Research Paper Engineering

Fuzzy Logic Controller Based THD Reduction in Non-Linear Load Using Shunt Active Filter

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ABSTRACT

This paper deals with an indirect current controlled shunt active power filter (SAPF) for improving power quality by reactive power compensation and harmonic filtering. The presence of harmonics and reactive power in the power source because it will cause additional power losses and malfunctions. The proposed APF is based on a voltage source inverter (VSI). The VSI is controlled by two loops, the voltage control loop and the current control loop. The voltage control loop regulates the DC link capacitor voltage and the current control loop uses hysteresis band control to shape the source current such that it is in-phase with and of the same shape as the input voltage. The major advantage of the proposed APF is that the reference current for power quality improvement is generated from the DC link capacitor voltage. This work proposes a Fuzzy logic controller based 1-phase and 3-phase shunt active filter for THD reduction in Non-linear load. The system with control scheme is going to be analyzed in computer simulation using MATLAB/Simulink.

KEYWORDS Shunt Active filters, VSI, HB current controller, Fuzzy logic controller, THD, LPF

INTRODUCTION

The Harmonic distortion is one of the vital power quality problems in power systems. Theacpowersupplyfeedsdifferent-kindoflinearand non-linearloads. The non linearloads produce harmonics and reactive powerrelatedproblems.This harmonics and reactive powercause poor powerfactorand distortthe supply voltage. Thecurrentharmonicscreate a problemsinpower-systems suchasmalfunctionsinsensitiveequipment, over voltage by causesresonance and harmonic voltage drop acrossthe networkimpedance;thatresultinpoorpower factor.

Increase in such non-linearity causes different undesirable features like low system efficiency and poor power factor. It also causes disturbance to other consumers and interference in nearby communication networks. The effect of such non-linearity may become sizeable over the next few years[1,2].

Modern concept of FACTS devices is an effective solution for power quality problems. One of the FACTS device is static compensator used for reactive power compensation in power transmission system. Active Power Filters compensate load current harmonics by injecting equal but opposite harmonic compensating current [3,4]. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180^0.

Classically, shunt passive filters, consist of tuned LC filters and/or high passive filters are used to suppress the harmonics and power capacitors are employed to improve the power factor. But they have the limitations of fixed compensation, large size and can also exile resonance conditions[8].Active power filters are now seen as a viable alternative over the classical passive filters, to compensate harmonics and reactive power requirement of the non-linear loads. The objective of the active filtering is to solve these problems by combining with a much-reduced rating of the necessary passive components.

Passive filters have the advantages of low cost and losses; however, they have the problems of harmonic resonance with the source and/or the load [5,8]. Such as dependency on the load impedances, parallel/ series resonance, aging of passive components, uncontrollable filter currents and reactive power could be produced. However, APF performance is challenging in high voltage systems due to switch voltage rating and frequency limitations. Reducing the filter side voltage affects system size, cost and allows higher switching frequency operation.

Various topologies of active power filters have been developed so far [4,12]. The shunt active power filter based on current controlled voltage source type PWM converter has been proved to be effective even when the load is highly non-linear [1,4,11]. Most of the active filters developed are based on sensing harmonics [7,10,11] and reactive volt-ampere requirements of the non-linear load [14-18] and require complex control. A new scheme has been proposed in which the required compensating current is determined by sensing load current which is further modified by sensing line currents only [21,22]. An instantaneous reactive volt-ampere compensator and harmonic suppressor system is proposed without the use of voltage sensors but require complex hardware for current reference generator.

The compensating signal is generated by the contribution of reference current generation, current control, and PWM techniques, The delay presents in the reference signals switching frequency is low. Some solutions have been proposed to solve such a problem. Conventional proposed techniques used filter circuit for the current control usinghysteresis control to control the harmonic extraction presents[23] in the source current.

The proposed control techniques is overcome SAPF delay effects for the conventional topologies introduced classical controllers such as fuzzy logical control based active filter to reduce the harmonics and avoids passive elements to determine the delays and compensate the current harmonics for better reactive power compensation. The proposed method is used to produce the desired compensating current under selected loading conditions. This paper presents a single phase and three phase active filter using fuzzy logic based harmonic reduction and compensating the reactive power.

