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Adaptive Neuro-fuzzy Inference system based control of three-phase hybrid power filter for harmonic mitigation

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***Abstract*— This paper presents a three-phase hybrid power filter based on artificial intelligence control approach. It consists of C-type passive filter in parallel with a shunt active filter that is controlled by an adaptive Neuro-Fuzzy inference system (ANFIS) controller. The active filter is based on a three-phase voltage inverter with six control switches. The AC side of the filter is connected in parallel with the nonlinear load through an interface reactor, while the DC side connected to a DC-link capacitor. The system will estimate harmonic content in the source current, produced by nonlinear load and generate reference waveform for control voltage source inverter. This paper describes circuit topology, control strategy, C-type high-pass filter, compensation current reference estimation and generation of gating signals. ANFIS controlled three-phase hybrid power filter is modeled under MATLAB/Simulink environment. The results show this kind of filter has a better harmonic compensation in utility current of three-phase three wire system.**

***Keywords*— Adaptive neuro-fuzzy inference system (ANFIS) Controller, Active Power Filter (APF), Harmonics, Hybrid Power Filter (HPF), Passive filter, Power quality.**

I. INTRODUCTION

Introduction of semiconductor devices and switched converters has resulted in faster and efficient control of power; however harmonic distortion has become one of the main power quality disturbances frequently encountered by the utilities. The harmonics in power supply are caused by nonlinear characteristics of the loads commonly found in industries and our homes. The presence of harmonics leads to diverse effects such as solid state devices malfunction, electromagnetic interference, motors and transformer heating and false triggering of stand-by generators [1]. Therefore, it is very important to mitigate dominant harmonics to the specifications outline in IEEE 519-1992 harmonic standard [2]. Filters have emerged as the means of power quality improvement in nonlinear load systems. Passive filters have been used for long. However, they are bulky in size under low order harmonic filtering, characterized with fixed harmonic compensation and may cause resonance with other elements of the system.

Recent advancement in semiconductor devices has greatly improved development of active power filters (APF) for harmonic suppression with several topologies proposed [3,4]. The shunt APF based on voltage-source inverter topology has proven to be the best solution so far for harmonic current mitigation as they do not carry load current. Despite various advantages of APF, the complexity and cost have always been major drawbacks. Combination passive filters with the APF result in hybrid configuration that brings down the cost of active filters drastically. However, effective compensation of APF depend on accurately capture of system variables. Artificial intelligence has shown good results in approximation of nonlinear signals [5]. This paper presents the use of ANFIS in control of the new hybrid power filter to enhance generation of gating signals for the voltage-source inverter.

A. Shunt APF Control Algorithms

The algorithms used to generate reference compensation signal for active power filter determines its effectiveness. The control scheme depends on compensation signals sensed from the system. The control algorithm may be based on frequency domain or time domain techniques. In frequency domain the compensation signal is computed using Fourier analysis of the input voltage/currents signals, while in time domain, the instantaneous values of the compensation voltages/currents are derived from the sensed values of input signals. There are many methods for harmonic extraction that have been implemented such as synchronous reference frame (dq) [6], discrete Fourier transform, fast Fourier transform [7] and instantaneous power (pq) theory [8].

The pq theory is associated with a limitation of determining harmonic components under load conditions only [3]. Fourier transform is the most used method for specific harmonic component compensation [9]. However it requires one more cycle of the voltage waveform data and corresponding time such that delayed harmonic cancellation can occur, on the other hand the dq technique is substantially slow in responding to harmonic distortion and gives inaccurate result though it is within the acceptable range.

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B. *Hybrid Power Filters*

Active power filters are ideal solution for mitigating harmonics, eliminating all disadvantages of the conventional passive filters such as fixed compensators with problems due to resonance and huge size. However the major disadvantage with active filters is the high cost. Hybrid filter which are different combinations of active and passive filters is a solution to the problem. In this paper, shunt active filter is used to compensate for low order harmonics produced by a three-phase nonlinear load, minimizing overall system pollution, and also providing reactive power requirement of the load. The passive filter when connected in shunt with harmonic producing load and the active filter is capable of reducing the burden on active filter by supplying some portion of the reactive power and also by eliminating high order harmonic currents, thereby reducing its rating and cost [6,10].

