}(n) - V_{l21e}(n-1)\right) + k_i V_{l21e}(n) + V_{b21}(n-1) \quad (11)$$

$$V_{a21}(n) = k_p\left(V_{l31e}(n) - V_{l31e}(n-1)\right) + k_i V_{l31e}(n) + V_{a21}(n-1) \quad (12)$$

The current controller is implemented by using the PI controller. This current controller defines the reference voltage V_{b31}, which is used for the harmonic control, operating as a shunt filter. The line voltage V_{l31} has been defined by the series active power filter; the controller defines V_{a21}. The line voltage V_{l21} has been regulated by PI controller, which defines V_{b21}. Once the reference voltages are defined, the PWM strategy is directly applied. It produces the reference line voltages [17], [18].

5.2. Neural Network Controller

In Fig.3 shows the block diagram of the proposed NN controller system. This controller block diagram is same as the instant of PI controller. The capacitor dc-link voltage V_{dc} is adjusted to a reference value by using Neural Network (NN) controller. This controller provides the amplitude of the reference current I_{gr}. For the harmonic control, the instantaneous reference current i_{gr} must be synchronized with voltage e_g. This is obtained through PLL block, this block indicates the instantaneous phase δ of voltage e_g and generates the current i_{gr} from I_{gr} and δ. The current controller is implemented by using the controller indicated by NN block. This current controller defines the reference voltage V_{b31}, which is used for the power factor control, operating as a shunt filter. The line voltage V_{l31} has been defined by the series filter; the controller NN defines V_{a21}. The line voltage V_{l21} has been regulated by controller NN, which defines V_{b21}. Once the reference voltages are defined, the PWM strategy is directly applied. It produces the reference line voltages.