Proposed system configuration

The current controlled shunt active filter is based on voltage source inverter as shown in Fig 1.The topology of the proposed single phase shunt APF is shown in Fig 2. The proposed circuit has two control loops, voltage control loop and current control loop. The voltage control loop regulates the DC link capacitor voltage (V_c). The output of capacitor voltage is given to the low pass filter to remove the ripples present in V_c. The voltage is compared with reference DC voltage and the error signal is fed to the fuzzy controller. The output of the fuzzy controller is amplitude (K) is used to derive the reference current. This derived current is compared with source current to control the reference current using hysteresis current control.

The proposed three phase shunt active power filter is shown in Fig 3.

Principle of SAPF

The switches are operated in such a way that total current drawn from the source is of the same shape as that of the source voltage V_s. By suitable operating condition of the switches a voltage V_{comp} having a fundamental component is generated at the output of the inverter. When $V_{comp1}<V_s$, the inverter draws lagging current and it supplies leading vars to the system. When$V_{comp1} = V_s$, no current flow into or out of the system. The var supplied by the system is given by

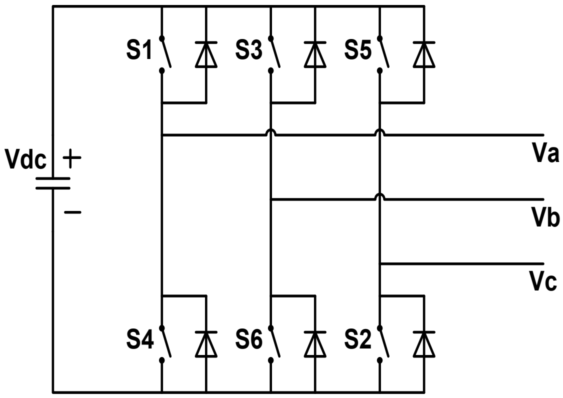


Fig 1. Voltage source inverter

$$Q = \frac{V_s \left| V_{comp1} - V_s \right|}{\sqrt{\omega^2 L^2 + R^2}} \quad (1)$$

$$\frac{di_{comp}}{dt} = \frac{Vs - Ri_{comp} - sVc}{L} \quad (2)$$

$$\frac{dVc}{dt} = \frac{si_{comp}}{c} \quad (3)$$

The APF forces the source current to become same in shape as the source voltage Vs.PWM techniques applied to a voltage source inverter consist of an arbitrary wave form. There are a large number of PWM techniques available to synthesize sinusoidal patterns or any arbitrary waveform. Voltage source inverters are preferred for SAPF to lower initial cost and more efficiency than current source inverter. They can be readily expanded in parallel to increase their switching cost is increased.

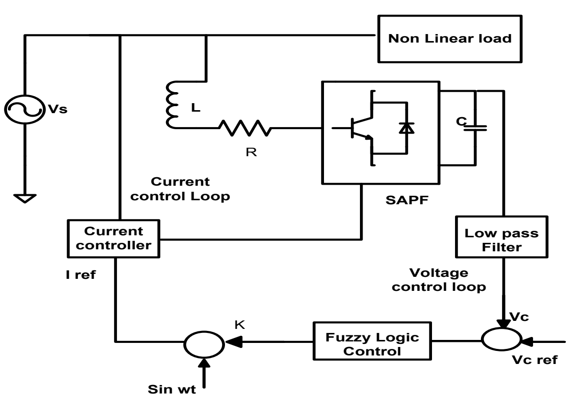


Fig 2. Indirect current control shunt active power filter

$$\frac{di_s}{dt} = \frac{Vs - Ricomp - sVc + L\dfrac{diload}{dt}}{L} \quad (4)$$

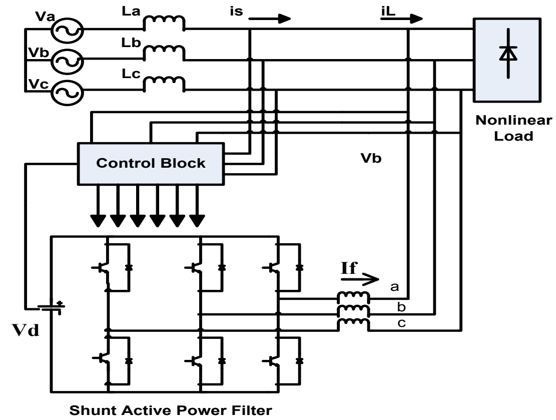


Fig 3. Indirect current control 3-phase shunt APF

The switching function s, controlled Vc is maintained at a voltage higher than Vs. This is done by the voltage control loop. The dynamic stability of the indirect current controlled APF depends on its ability to maintain the DC link capacitor voltage closer than the reference value. The capacitor values decreases by the energy stored in the Dc link capacitor supplies power. The increase in the reference current to increase the capacitor reference value.