There are three major types of hybrid filter configurations, the first one consist of an active filter in series with passive filter, second; a hybrid parallel active filter in which both the active filter and passive filter are in parallel with the non-linear load and third; a hybrid series filter which is a combination of a series active filter and parallel passive filters [10]. However the first configuration seems to be the best because of low current rating, easier protection, and no resonance possibility with source and load. This work has taken the approach of the first configuration, with control scheme of ANFIS to enhance its tracking and estimation of the harmonics, boosting the overall system performance [11].

II. New Topology Of Hybrid Power Filter

The new hybrid power filter system consist of the following major parts; mains supply, nonlinear load, data acquisition and controller, APF with interface reactor and C-type high-pass passive filter network as illustrated in fig. 1. Harmonic current generated by a nonlinear load is detected and used to generate gating pulse with the use of ANFIS controller. The output of the gating signals controller controls the voltage-source inverter that provides part of reactive power required by nonlinear load. The passive filter is placed in parallel with the APF which makes the inverter to be smaller than when it was used alone, because it also provide reactive power and attenuate high frequencies that might be generated by the filter itself.

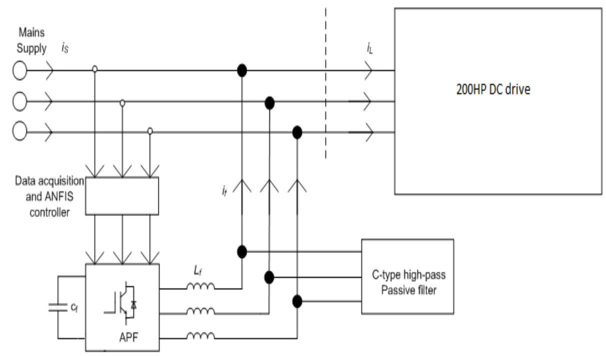


Figure 1: principle topology of analysed hybrid power filter

A. *Topology Operation Description*

Considering each phase in a three-phase system, where mains voltage is v_s is a purely sinusoidal:

$$v_s = V_p sin\omega t \qquad (1)$$

With V_p representing peak voltage and ω is the angular frequency

The periodic non-sinusoidal currents of nonlinear loads can be represented by Fourier progression as follows:

$$i_l(t) = I_1 \sin(\omega t + \varphi_1) + \sum_{n=3}^{\infty} I_n \sin(n\omega t + \varphi_n) \qquad (2)$$

Where t is the time in seconds, I_1 is the fundamental component; φ_n is the respective angle and I_n is the harmonic component.

The non-linear current i_l can be written as:

$$i_l = i_a + i_d \qquad (3)$$

Where i_a is the active component and i_d is the reactive component and harmonics

The converter control method will be such that it validates the following expression:

$$i_f = -i_d \qquad (4)$$

Where i_f is the current form the filter

Making the assumption that it is easy to verify that the mains current will result in its active component then,

$$i_s = i_l + i_f = i_a + i_d + (-i_d) = i_a \qquad (5)$$

$$i_s = i_p \sin(\omega t) \qquad (6)$$

Where i_p is the amplitude of the source current

This means that the non-linear load current plus the hybrid filter actuates as a pure resistive linear load current.

In a three phase six switches system the active harmonics is as follows:

$$n = 6k \pm 1. for\ k = 1, 2, 3 \qquad (7)$$

Where n is the active harmonic component and k is the sequence.

The target of the HPF is to identify these harmonic currents and generate inverse equivalent that will cancel out maintaining characteristics of linear load for a nonlinear load connected to the power supply system.

