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Comparison of Neural Network and Fast Fourier Transform Based Selective Harmonic Extraction and Total Harmonic Reduction for Power Electronic Converters

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Abstract - A new strategy to estimate harmonic distortion from an AC line is presented for power electronic converters. An Adaptive linear neural network (ADALINE) is used to determine precisely the necessary currents in order to cancel harmonics. The proposed strategy is based on an original decomposition of the measured currents to specify the neural network inputs. This new decomposition is based on the Fourier series analysis of the current signals and Least Mean Square (LMS) training algorithm carries out the weights. This new estimation strategy appreciably improves the performances of traditional compensating methods and is valid both for single-phase and three-phase systems. The proposed strategy also allows extracting the harmonics individually. The method is based on the extraction of fundamental components of distorted line current using an ADALINE network. The output of the ADALINE is compared with distorted supply current to construct modulating signals and to generate PWM pulses for active line conditioner. Speed and accuracy of ADALINE results in improved performance of the active power line filter. In this paper converter is used as a non-linear load. The performance of ADALINE is verified with single phase fully controlled AC-DC converter simulated with neural network based active filter using MATLAB/SIMULINK. Also in this paper, harmonic components can be selectively extracted using ADALINE network and harmonic content analyzed by artificial neural network (ANN) is compared with the Fast Fourier Transform (FFT).

Keywords - FFT, ADALINE, LMS, Active Power Filter, THD

I. INTRODUCTION

The deterioration of currents and voltages in electrical networks is due to the presence of non-linear loads (rectifiers, variable speed transmissions, lighting etc) absorbing non sinusoidal currents. These harmonic current circulate in the electrical network, disturb the correct operation of the components and even it may damage them. The harmonic compensators called Active Power Filters (APFs) are advanced solutions for eliminating harmonic distortion [1]. APFs are able to correct the power factor without any additional equipment. The concept of the active power filter is to detect or extract the unwanted harmonic components of a line current, and then to generate and inject a signal into the line in such a way to produce partial or total cancellation of the unwanted components.

Active power filters could be connected either in series or in parallel to power systems. Therefore, they can operate as either voltage sources or current sources. The shunt active filter is controlled to inject a compensating current into the utility system so that it cancels the harmonic currents produced by the nonlinear load. B.M.Bird, the first attempts to reduce harmonics without the use of conventional passive filter [2]. Their proposed design is changing the waveform of the current drawn by the load by injecting a third harmonic current, displaced in phase, in to the converter itself. With this method it is not possible to eliminate all the harmonic components. Ametani, et.al proposed an idea to expand the current injection method by to eliminate multiple harmonics [3]. According to this theory, an active control circuit could be used to precisely shape the injected current. Ideally this current would contain harmonic currents of opposing phase, thus the harmonics would be neutralized, and only the fundamental component would remain. Ametani was not successful in producing a practical circuit capable of creating a precise current. The total harmonic distortion was reduced, but single harmonics were not completely eliminated. Gyugyi and Strycula presented the concept to compensate for harmonics by the applications of semiconductor switches in the form of PWM inverter [4]. They developed a method by injecting PWM current using Voltage Source Inverter (VSI) and Current Source Inverter (CSI), results are verified experimentally.Akagi, and et.al introduced PQ theory and developed a PWM voltage type converter topology for instantaneous reactive power compensation [5]. In their work, the authors decomposed the instantaneous voltages and currents into orthogonal components yielding, in the time domain, a component termed the instantaneous reactive power. The active filter is controlled to eliminate this instantaneous reactive power thus resulting in reactive power compensation in the time domain.

The performance in terms of the harmonic compensation strongly depends on the selected identification method. Indeed, an efficient control device will not be able to make the sufficient corrections if the harmonic currents are badly identified. For this reason several identification methods have been developed in recent years. For example, Kalman filters have been applied with the need for a dynamic state model [6]. The simplest way to identify harmonics and generate the harmonic current is to use discrete Fourier transformation (DFT) of fast Fourier transformation (FFT). Although it has wide applications, the DFT or FFT has certain limitations in harmonic analysis [7]. The Fast Fourier Transform (FFT), which needs a lot of computation resources, has also been applied. [8] Presently, neural network has received special

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attention from researchers because of its simplicity, learning and generalization ability, and it has been applied in the field of engineering , such as in harmonic detection since early 1900s[9].

K.Hartana and G.G.Richards were among the first who used back propagation ANN to track harmonics in large power systems, where it is difficult to locate the magnitude of the unknown sources [10]. In their method, an initial estimation of the harmonic source in a power system was made using neural network. P.K.Dash et.al utilized the ADALINE, a version of ANN, as a new harmonic estimation technique [11]. The learning rule of the method is based on the LMS introduced by Widro-Hoff. J.R.Vazquez and P.Salmeron presented an active power filter control using neural network technologies. The proposed control design is a pulse width modulation control with two blocks that include neural networks [12]. Adaptive networks estimate the compensation currents. In their scheme, J.R.Vazquez and P.Salmeron used two signals load voltage and load current as the input to the adaptive network block and the compensation current is compared with actual current error, is trained in feed forward network block. The actual compensation currents are the result of controlling the switching logic of the power transistors.