Estimation of reference current

Source voltage is given by

$v_s(t) = v_m \sin \omega t$ (5)

If a non-linear load is applied, then the load current will have a fundamental component and harmonic components which can be represented as

$I_L(t) = \Sigma_{n=1} I_n \sin(n\omega t+ \varphi_n)$

$= I_l \sin(n\omega t+ \varphi 1)\Sigma_{n=2} \sin(n\omega t+ \varphi_n)$ (6)

The instantaneous load power can be given as

$P_L(t) = v_s(t) * i_l(t)$(7)

$= V_m I_l \sin^2\omega t * \cos\varphi_1 + V_m I_l \sin\omega t * \cos\omega t * \sin\varphi_1$

$+ V_m \sin\omega t * \varphi_1 \varphi_2 (n\omega t+ \varphi_n)$

$= P_f(t) + P_r(t) + P_h(t)$ (8)

From (6), the real (fundamental) power drawn by the load is

$P_f(t) = V_m I_l \sin^2\omega t * \cos\varphi_1 = v_s(t) * i_s(t)$ (9)

From (8), the source current supplied by the source, after compensation is

$I_s(t) = P_f(t)/v_s(t) = I_1 \cos \varphi_1 \sin\omega t = I_m \sin\omega t$ (10)

Where $I_{sm} = I_1 \cos \varphi_1$

There are also some switching losses in the PWM converter, and hence the utility must supply a small overhead for the capacitor leakage and converter switching losses in addition to the real power of the load. The total peak current supplied by the source is therefore

$I_{sp} = I_{sm} + I_{s1}$(11)

If the active filter provides the total reactive and harmonic power, then i (t) will be in phase with the utility voltage and purely sinusoidal. At this time, the active filter must provide

the following compensation current:
$I_c(t) = i_L(t) - i_s(t)$ (12)

Theinstantaneouscurrentscanbewrittenas
$I_s(t)= I_L(t)–I_c(t)$ (13)

The capacitor voltage is compared with the reference dc voltage and the error signal is processed in controller as shown in Fig 3. and is given by
$e = V_{dc}$ ref $–V_{dc}$(14)

The source voltage (Va, Vb, Vc) is given by
V_{sa} = Vm sin (ωt) (15)
V_{sb} = Vm sin (ωt -120) (16)
V_{sc} = Vm sin (ωt +120) (17)

The references current are generated by multiplying of desired ac current source and (Imax) maximum amplitude of the current source. The reference current must be sinusoidal and in phase with the voltage source are given by
I*sa = Imax/Vm*Vsa = Imax sin (ωt) (18)
I*sb = Imax/Vm*Vsb = Imax sin (ωt -120) (19)
I*sc = Imax/Vm*Vsc = Imax sin (ωt +120) (20)

The difference between the reference current (Is*) and the load current (IL) can generate the three compensating current (Ica, Icb, Icc)
Ica = $I_{La}-I^*_{sa}$ (21)
Icb = $I_{Lb}-I^*_{sb}$ (22)
Icc = $I_{Lc}-I^*_{sc}$ (23)

The reference current has been estimated by regulation the dc capacitor voltage of the filter. The capacitor voltage (Vdc) is compared with a reference value (Vdc ref) and the error is processed in the Fuzzy logic controller. The output of the controller is considering the maximum amplitude of the current (Imax).