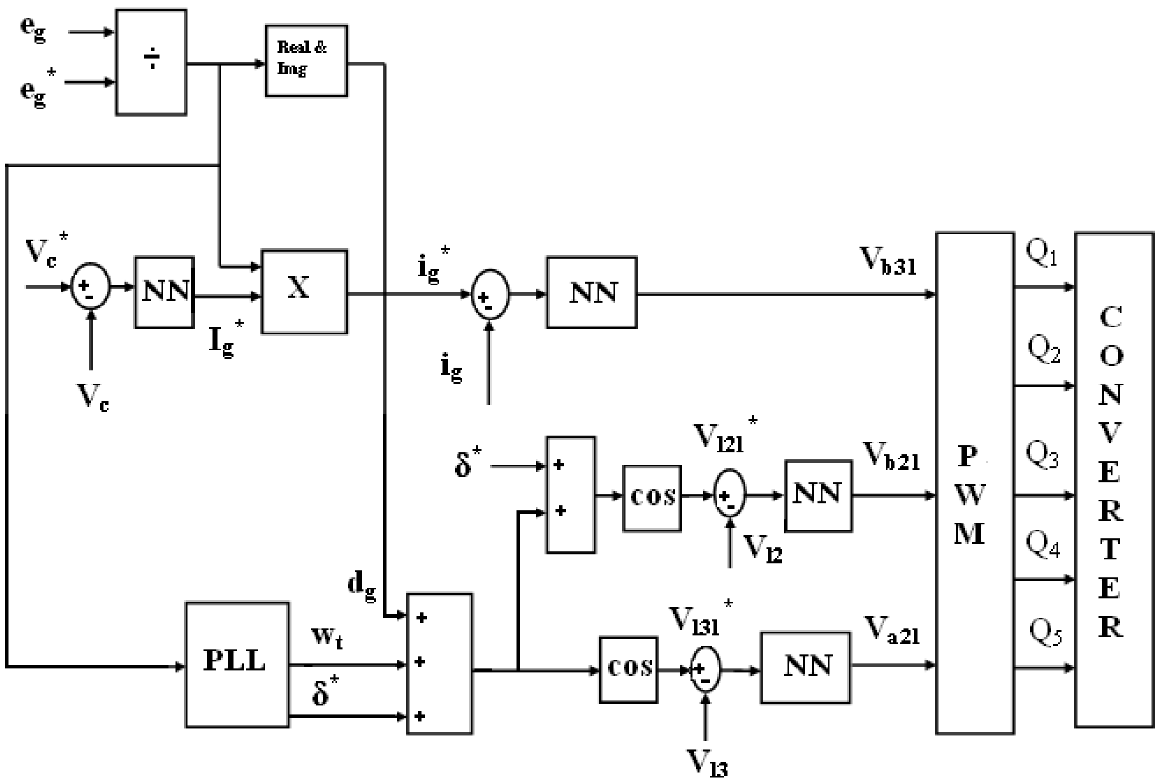


Fig.3 Block diagram NN Controller block diagram

Fig.4 (a), (b) &(c) shows the internal structure of Neural Networks controller. The trained input is given to the delay and then it is given to the weighted block. After that, the bias value and weight value are combined and it is given to the logsig. From this block obtained output a {1}. Then a {1} is given to the delay and then it given to the weighted block. After that the bias value and weight value are combined and it is given to the logsig. From this block obtained output a {2}. After that a {2} is given to the delay and then it given to the weighted block. After that the bias value and weight value are combined and it is given to the pure lin from this block will be get process output y {1}.

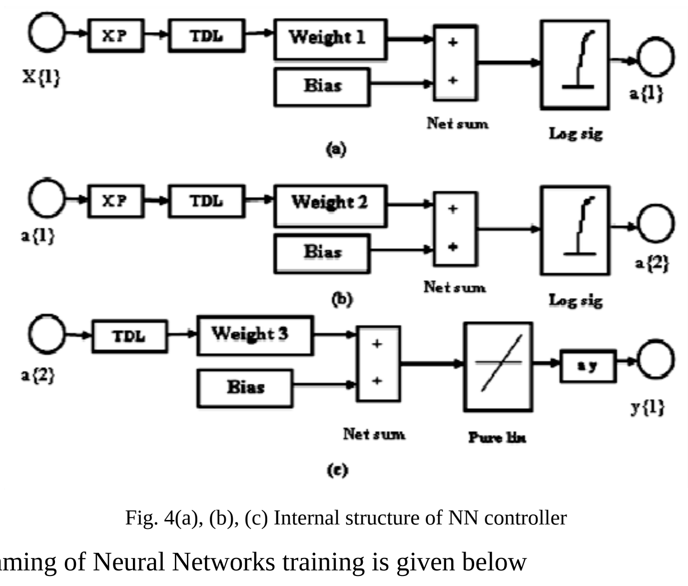


Fig. 4(a), (b), (c) Internal structure of NN controller

The MATLAB programming of Neural Networks training is given below

```
A1 = [-20 -10 -8 -6 -4 -2 -1 -0.02 -0.0002 0 0.0002 -0.02 1 2 4 6.452 8 10 20];
x = [-1 -1 -1 -1 -1 -1 -1 -1 -1 -0.5 +0.25 1 1 1 1 1 1 1 -1];
net1=newff(minmax(A1),[20,4,1],{'logsig','logsig','purelin'},'trainrp');
net1.trainParam.show = 100;
net1.trainParam.lr = 50e-6;
```

```
net1.trainParam.epochs = 1000;
net1.trainParam.goal = 1e-3;
[net1] =train (net1, A1, x);
 gensim (net1,-1)
```

The neural network is trained for outputting fundamental reference currents. The signals thus obtained are compared in a Neural Networks controller, to give switching signals to PWM [19], [20].

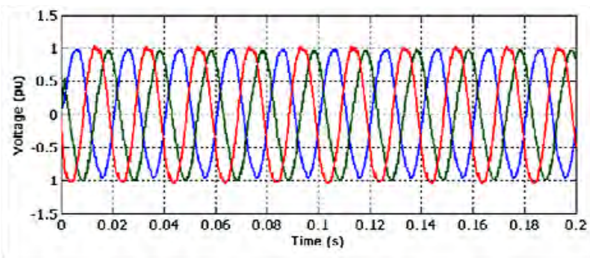
6. SIMULATION RESULTS AND DISCUSSION

The nonlinear loads on the power system draw highly distorted currents, resulting in voltage distortions that can affect the other loads. For compensation of voltage and current harmonics the model of Universal Active Power Filter has been implemented by using MATLAB/SIMULINK and PSB toolboxes. The simulation result has been shown for both PI and NN controlling techniques.