In this paper an improved scheme is proposed in which only the actual load current is given to adaptive neural network and the reference current is obtained. The load voltage is given to a DC regulator with a simple PI controller which gives the actual filter current and which is compared with reference current the gating pulses to IGBTs are provided through a hysteresis band comparator. The proposed model can be used to eliminate harmonics in on line. The ADALINE neural network uses to separate the fundamental component form the distorted supply current. Based on the Fourier series, this new decomposition of current signals allows to define the neural network inputs for which an LMS algorithm carriers out the weights training. The method utilizes adaptive neurons (ADALINE) to process the signals obtained from the line. This ADALINE is current ADALINE. [13, 14]

This current ADALINE extracts the fundamental components of the distorted line current signal and the output of the ADALINE is compared with distorted supply current to construct the modulating signal. This modulating signal is used to generate the PWM pulses and PWM pulses are fed to the active power filter to generate compensating current. This compensating current is fed against to the distorted line current. Thus the power quality will be maintained.

Many frequency domain approaches to active power line conditioning are available, among these ADALINE-based harmonic extraction has been chosen because of its superior characteristics compared with other available methods. [6, 8, 13].
In the following sections, first basic principle of harmonic compensation is discussed. In section III ADALINE based Active Power Filter is explained with detailed discussion on basics of LMS or Widrow-Hoff learning rule. In section IV proposed scheme is described with simulated model. In section V the simulated results are given. In section VI comparisons of the results are given with the advantages of the proposed scheme.

II. BASIC PRINCIPLE

The harmonic compensation is of high importance for the energy suppliers as well as consumers. The APF thus constitutes the solution the most commonly used today in industry [15]. These systems are placed in derivation between the nonlinear load and the electrical supply network. Only small portion of the energy is processed, resulting in greater overall efficiency and increased power processing capability. An identifying module estimates the harmonic currents from the AC line and a control module injects these currents in the network. The second module strongly depends on the first one. Indeed, if the harmonic currents are badly identified, this inevitably involves a lower quality of the compensation. Several methods can be used to estimate the harmonic currents in an electrical network [1, 13].

A typical topology of a shunt active filter is shown in Fig.1 The active filter injects the equal amplitude compensating currents, opposite in phase, at the point of connection to cancel the harmonics currents caused by any nonlinear load.

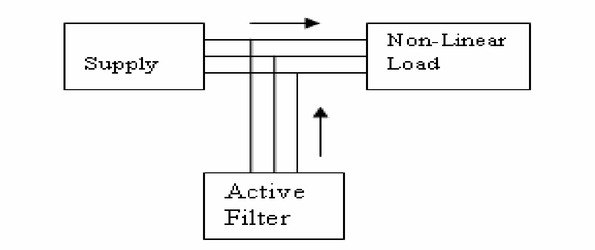

Fig. 1: Simplified diagram of a shunt active filter

III. LINEAR ADAPTIVE NEURAL NETWORK (ADALINE)

Neural networks are composed of simple elements operating in parallel. These elements are inspired by biological nervous systems. As in nature, the network function is determined largely by the connections between elements. A neural network can be trained to perform a particular function by adjusting the values of the connections (weights) between elements.

The ADALINE networks are similar to the perceptron, but their transfer function is linear rather than hard-limiting. This allows their outputs to take on any value, whereas the perceptron output is limited to either 0 or 1. Both the ADALINE and the perceptron can only solve linearly separable problems. However, here the Least Mean Square (LMS) learning rule is used, which is much more powerful than the perceptron learning rule. The LMS or Widrow-Hoff learning rule minimizes the mean square error and, thus, moves the decision boundaries as far as it can from the training patterns. [11, 13, 16]

Consider a single ADALINE with two inputs as shown in fig2. The weight matrix W in this case has only one row. The input to the ADALINE is the vector $X = [X_0 X_1 X_2 ....X_n]^T$ where X_0 is the bias term and is set to 1. The ADALINE has a weight vector $W = [W_0 W_1 W_2 .....W_n]^T$ and its output, can be, simply written as

$$y = W^T X = W_0 + W_1 X_1 + ...W_n X_n \qquad (1)$$

The weight adjustment, or adaptation, is performed during the training process of the ADALINE using a nonlinear adaptation algorithm.

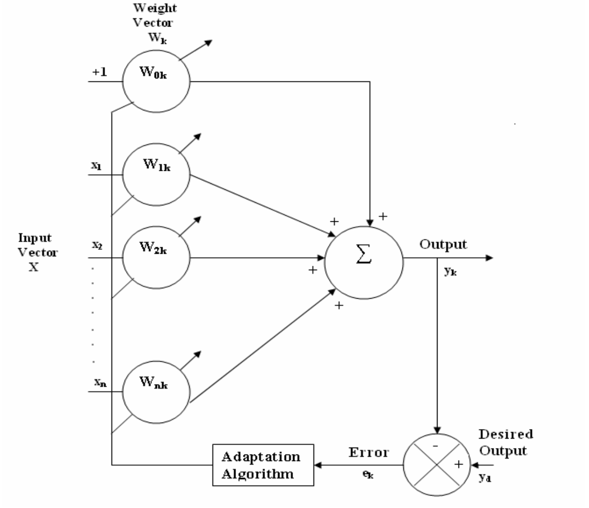

Fig. 2: ADALINE Network

The weight vector is updated using Widrow-Hoff delta rule [12]:

$$W(k+1) = W(k) + \alpha \left[\frac{e(k) * X(k)}{X^T(k) X(k)} \right] \qquad (2)$$

where k = time index of iteration,

$W(k)$ = weight vector at time k,

$X(k)$ = input vector at time k,

$e(k) = y_d(k) - y(k)$ =error at time k,

and α = learning parameter.