DC link capacitor design
The dc link capacitor stores the energy sudden changes in the load such as Dc capacitor supplies to require load demand for the half period of the supply frequency. The energy stored in the capacitor is same as to the energy demand to the load demand.

$$\frac{dis}{d} = \frac{2\pi v_s i_s}{\omega}\left(\frac{1}{V^2c - V^2c\min}\right) \text{(24)}$$

Filter inductor design
The filter inductor is used to injected current is greater than the reference current for the injected current by reference current is expressed as

I_{ref} = k sin ωt(25)

The maximum of the reference current is determined by harmonic component based on its amplitude. The harmonic giving the highest individual is the third harmonic for the single phase and fifth harmonic for three phase nonlinear loads.

controller for SAPF
Hysteresis band current controller
The current control loop is controlled by the hysteresis band control. In this control method , the switching frequency is to force the reference current remain within a hysteresis band. This control is used for pulse generation in current controlled VSIs. The control method employed in active power filter for the control of line current. It consists of a hysteresis band surrounding the generated error current. The switching signals thus generated are fed to the power circuit which comprises of a three phase VSI with a DC link capacitor across it. Based on these switching angles the inverter generates compensating current in phase opposition to the line current. The compensating current is injected back into the power line and suppressing the current harmonics.

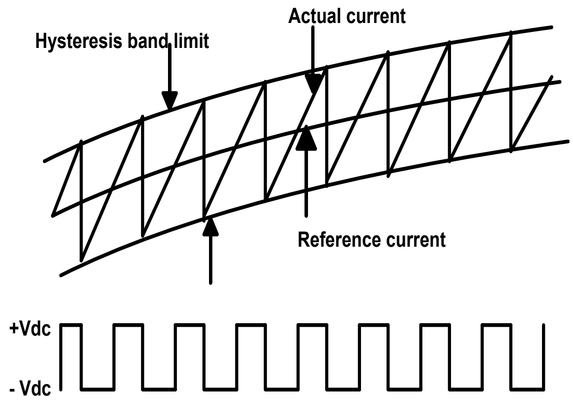


Fig 4. Hysteresis band current control

The respective equations for switching intervals t_1 and t_2 can be written as

$$\left(\frac{di_s^{+}}{dt} - \frac{di_{ref}}{dt}\right)t_1 = 2HB \quad (26)$$

$$\left(\frac{di_s^{-}}{dt} - \frac{di_{ref}}{dt}\right)t_2 = 2HB \quad (27)$$

The relation between t_1 and t_2 can be written in terms of switching frequency of the hysteresis band ω_s as

$$t_1 + t_2 = \frac{2\pi}{\omega_s} \text{(28)}$$

$$HB = \left(\frac{0.5mV_{dc}}{\omega_s L}\right)\left[1 - \left(\frac{V_s - Ri_{comp} + L\frac{di_{load}}{dt} - L\frac{di_{ref}}{dt}}{V_s}\right)^2\right] \text{(29)}$$

Where, $i_{ref} = k\sin\omega t$ (30)

$$\frac{di_{ref}}{dt} = k\omega\cos\omega t \text{(31)}$$

Fuzzy logic controller scheme
In a fuzzy logic controller, the control action is determined from the evaluation of set of simple linguistic rules. The development of the rules requires a through understanding of the process to be controlled. A fuzzy logic controller consists of three main processors, Fuzzification, Rule base & inference and defuzzification. The proposed internal structure of the fuzzy logic controller is shown in Fig 5.

Fuzzification
Fuzzification is the process of transforming crisp variables of respective fuzzy variables according to the chosen membership functions. Membership functions used for input and output variables .According to the chosen membership functions each variables, error(e), rate(r), and output(du) has three linguistic variables are negative(n), zero(z) and positive(p). The block converts each piece of input data to degrees of membership functions by a look up one or several function. There is a degree of membership function for each linguistic term that appears to that input variable.

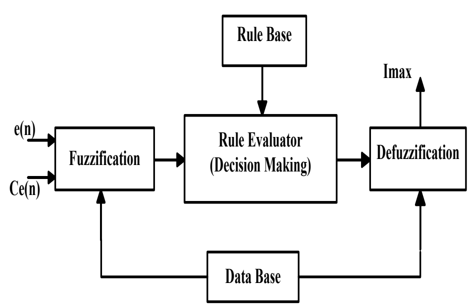


Fig 5. Internal structure of fuzzy logic controller

Rule base and Interference

The rule base of a fuzzy logic controller consists of all the necessary relationships among the input and output variables. These are usually derived based on analytical, hysterical or expert knowledge about the system. In this paper rule base is derived based on the of the proposed pulse test response approach. For example, the rule base derived for the second order system controller from pulse test response is given in table.