B. Active Power Filter Control Strategy

Pure active power filter is considered the best solution for current harmonics mitigation. The topology has been well researched and it is already used in practical applications. It consists of a power inverter connected to the power system in shunt connection. It may be connected in front of either single non-linear loads or at common bus-bar and it has the task to detect and cancel out the harmonic content of the load current. A common control method for hybrid power filters is the feedback current control. The source current (i_S) is detected and the inverter is controlled as a voltage source. Fig. 2 shows the system that has been employed to estimate current sine wave. It consists of a band pass filter with the centre-frequency of the fundamental current.

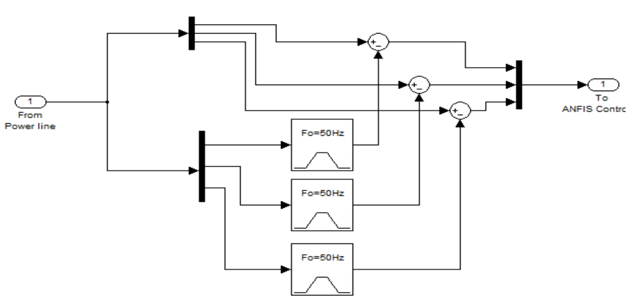


Figure 2: Compensation reference current estimator

C. ANFIS Controller Design

The basic principle of the ANFIS method is the use of the network neuron to optimize the membership's functions of the fuzzy controller in other words; an ANFIS is one optimized fuzzy inference system (FIS). In the Neuro-Fuzzy controller, the simplicity of a Fuzzy controller is combined with the intelligent and adaptive nature of the Neuron Network optimization. Fig. 3 illustrate ANFIS controller with two input; error (e(k)) and change in error (Δe(k)) is modeled as follows;

$$e(k) = i_{ref} - i_f$$

$$\Delta e(k) = e(k) - e(k-1) \qquad (8)$$

Where the i_{ref} is the reference current, i_f is the actual filter output, *e(k)* is the error and Δ*e(k)* is the change in error.

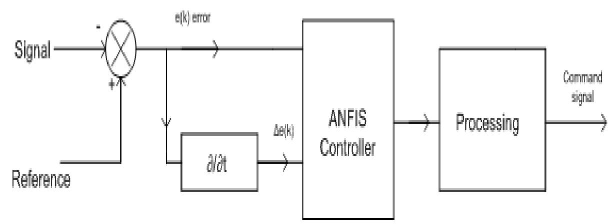
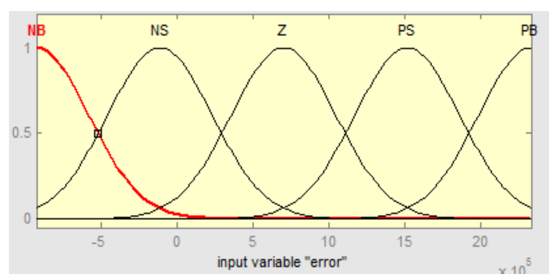
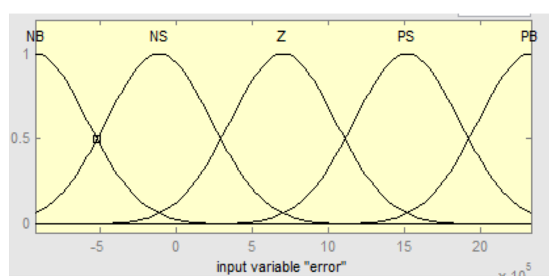


Figure 3: Illustration of ANFIS controller

The training data has been obtained using a PI controller. The inputs are converted into linguistic variables. In this case, five fuzzy membership functions; negative big (NB), negative small (NS), zero (Z), positive small (PS) and positive big (PB) has been used. The membership functions used for the inputs before and after training are shown in fig. 4 and 5 respectively.