The ADALINE is used to estimate the time varying magnitudes of selected harmonic in a distorted waveform [13].Consider a distorted signal f (t) with the Fourier series expansion as

$$f(t) = \sum_{n=1}^{N} A_n \sin(n\omega t + \phi_n) \qquad (3)$$

where An and φn, are the amplitude and the phase angle of the harmonic, respectively, N is the total number of harmonics. The discrete-time representation of f(t) will be

$$f(k) = \sum_{n=1}^{N} \frac{A_n \cos\phi_n * \sin(2\pi nk)}{N_s} + \sum_{n=1}^{N} \frac{A_n \sin\phi_n * \cos(2\pi nk)}{N_s} \qquad (4)$$

where N_s = sampling rate = $\frac{F_s}{F_o}$, F_s = sampling Frequency, and F_o = nominal system frequency.

Fig 3.shows the proposed current adaline network. The input to the ADALINE input vector is chosen to be:

$$x(k) = \left[\frac{\sin(n\pi k)}{N_s} * \frac{\cos(n\pi k)}{N_s} \right]^T \qquad (5)$$

where n is the selected harmonic order, t (k) is the time and its desired output Yd (k) is set to be equal to the actual signal, f (k). The weight vector is set to be

$$Wo = [A_1 \cos\phi_1 A_1 \sin\phi_1 ....A_n \cos\phi_n A_n \sin\phi_n] \qquad (6)$$

The tap weight vector of the adaptive filter is denoted by $e(k) = y_d(k) - y(k)$ and perfect tracking is attained when the tracking error e (k) approaches zero. This optimum condition is realized when the estimation variance and the lag variance contribute equally to the mean square deviation. Therefore,

$$y(k) = y_d(k) = f(k) = W_o^T * x(k) \qquad (7)$$

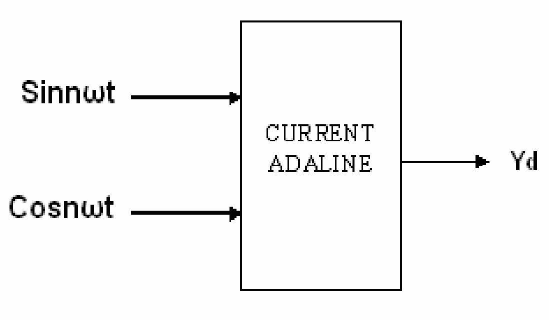

Fig. 3: Proposed Current ADALINE Network

IV. Operation Of The Proposed Scheme

The block diagram of the proposed power line conditioner using active power filter is shown in Fig.4. The proposed Modular Active power filter connected to the electric Distribution system. The line current signal is obtained and fed to an ADALINE which extracts the fundamental components of the line current signal. In the controller block, fundamental component is compared with distorted line current to generate modulating signal. This modulating signal is used to generate Pulse-Width Modulated (PWM) switching pattern for the switches of the active line conditioner module.[12][17] The output current of the active filter is injected into the power line. The injected current, equal-but opposite to the harmonic components to be eliminated. Harmonics are suppressed by connecting the active filter modules to the electric grid. The higher-order harmonics are taken care of by a passive low-pass filter[11]. Fig.5.shows the simulated block diagram of proposed ANN based active filter connected to the electric distribution system. Fig.5 consists of a single phase fully controlled converter feeding RL load, Active filter and its ANN based control circuit. Fig.6 shows the details of control block using ANN. In the control block an improved scheme is proposed in which only the actual load current is given to adaptive neural network and the reference current is obtained. The load voltage is given to a DC regulator with a simple PI controller which gives the actual filter current and which is compared with reference current the gating pulses to IGBTs are provided through a hysteresis band comparator.