De-fuzzification

De-fuzzification is the process of combining the results of inference process to find crisp outputs. The rules of fuzzy logic controller generate required output a linguistic variable format according to real world requirements, linguistic variables have to be transformed to crisp output.

The result of the implication and aggregation steps is the fuzzy output which is the union of all the outputs of individual rules that are validated.The error e and change of error ce are used as numerical variables from the real system.To convert these numerical variables into linguistic variables, the following seven fuzzy levels or setsare chosen as NB(negative big), NM(negative medium), NS(negative small), ZE(zero error), PS(positive small), PM(positive medium), PB(positive big).

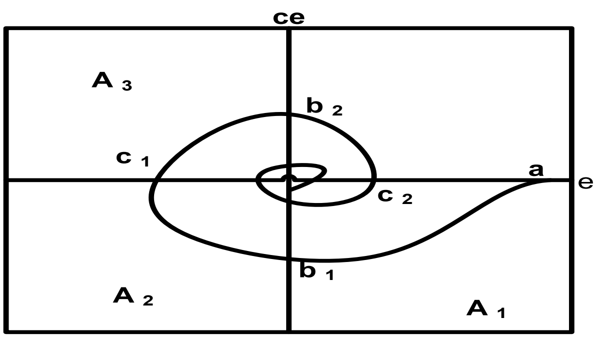


Fig 6. Phase plane trajectory of step response

The input variables of the FLC are the error *e* and the change of error *ce*. The output is the change of the reference current (δI). The time step response of a stable closed loop system should have a shape shown in figure 6. shows the phase plane trajectory of the step response, which shows the mapping of the error against the change in error.

The system equilibrium point is the origin of the phase plane. The time response has been divided into four regions A_1, A_2, A_3, and A_4 and two sets of points - cross-over (b_1, b_2) and peak (c_1, c_2). The index used for identifying the response area is defined as

A_1: if e>0&ce<0, A_2: if e<0&ce<0

A_3:if e<0&ce>0, A_4: if e>0&ce>0

The cross over index:

b_1 : e>0 to e<0,ce<0

b_2 : e<0 to e>0,ce>0

and the peak valley index:

c_1: ce=0,e<0, and c_2: ce=0,e>0

Based on these four areas, two sets of points and phase plane trajectory of *e* and *ce*, the rule base is framed. The corresponding rule 1 for region 1 can be formulated as rule R_1 and has the effect of shortening the rise time

R_1 : if *e* is + ve and *ce* is - ve, then δI_{max} is +ve

rule 2 for region 2 decreases the overshoot of the system response, which can be written as

R_2 : if *e* is - ve and *ce* is - ve; then δI_{max} is – ve

Similarly, rules for other regions can be formed for determined based on the rule control the theory that in the transient better control performance finer fuzzy partitioned sub- state, large errors need coarse control, which requires spaces (NB, NM, NS, ZE, PS, PM, PB) are used and input/output variables; in the steady state, are summarized in Table 1.

e(n)\C e(n)	NM	NS	ZE	PS	PM
NM	NM	NM	NM	NS	ZE
NS	NM	NM	NS	ZE	PS
ZE	NM	NS	ZE	PS	PM
PS	NS	ZE	PS	PM	PM
PM	ZE	PS	PM	PM	PM

Table 1. Control rule table

Source Voltage (Vs)	230V, 50Hz
Dc Capacitor & Dc Capacitor Reference voltage	5e-5mF, 550v
Source Resistance(Rs)& Inductance(Ls)	0.1ohms, 3e-3H
Diode Rectifier Non-linear load Resistance and Inductance	10ohms, 100e-3H
Filter Inductance(LF), Filter Capacitance(CF)	1e-3H, 2e-3F
Switching Frequency	1kHz

Table 2. Specification table

simulation results

The proposed shunt active power filter has been simulated using MATLAB for a single phase shunt active power filter with diode rectifier feeding an RL load, three phase shunt active power filter with diode rectifier feeding RLE load.The single phase SAPF with diode rectifier with diode rectifier feeding RL load as shown in fig 7. The SAPF is switched on at 100 ms initially. The control loops HB1 and HB2 are same as that of current control loops. The voltage control loop is obtained the output of LPF is compared with a reference voltage and the difference is sent to the fuzzy logic controller.