(a)



(b)

Figure 4: Error (e) membership functions; (a) before training (b) after training

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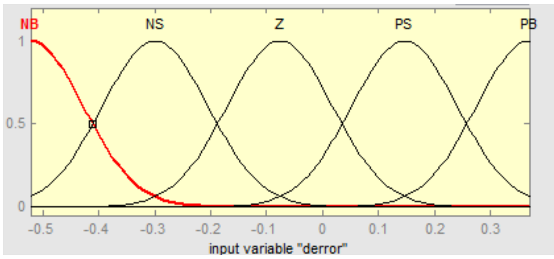

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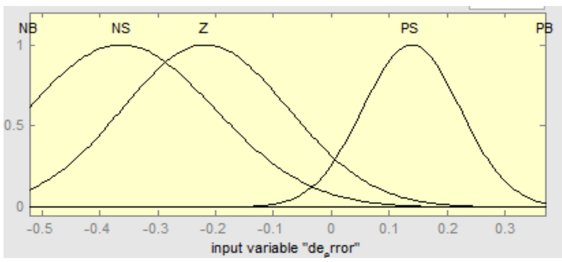

(b)

Figure 5: Change in error (Δe) membership functions; (a) before training (b) after traninig

D. Gating Signal Generation

In order to generate the compensation current that follows the current reference signal, the PMW strategy is adopted. The PMW can be carried out using numerous techniques. However, carrier-based PMW has been employed in this work. It compares a high frequency periodic triangular waveform (the carrier signal) with a slow-varying waveform from the ANFIS controller (modulating signal). The carrier signal has a periodic waveform with period T_s and swings between -1 and 1. The signal is the passed through a relay or hysteresis comparator in order to eliminate noise which may be present. The output of the relay drives switches S_i and through inverter for S_i' in each arm of the VSI as illustrated in figure 6. Where, the switching action is defined by eq. 9.

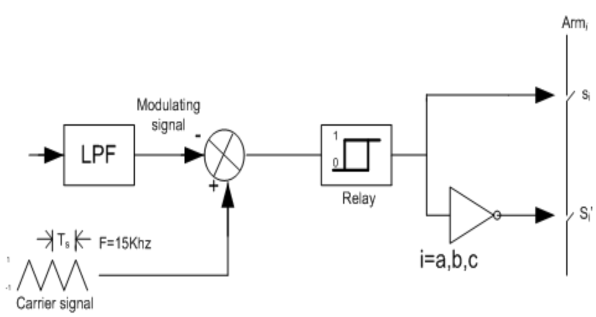

Figure 6: PWM comparator synoptic diagram

$$s(t) = \begin{cases} 1 & \text{if the switch is commanded to conduct} \\ 0 & \text{if the switch is turned off} \end{cases} \qquad (9)$$

III. Design Procedures For C-Type High Pass Filter

The C-type HPF topology is employed in the proposed hybrid power filter as mention earlier. It consists of a capacitors *C*, C_a, an inductor *L* and an inductor bypass resistor R as shown in fig.7. This section describes the design procedure for C-type high pass filter using the passive elements. These elements are determined based on the filter type and the following parameters;

(i) Reactive power at nominal voltage
(ii) Cut-off frequency
(iii) Quality factor

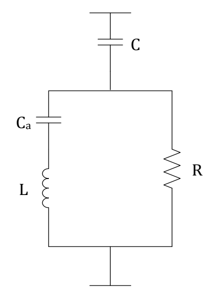

Figure 7: C-type high-pass filter

Using the following formulae, the damped C-type passive filter is set to attenuate 13th order harmonic and above.

$$X_C = \frac{3V_{CN}^2}{Q_C}, \quad C = \frac{1}{2\pi f_1 X_c}, \quad X_L = \frac{X_{C(a)}}{h_n^2},$$

$$X_n = \sqrt{X_{C(a)} X_L} \qquad (10)$$

Where f_1 = the fundamental frequency.
V_{CN} = System phase voltage
Q_C = Reactive power
X_c = Capacitive reactance at tuned frequency
h_n= Harmonic order
$X_{C(a)}$ = Capacitive reactance of the auxiliary capacitor

The other parameters of the C-type high pass filter has been determined using current transfer function since the filter will inject current through source current, this can be determine as follows;

$$H_{hp}(s) = \frac{A}{s(\frac{s}{\omega_p}+1)} \cdot \left[\left(\frac{s}{\omega_\circ}\right)^2 + \frac{1}{Q}\left(\frac{s}{\omega_\circ}\right) + 1\right] \qquad (11)$$