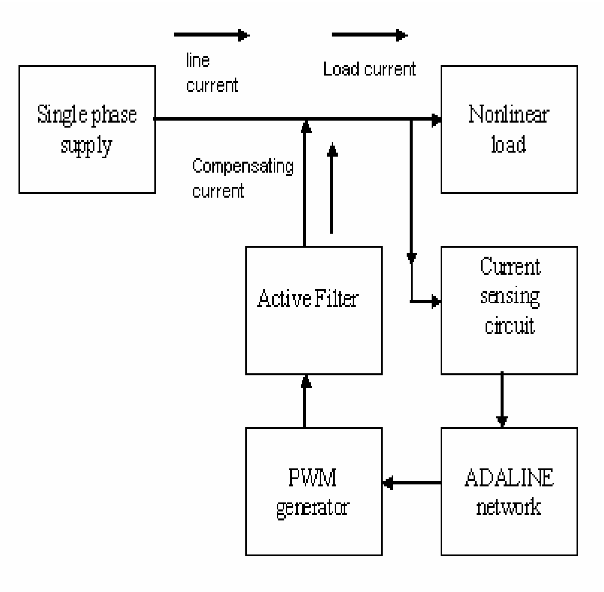

Fig. 4: Block Diagram of the Proposed Scheme

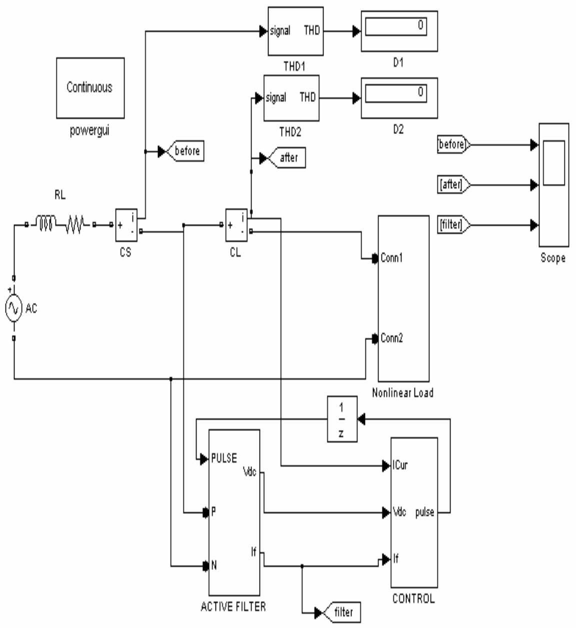

Fig. 5: Simulated circuit diagram of proposed ANN based active filter connected to non-linear load.

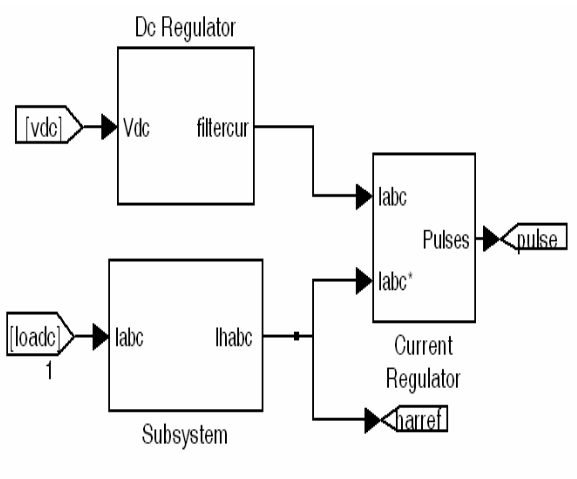

Fig. 6: Control block using ANN

V. SIMULATION RESULTS

The effectiveness of the proposed model is verified with a single phase fully controlled converter with the following parameters. Supply voltage = 220V, frequency=50Hz, load Resistance(R) = 153 Ω and load inductance(L) =0.328 H. The converter is tested with different firing angles. First the converter is operated with a firing angle of 18°. Fig.7 shows the waveforms of the supply current, load current and filter current after the application of the proposed active power filter filter. Fig.8. and Fig.9 represent the harmonic spectrum of the supply current before and after the application of the proposed shunt active power filter respectively. The supply current waveform is improved and its THD is reduced to 2.14% from 16.32%.

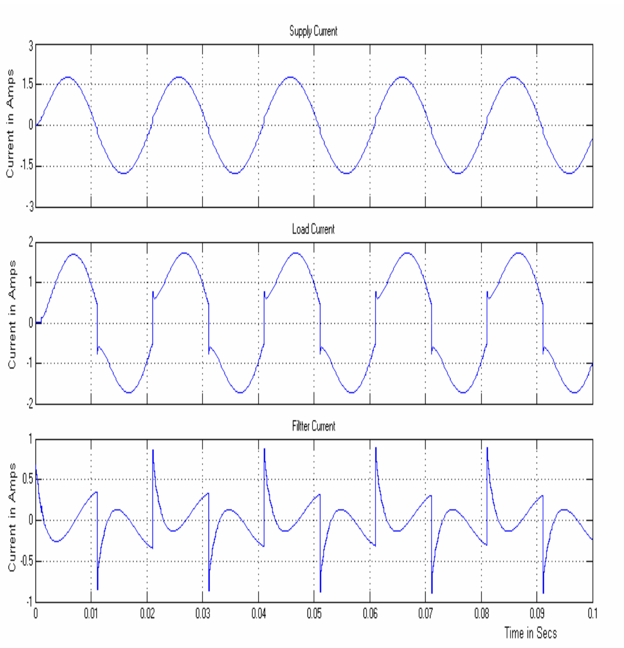

Fig. 7: Supply current, Load current and filter current waveforms of the converter (with filter for a firing angle of 18°)