The output of the fuzzy controller is multiplied by a sine wave of unity magnitude to obtain reference current. The source current in phase with the supply voltage. The compensating current clearly show the contribution of the respective inverters. The performance

of the inverters to take care of reactive power demand and harmonic components of the load current.

The simulated waveforms with reference to simulation circuit of Fig 7. and output waveforms are shown in Fig 8.(a)-(d),(a) Supply voltage and source current, (b)load current (c) compensating current (d) DC capacitor voltage for FLCSAF. The harmonic spectrum of I (RL) and (LS) after step change in diode rectifier are as shown in Fig 9.

The simulation circuit of three phase SAPF with diode rectifier feeding RLE load is shown in Fig 10. The hysteresis band controller HB1, HB2 and HB3 are voltage control loops and HB4, HB5 and HB6 are the current control loops. The simulated waveforms of three phase SAPF is shown in Fig 12, fuzzy logic based shunt APF with diode rectifier feeding an RLE load, (a) source current (b) load current (c) current supplied by APF (d) DC link capacitor voltage.

The simulation model is examine the performance of the proposed SAPF system and to compare the conventional low pass filter based SAPF. The specification of the proposed SAPF and other system parameters are based on the specification table 2.

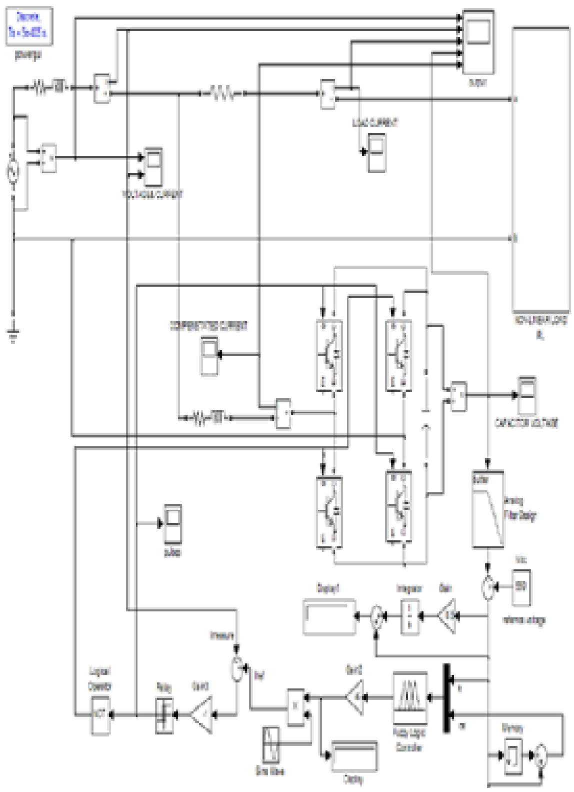
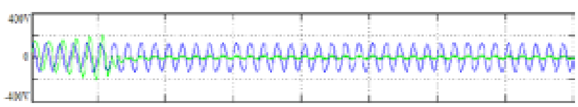
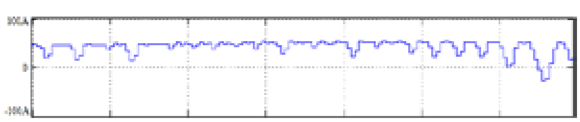


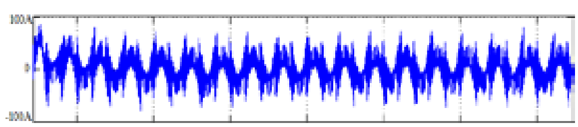
Fig 7. Simulation circuit for single phase shunt APF with diode rectifier feeding RL load



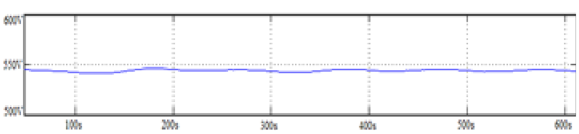
(a)



(b)



(c)



(d)

Time (s)

Fig. 8. Simulated waveforms of single phase shunt APF with diode rectifier feeding an RL load, (a)Supply voltage & source current, (b)load current (c) compensating current (d) DC capacitor voltage for FLC based SAF