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$$A = \frac{1}{C_a}, \quad \omega_\circ = \frac{1}{\sqrt{LC_a}}, \quad \omega_p = \frac{R}{L},$$

$$Q = R\sqrt{\frac{C_a}{L}}$$

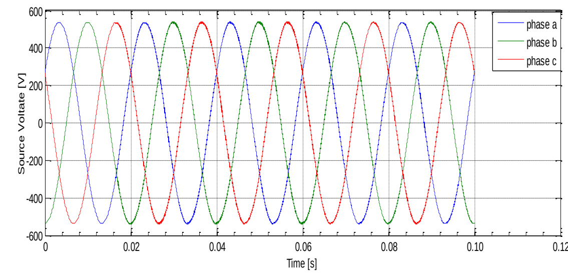
Where A = Gain coefficient,
ω_o = Series resonant frequency
ω_p = Pole frequency
Q = Quality factor.

IV. Simulation Results And Discussions

The performance of new hybrid power filter was examined through simulations. The system given in fig.1 was modelled under MATLAB/simulink environment. The simulation parameters are given in table 1. The nonlinear load considered is 200HP four-quadrant three-phase rectifier DC drive.

Table1
Simulation parameters

Source	Voltage (line to line)= 415V rms Frequency = 50Hz
Source impedance	Resistance = 1Ω Inductance = 0.1mH
Power converter	6 IGBTs
Dc-link capacitor	1000µF
Interface reactor	10mH
C-type high pass-filter	Main capacitor (C) = 470µF Auxilary capacitor (Ca) = 10µF Resistor = 20Ω Inductor = 12.5mH



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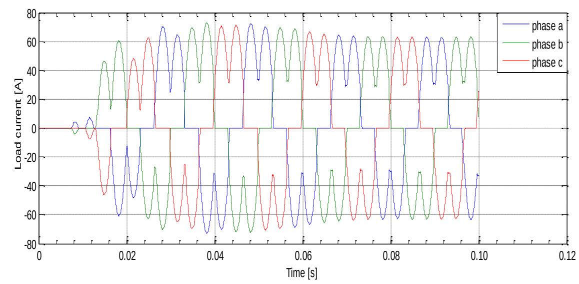

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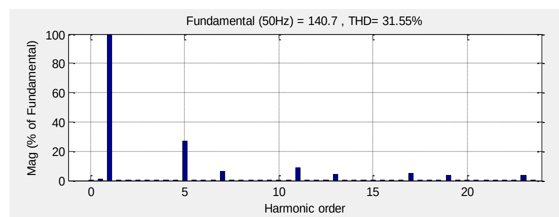

(c)

Figure 8: System results without any form of compensation. a) Source voltage,b) Line current and c) line current THD

In steady state condition the simulation time is taken as t=0 to t= 0.1 seconds with constant torque reference. The three-phase source voltage is shown in fig. 8(a). The load current is shown in fig. 8(b) which is highly nonlinear in nature and %THD of the mains current are shown in fig.8(c), it is shown clearly that the load current has THD of 31.37% . This is the steady-state performance of the system without any form of compensation.

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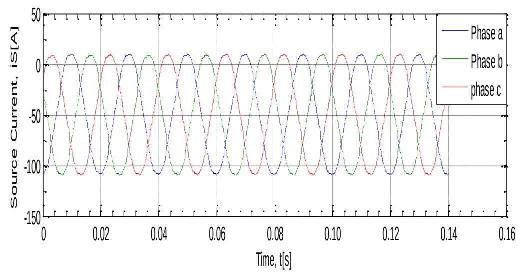
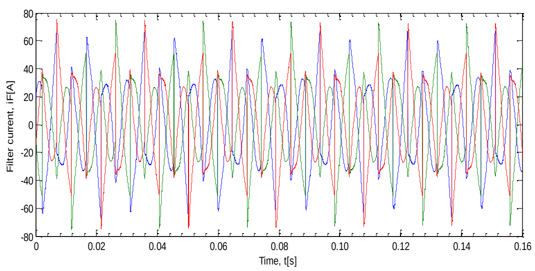