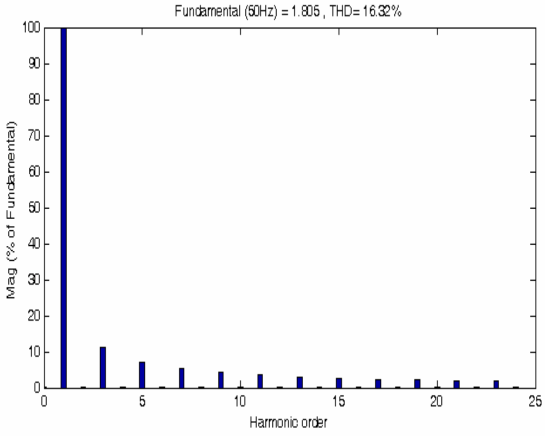

Fig. 8: Harmonic spectrum of the supply (Load) current (without filter for the firing angle of 18°)

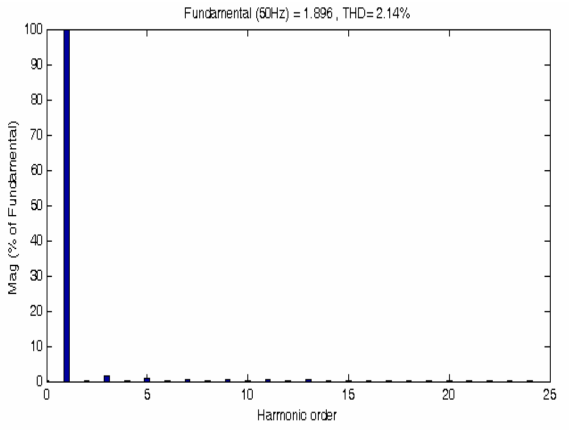

Fig. 9: Harmonic spectrum of the supply current (with filter for the firing angle of 18°)

In the second case the firing angle of the converter is varied to 36°. Fig.10 shows the waveforms of the supply current, load current and filter current after the application of the proposed active power filter. Fig.11. and Fig.12 represent the harmonic spectrum of the supply current before and after the application of the proposed shunt active power filter respectively. The supply current waveform is improved and its THD is reduced to 2.43% from 22.43%.

Finally the firing angle of the converter is varied to 54°. Fig.13 shows the waveforms of the supply current, load current and filter current after the application of the proposed active power filter. Fig.14. and Fig.15 represent the harmonic spectrum of the supply current before and after the application of the proposed shunt active power filter respectively. The supply current waveform is improved and its THD is reduced to 3.49% from 25.11%.

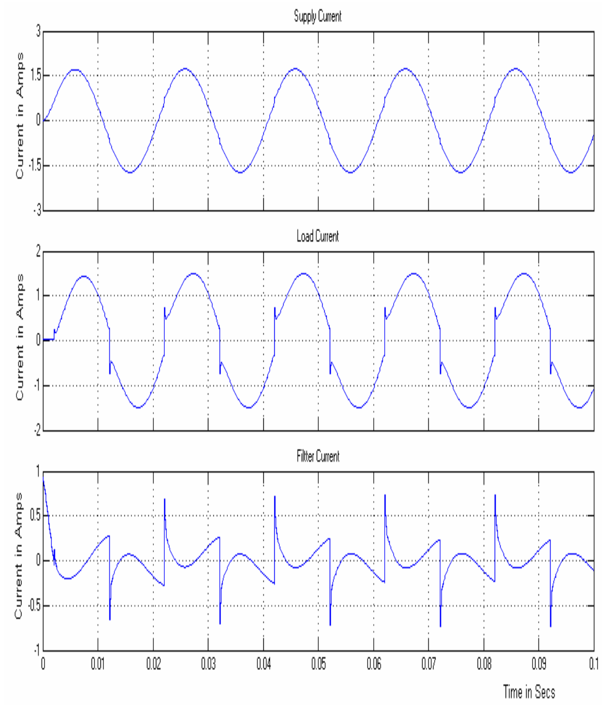

Fig. 10: Supply current, Load current and filter current waveforms of the converter (with filter for a firing angle of 36°)

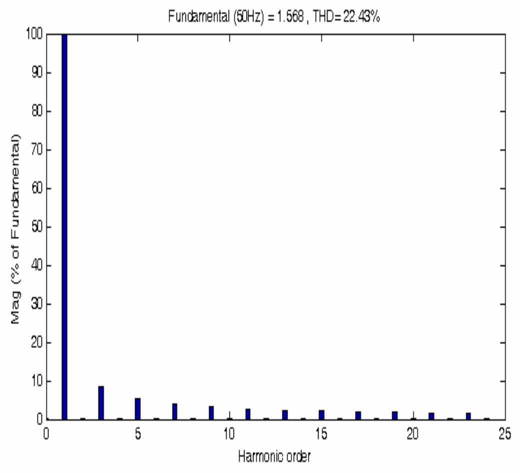

Fig. 11: Harmonic spectrum of the supply (Load) current (without filter for the firing angle of 36°)

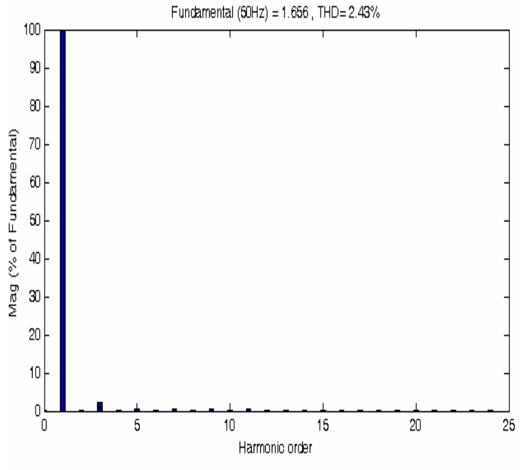

Fig. 12: Harmonic spectrum of the supply current (with filter for the firing angle of 36°)