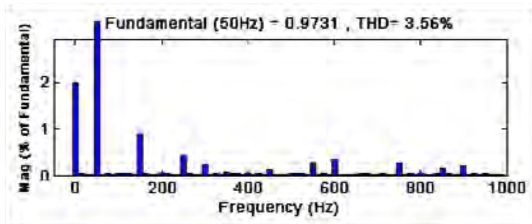
6.1. Simulation Result with PI Controller

The THD level of the load voltage and load current, which were approximately14.7% and 29.9% respectively before compensation, were about 4.66% and 4.86% after compensation by using universal active power filter with PI controller. Fig.6, from top to bottom, shows the Load voltage waveform,THD level of load voltage for the Phase-A, Load current waveform and THD level of load current for Phase-A. By means of the series AF compensation, the load voltage THD values were decreased from 14.7% to about 4.46%. After the shunt AF compensation, the THD values of the load currents were decreased.

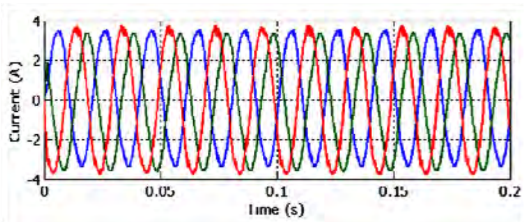
The injected current from the shunt active filter for the load current compensation is shown in fig.7(a) and the DC link capacitor voltage wave form is shown in fig.7(b).



(a)



(b)



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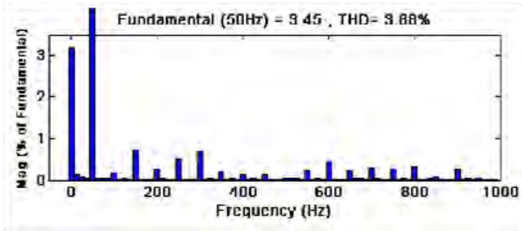
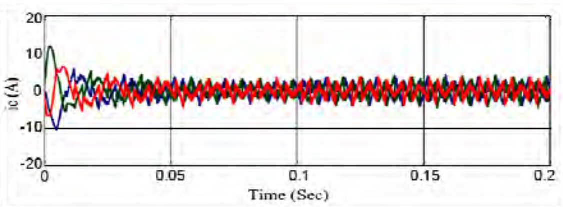
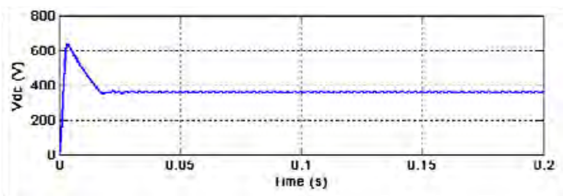


(d)

Fig. 6 Simulation results by using PI controller (a)Load voltage waveform (b)THD level of load voltage for Phase-A(c)Load current waveform (d)THD level of load current for Phase-A.





(a) (b)

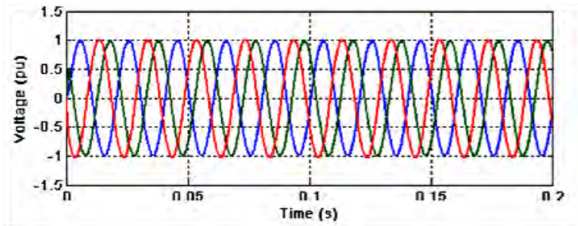
Fig. 7 Simulation results by using PI controller (a) Injected current in the shunt active power filter (b) DC link voltage

6.2. Simulation Result with NN Controller

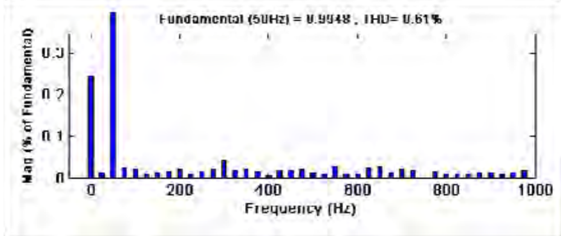
The THD of the load voltage and load current, which was about 1.03% and 1.22% after compensation by using a universal active power filter with Neural Network controller, which is well within the limits specified by IEEE-519.

Fig. 8 from top to bottom, Shows the Load voltage , THD level of load voltage for Phase-A, Load current and THD level of load current for Phase-A. By means of the series AF compensation, the load voltage THD value was decreased to about 1.03%, by using NN controller.