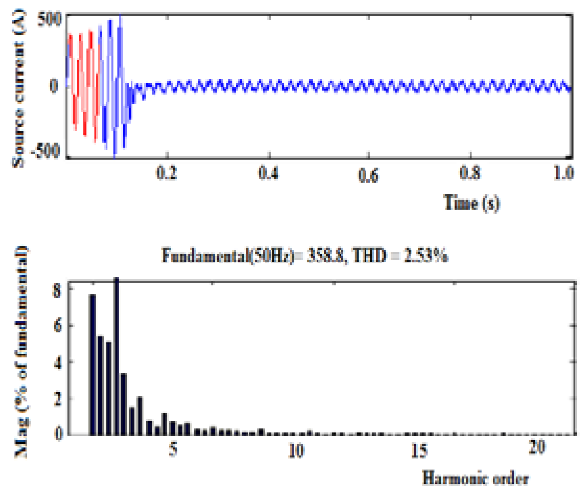
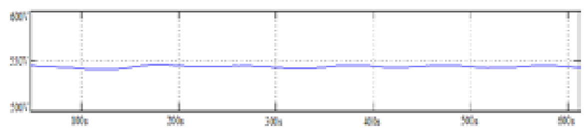


Fig 9. THD vs Source current for RL load

The results have confirmed very satisfactory performance in terms of waveform quality and response time. The THD for simulations remain less than 3%. Fig. 9 shows the individual harmonic contents for compensated source currents. The THD of the compensated source current is found to be 2.5%. The corresponding compensating currents show that the LPF has major role in such cases. The THD of the source current at steady state load change below 3%, which are satisfactory.



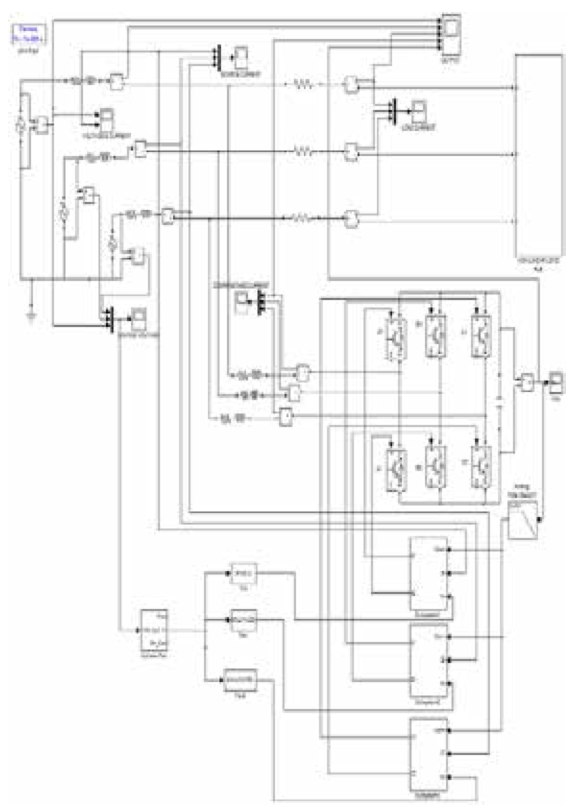


Fig 10. Simulationcircuit for three phase shunt APF with diode rectifier feeding RLE Load

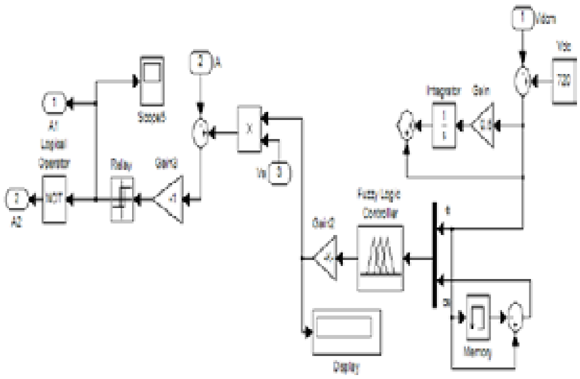
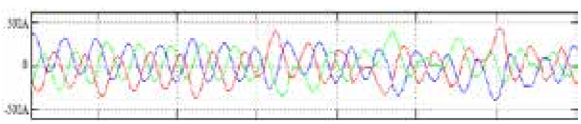
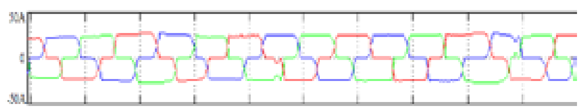


Fig 11. Subsystem of Fuzzy control loop for SAPF

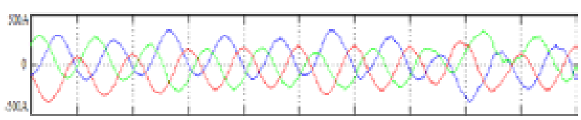
The three phase shunt active power filter using fuzzy logic controller is working based on control rule table the source current is compensating with reference current, the reference amplitude signal is giving back to the load current harmonics are reduced and the dc link capacitor voltage is maintained constant reference value.