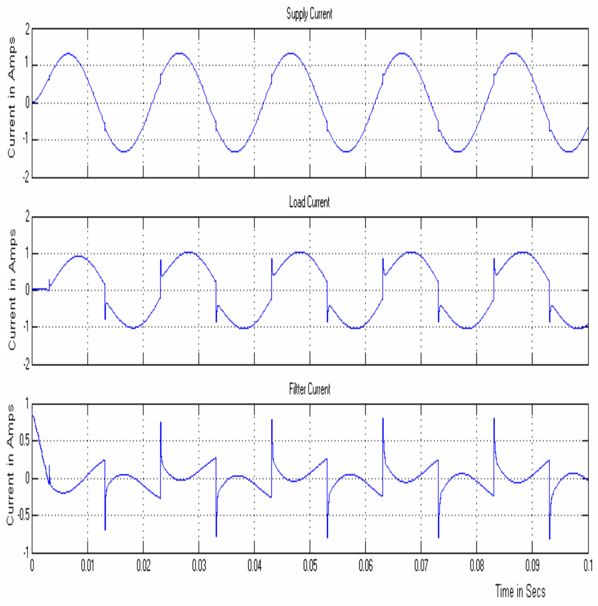

Fig. 13: Supply current, Load current and filter current waveforms of the converter (with filter for a firing angle of 54°)

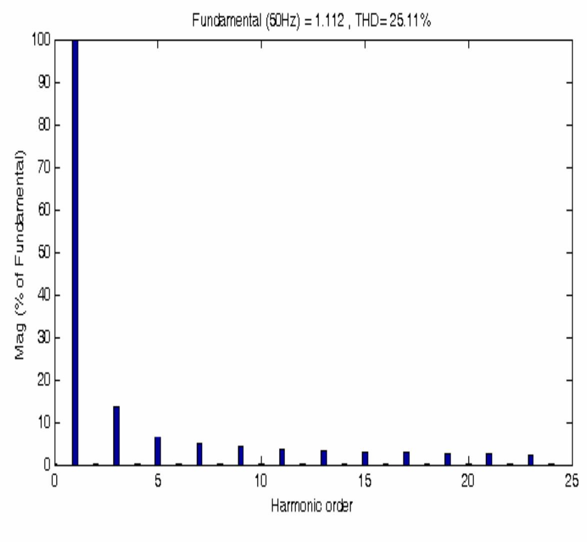

Fig. 14: Harmonic spectrum of the supply (Load) current (without filter for the firing angle of 54°)

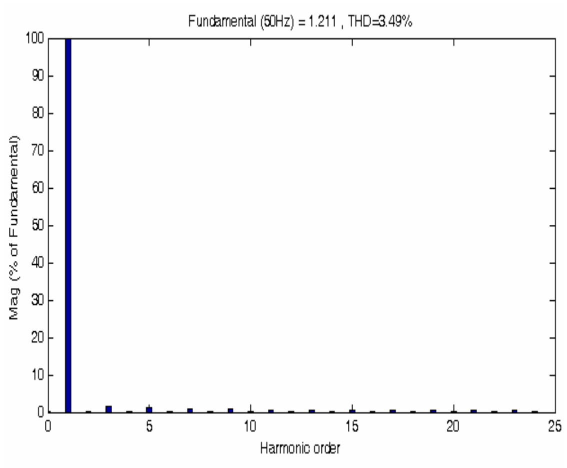

Fig. 15: Harmonic spectrum of the supply current (with filter for the firing angle of 54°)

The proposed shunt active power filter was also tested with different loads i.e by connecting a single phase half controlled converter parallel to the single phase fully controlled converter. The fully controlled converter is operated with the same load conditions with a firing angle of 18°. The half controlled converter is operated with a firing angle of 36° to supply a RL load (R=180Ω and L=1H). Fig.16 shows the waveforms of the total supply current, load current of fully controlled converter ,load current of half controlled converter, total load current and filter current after the application of the proposed active power filter. Fig.17. and Fig.18 represent the harmonic spectrum of the load (supply) current of the half controlled and fully controlled converter, before application of the proposed shunt active power filter respectively. The THD value for the supply current of half controlled converter is 23.55% and for that of fully controlled converter is about 16.53%. Fig.19. and Fig.20 represent the harmonic spectrum of the total supply current before and after the application of the proposed shunt active power filter respectively. So the supply current waveform is improved and its THD is reduced to 3.70% from 16.30%.