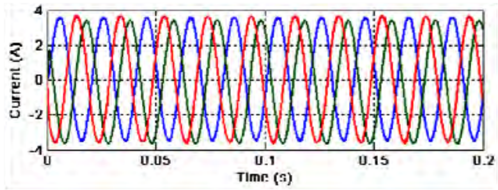
The injected current from the shunt active filter to the load current compensation by using a Neural Network controller is shown in fig. 9 (a) and the capacitor voltage waveform is shown in fig. 9 (b).



(a)



(b)



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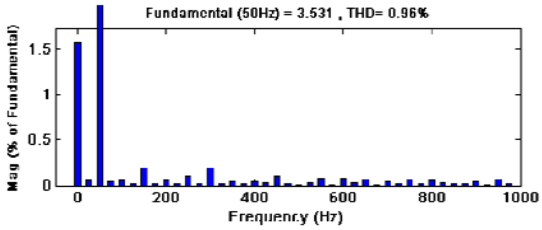
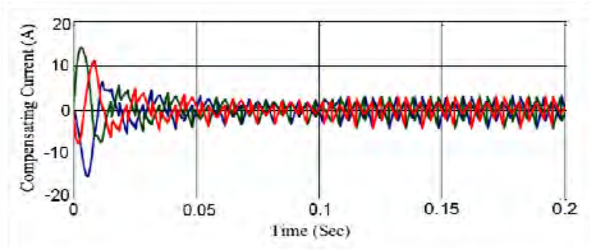
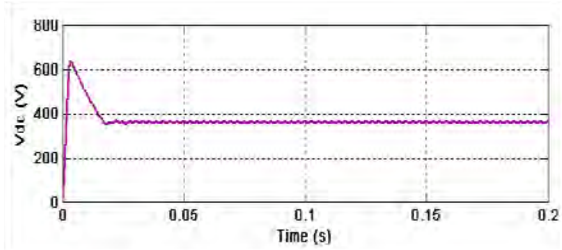


(d)

Fig. 8 Simulation results by using NN controller (a) Load voltage waveform (b) THD level of load voltage for Phase-A (c) Load current waveform (d) THD level of load current for Phase- A.



(a)



(b)

Fig. 9 Simulation results by using NN controller (a) Injected current in the shunt active power filter (b) DC link voltage

By using this universal active power filter, reactive power is compensated, voltage and current harmonics will be reduced and the THD levels of load currents and load voltages also have been reduced. The comparison of THD levels of load currents and load voltages by using PI and Neural Networks controller is shown in Table 1.

TABLE 1
SIMULATION RESULTS AND THD LEVELS OF VOLTAGE AND CURRENT WAVEFORMS

		Using PI controller		**Using NN controller**	
	Phases	**Currents (A)**	**Voltages (V)**	**Currents (A)**	**Voltages (V)**
THD (%)	A	3.88	3.56	0.96	0.61
	B	4.91	5.27	1.10	1.29
	C	5.79	5.26	1.60	1.19

7. EXPERIMENTAL RESULTS

A prototype was built to verify the simulation results of single phase to three phase converter using UAPF with an input supply of 230V, 50Hz. In this prototype hardware circuit single phase supply is connected to primary side of the series transformer. Series transformer secondary is connected to the series converter. Series converter has four MOSFET switches, it is used to convert single phase AC into DC and also minimizes the voltage harmonics in the source side. This DC voltage is stored by using the DC link capacitor. It is connected to shunt converter. This shunt converter has six MOSFET switches; it is used to convert DC into three phase AC and also minimizes the current harmonics in the load side by injecting the equal, but opposite current through the inductor. The dsPIC 30F4011 controller has been used for providing the pulses to series and shunt converter [21]. The dsPIC 30F4011 device contains extensive Digital Signal Processor (DSP) functionality with a high-performance, and in having with16-bit microcontroller (MCU) architecture. It has a high performance modified RISC (Reduced Instructions Set Computing) CPU. The block diagram for the experimental set up is shown in fig.10.