(a)



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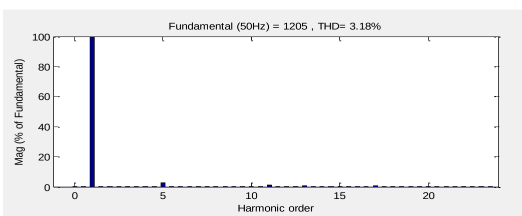
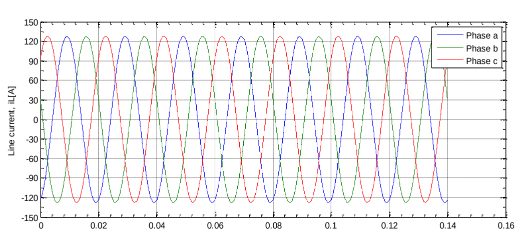


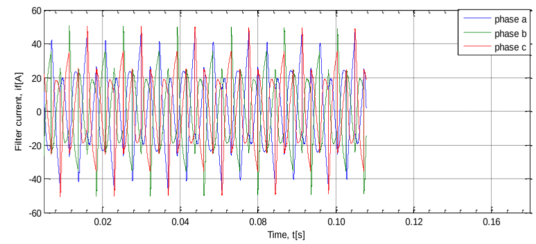
(c)

Figure 9: Results with Active power filter; a) Source current, b) Filter current and c) Source current THD

For the system with shunt active filter controlled by the ANFIS controller with the same load characteristics, corresponding waveforms are shown in fig.8. The load current waveform is shown in fig. 9(a) and filter current in fig. 9(b). The source current is almost a sinusoidal and has THD of 3.18 % as shown in fig.9(c). It is within the IEEE requirement. However, the filter current is too high as this will impose challenges in form of cost and size in implementation.



(a)



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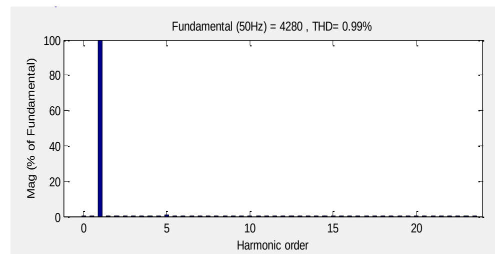

(c)

Figure 10: Results with hybrid power filter; a) Source current, b) Filter current, and c) THD of source current

The proposed approach of hybrid filter with intelligent controller in form of ANFIS and C-type high-pass passive filter under steady-state simulation gave good results as shown in fig. 10. Fig. 10(a) is the source current after compensation. It is clear from the figure that, the waveform is sinusoidal as compared to results without C-type high-pass passive filter. Fig. 10(b) is the filter current which shows a reduction this implies that the current handling by the voltage source inverter is reduced. The % THD has decrease drastically from 31.55% to less that 1% after compensation as shown in fig.10(c).

V. CONCLUSIONS

In this paper the effectiveness of the new hybrid filter topology and controlled strategy based on ANFIS control technique has been verified using MATLAB/Simulink environment. A three-phase balanced load of a DC drive is simulated with active filer and later with hybrid power filter. From the results, it clearly indicates that, the current compensation is much better using hybrid power filter compared to Active power filter. The steady state performances of these two filters have been compared. The THD of the source current after compensation is 1 % which is less than 5 %, the harmonic limit imposed by the IEEE-519 & IEC-6000-3 standard.

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VI. Future Work

The training of adaptive Neuro- Fuzzy controller and estimation of fundamental wave was done using off-line training method in this work. The next immediate step is to investigate the possibility of applying on-line training method to track time varying harmonics in power systems. However, there are many serious aspects that need to be investigated before on-line method can be put into use. Stability of the closed loop system is a major concern, since the controller parameters are updated at each sampling interval, without having efficient criteria to limit the parameter update, on-line learning method may lead the system to unstable region.

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