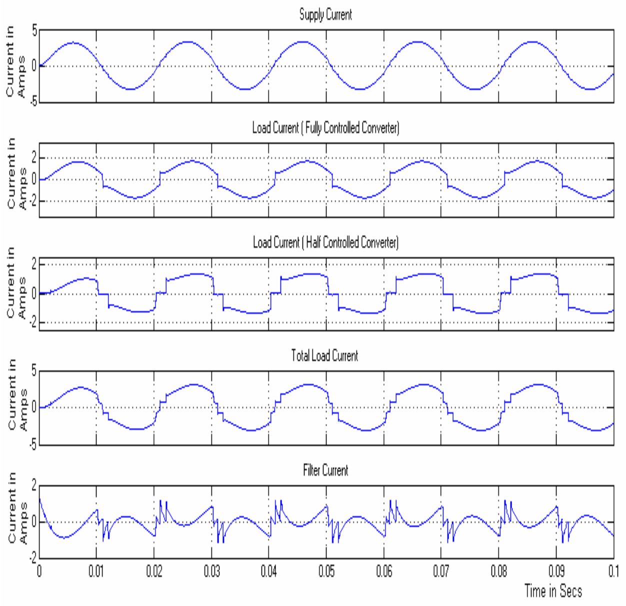

Fig. 16: Supply current, Load current and filter current waveforms of the parallel combination of half controlled and fully controlled converter

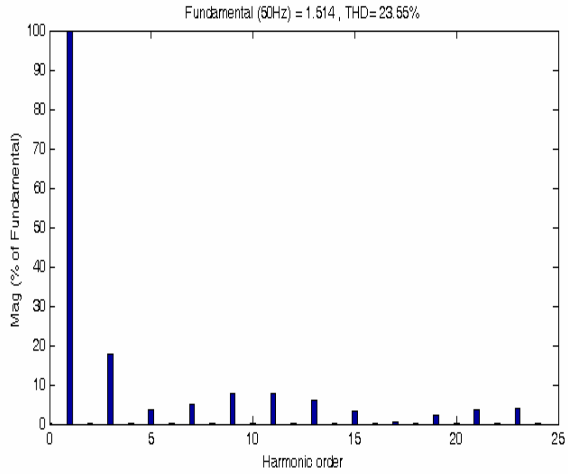

Fig. 17: Harmonic spectrum of the supply (Load) current of half controlled converter (without filter for the firing angle of 36°)

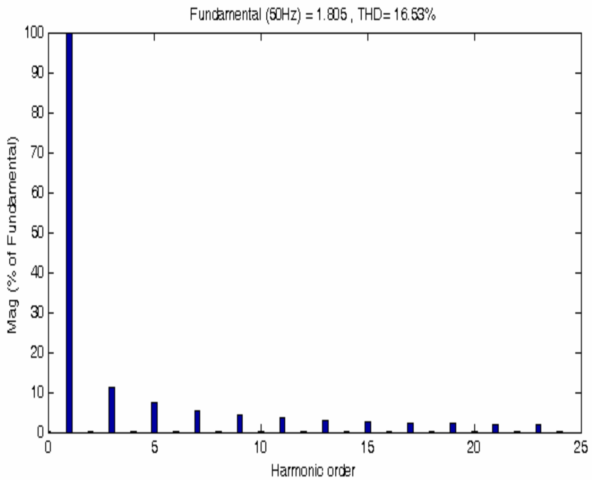

Fig. 18: Harmonic spectrum of the supply (Load) current of fully controlled converter (without filter for the firing angle of 18°)

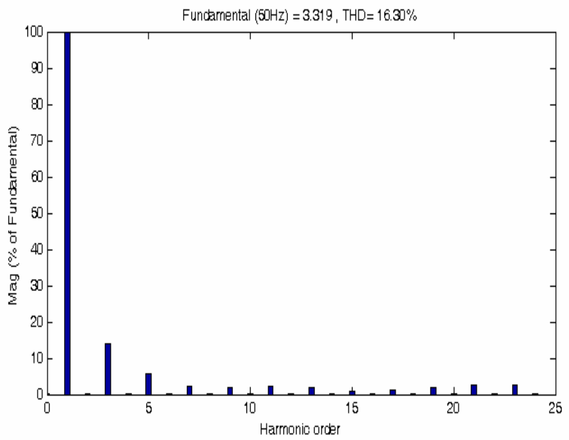

Fig.19:Harmonic spectrum of the total load current (without filter)

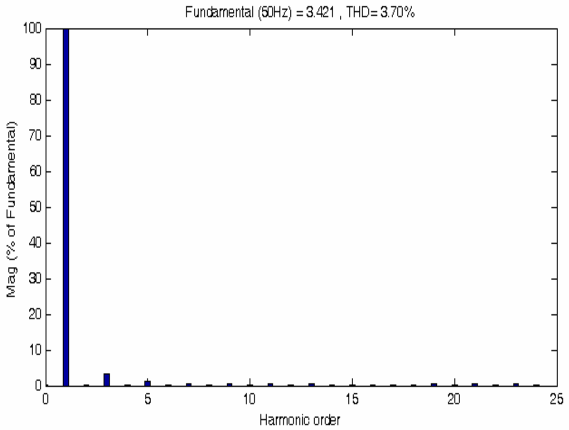

Fig.20:Harmonic spectrum of the total supply current (with filter)