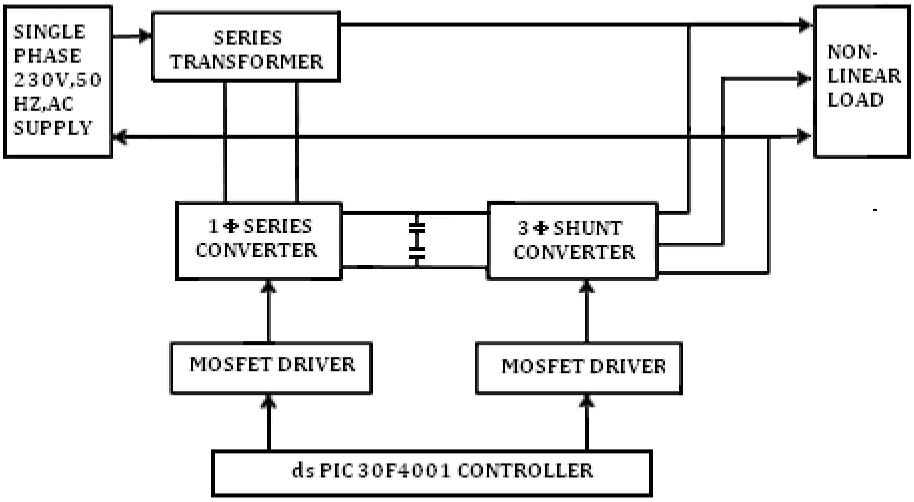


Fig. 10 Block diagram for experimental prototype

The experimental waveforms were recorded with digital oscilloscope, and the harmonic analyses were done with a Fluke 435 power quality analyzer. The experimental results of load voltages shown in Fig.11 and the harmonic spectra of the phase-a, phase-b and phase-c of load voltages after compensation are shown in Figures12a, 12b and 12c, respectively.

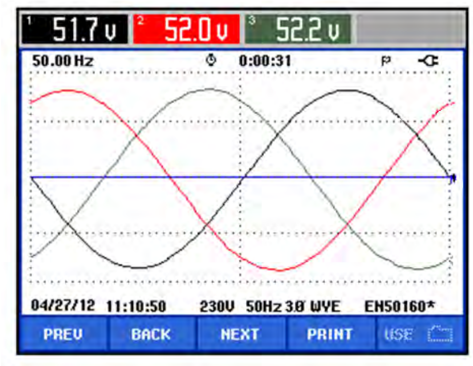
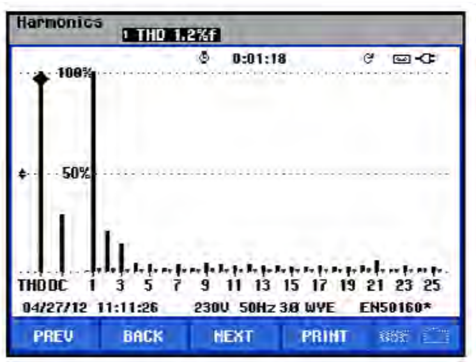
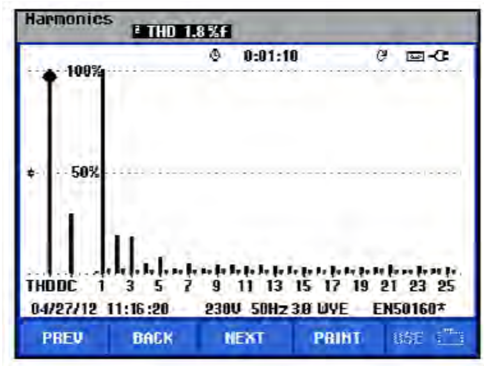


Fig. 11 Experimental results of load voltages



(a)