(a)



(b)



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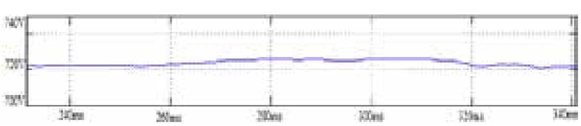

(d) Time (s)

Fig. 12. Simulated waveforms of three phase shunt APF with diode rectifier feeding an RLE load, (a) source current (b) load current (c) current supplied by APF (d) DC link capacitor voltage for FLC based SAF

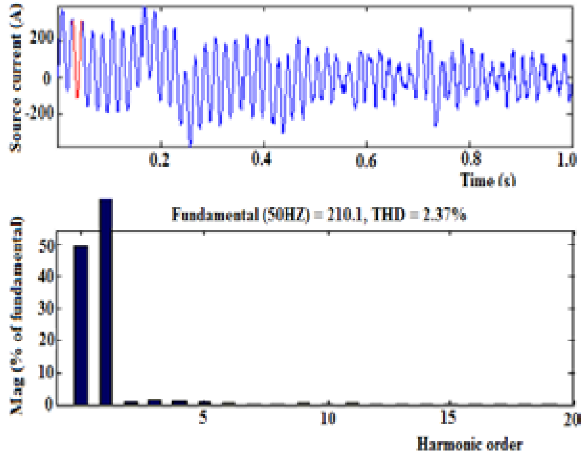

Fig 13. THD vsSource current for RLE load

In three phase circuit, THD value of source current in phase 'a' is reduced upto 2.3% of nominal value. THD values are presents in the order of 3rd, 5th,7th and 11th order of harmonics are reduced below 3%, the harmonic standard 519-1992. It may be observed from the simulation results of shunt active filter and the source current becomes sinusoidal after connecting the APF. In addition the DC link capacitor takes some time to respond to the change in load condition.

Conclusion

In this paper, control and implementation of fuzzy logic controller and hysteresis band current controltechniqueforSAF has beensuccessfullydemonstratedinMatLab/Simulink software platform. The reference current is generated by regulating the dc capacitor voltage using fuzzy logic controller. Harmonic distortion can be reduced by using passive filters were THD reduce to 9.12% but in the IEEE standard THD should be below 5%, therefore using shunt active filters to meet the requirement. After compensation, the source current is sinusoidal and in phase with the supply voltage. It compensates both harmonics and reactive power simultaneously. On using shunt active filters reduced THD value to 2.3% by using fuzzy logic control system. The SAFwas simulatedanditsperformancewasanalyzedinasamplepowersystem withasourceanda non linear load. The proposed SAPF controller is giving better results and supply current is more and less harmonics.

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IEEE Trans Power Electron; 2013, 28(1):101–11. | [22] Liu J, Cheng KWE, Ye Y., "A cascaded multilevel inverter based on switchedcapacitor for high-frequency AC power distribution system" IEEE Trans Power Electron, 2014, vol.29, no.8, pp 4219–4230. | 1. Alwin.S graduated in Electrical and Electronics Engineering in 2004 from St.Xavier's Catholic College of Engineering, Nagercoil. He obtained his M.Tech from Noorul Islam College of Engineering, Thuckalay,Tamilnadu, specializing in Applied Electronics and He is currently Pursuing Ph.D at St.Peter's University, Avadi, Chennai, Tamil Nadu, India. | | 2. Dr.M. Marsaline Beno graduated in Electrical and Electronics Engineering in 1998 from Govt. College of Engineering, Tirunelveli. He obtained his M.Tech from College of Engineering, Trivandrum in 2000, specializing in Electrical Machines and completed Ph.D from Anna University Chennai in 2009 under the specialization of Electrical drives & Control. 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