VI. Comparison Between ANN And FFT (Before And After Harmonic Reduction)

The most common frequency-domain harmonic analysis techniques are Fast Fourier transform (FFT) and Artificial Neural Network (ANN). In FFT method, the harmonic components are computed by implementing Fast Fourier Transform on digitized samples of a measured waveform in a time window. When the signal is distorted by noise and/or the decaying nature of the DC component, the harmonic extraction by FFT will lead to incorrect results. ADALINE has a better performance in terms of convergence speed and noise rejection compared with FFT for the dynamic systems with random noise. One of the common problems with FFT is the spectral leakage effect resulting from the deviation in fundamental frequency. A fundamental frequency offset of 0.4Hz produces an error of 10% in the amplitude of the 5th harmonic. To overcome this problem, a variety of numerical algorithms have been developed for frequency measurement, such as the zero crossing technique. This technique is simple and reliable but its performance has a cost ,i.e long measurement times (generally more than 3cycles of the fundamental) and this algorithm can cause computational error owing to rounding of errors.[18]. FFT may use zero crossing as an external algorithm to measure the fundamental frequency. Hence the performance of ANN is improved over FFT in both speed and accuracy. Table 1 describes the harmonic content of the individual harmonics up to 23rd harmonic for the firing angle of 36°. The THD supply current waveform is reduced to 3.84% from 22.43% after compensation in the FFT method, where as in the proposed neural network approach it further reduced to 2.43%. The same kind of table may be prepared for other firing angles also. From this, it may be concluded that ADALINE based Active power Filter gives better result than FFT and also it can be observed that the harmonic content is greatly reduced by the control scheme through the same.

Table 1 : Comparison of harmonic analysis by ANN network (For firing angle α =36°)

Sl.No.	Harmonic Order	Before Compensation	After Compensation	
			Using FFT Method (%)	Using Neural Network (%)
1.	1	100.00	100.00	100.00
2.	3	18.36	3.12	1.93
3.	5	9.40	1.12	0.84
4.	7	5.94	0.90	0.71
5.	9	4.27	0.77	0.53
6.	11	2.42	0.38	0.46
7.	13	2.12	0.67	0.38
8.	15	2.02	0.76	0.32
9.	17	1.84	0.44	0.28
10.	19	1.72	0.47	0.23
11.	21	1.51	0.68	0.21
12.	23	1.31	0.53	0.19
THD		**22.43**	**3.84**	**2.43**

VII. Conclusion

The proposed neural network based shunt active power filter can compensate a highly distorted line current by creating and injecting appropriate compensation current. In the test cases simulated for different firing angles , the THD of the supply current is improved to less than 5% with the proposed shunt active power filter. In addition to this the simulation was carried out for the additional non linear loads (single phase half controlled converter) and the THD in the supply current is also improved to less than 5%. The performances reached by the proposed method are better than those obtained by more traditional techniques as mentioned in the introduction. It enhances the reliability of active filter. The overall switching losses are minimized due to selected harmonic elimination. Speed and accuracy of ADALINE results in improved performance of the Active Power Filter. Finally the harmonic content analyzed by artificial neural network (ANN) is compared with the Fast Fourier Transform (FFT) and it shows ANN gives accurate result than FFT, because of its speed and accuracy. In future it is planned to implement the hardware model of the Shunt Active Power Filter using DSP based controller.

Acknowledgement

The authors wish to express their sincere thanks to the respectable reviewers for providing valuable suggestions to improve the quality of the paper.

APPENDIX

MATLAB CODE FOR ANN

```
clc;
function Y = bb(loadcurrt)
N=1;newW= rand(2*N);
delw= 0;e=rand(2*N);
error=0.2;alpha=0.005;
num=0;dina=0;out=0;Ts=10e-5;
f=50;phase_degree=90;w=0;
M=0;max=2*pi;Wt=0;
phase_rad=phase_degree*pi/180;
sines= fopen('E:\Tsine.dat','r');
cosines=fscanf(sines,'%g');
fclose(sines);
format long;
cosines=cosines+Ts;
Ts=cosines;
sines= fopen('E:\Tsine.dat','w');
fprintf(sines,'%g',cosines);
fclose(sines);
w=f*Ts*2*pi;
w=w+phase_rad;
M=mod(w,max);
wt=M;
for n=1:N
c(n)=(cos((2*n-1)*wt))/(2*n-1);
s(n)=sin((2*n-1)*wt)/(2*n-1);
x(2*n-1)=c(n);
x(2*n)=s(n);
y(2*n-1)=0.5*((1-exp(-alpha*c(n)))/(1+exp(-
alpha*c(n))))+0.5*c(n);
y(2*n)=0.5*((1-exp(-alpha*s(n)))/(1+exp(-
alpha*s(n))))+0.5*s(n);
end
for n=1:2*N
dina=dina+x(n)*y(n);
end
weight= fopen('E:\tst.dat','r');
W=fscanf(weight,'%f');
fclose(weight);
E= fopen('E:\eror.dat','r');
error=fscanf(E,'%f');
fclose(E);
for n=1:2*N
out=out+x(n)*W(n);
delw=(alpha*error*y(n))/dina;
W(n)=W(n)+delw;
end
error=loadcurrt-out;
E= fopen('E:\eror.dat','w');
fprintf(E,'%f',error);
fclose(E);
weight= fopen('E:\tst.dat','w');
fprintf(weight,'% f',W);
fclose(weight);
Y=error;
```

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