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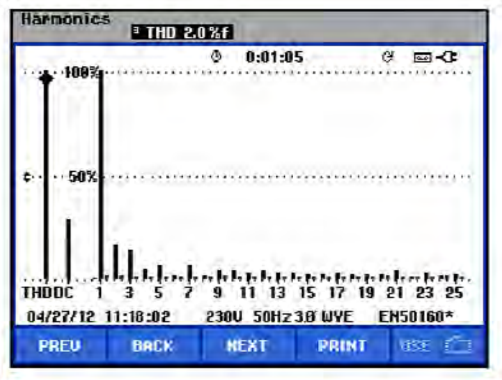
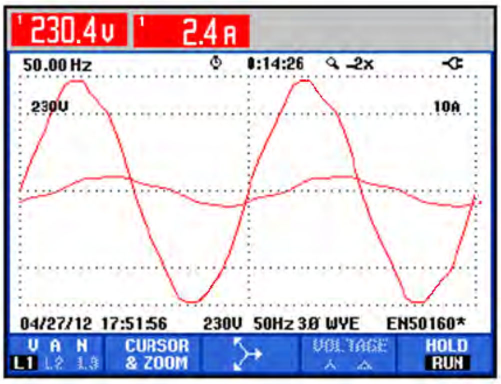
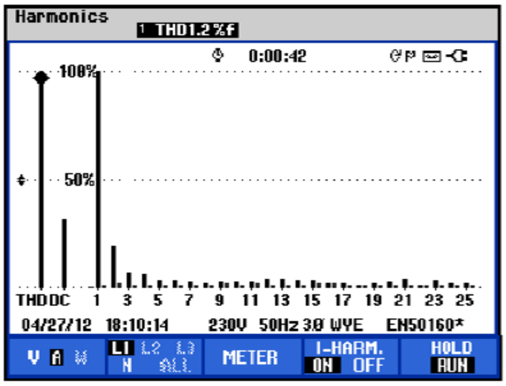


(c)

Fig. 12 Experimental results harmonic spectra of load voltages (a) THD level of load voltage for Phase-A (b) THD level of load voltage for Phase-B (c) THD level of load voltage for Phase-C.



(a)



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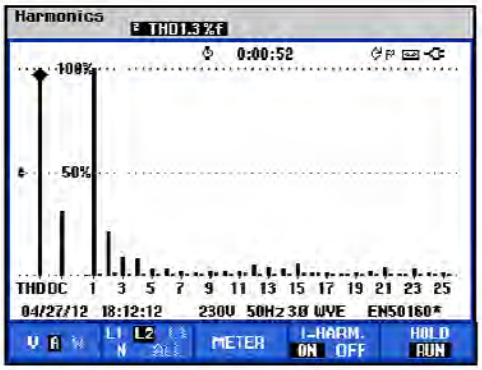

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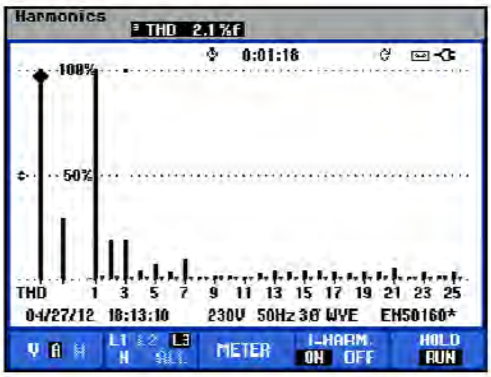

(d)

Fig. 13 Experimental results harmonic spectra of load current (a) Load voltage and load current of phase-A (b) THD level of load current for Phase-A (c) THD level of load current for Phase-B (d) THD level of load current for Phase-C.

The experimental results of load voltage and load current of phase-A are shown in Fig. 13(a) and the harmonic spectra of the phase-a, phase-b and phase-c load current after compensation are shown in Figures 13b, 13c and 13d, respectively. The compensation results are summarized in Table 2.

TABLE 2
EXPERIMENTAL RESULTS AND THD LEVELS OF VOLTAGE AND CURRENT WAVEFORMS

	Phases	Currents (A)	Voltages (V)
THD (%)	A	1.2	1.2
	B	1.3	1.8
	C	2.1	2.0

8. CONCLUSION

The Universal Active Power Filter for eliminating harmonics and reactive power compensation in single- phase to three-phase system is developed. This model of the system is used to solve the typical problem found in the remote area. The proposed model with PI controller technique and Neural Networks controller techniques are developed and the performance of the systems is compared. From this comparison it is found that the THD value of NN controller output is less than PI controller. The THD value of the phase current will be below the permissible limit of 5% (IEEE-519-1992).For validation of simulation results prototype experimental setup was developed by using dsPIC 30F4011 controller and obtained its results.

APPENDIX

Simulation parameters are Source voltage= 230 V, Frequency = 50 Hz; Inductor (L_1, L2) = 8.42 mH, 8.28 mH; Dc link capacitance (C) = 2200μF, Dc link voltage= 375V; Inductors (L_3, L_4&L_5) = 19.41 mH, 20.04 mH and 19.49 mH180 mH; Non-linear load: Three phase bridge rectifier with RL load:Active power = 1000 W, Inductive reactive power = 50 Positive var

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