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Power Quality Improvement Using Four Leg Shunt Active Power Filter

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Abstract

This paper presents a comparative study of control strategies for a three phase four wire systems with four leg shunt active power filter (SAPF) to enhance its dynamic response when it is used to compensate for harmonic currents in line, neutral and reactive power. Two control strategies used to determine the compensation currents are the instantaneous real and reactive power theory (p-q) and instantaneous current component theory ($i_d - i_q$). The Proportional Integral (PI) and Adaptive neuro fuzzy inference system (ANFIS) controllers are utilized to control four leg SAPF input current and regulate the DC link voltage. The generation of gate pulses for VSI based four leg SAPF using dead beat control with sinusoidal pulse with modulation (SPWM). On owing i_d-i_q method with ANFIS controller gives less THD value under balanced and unbalanced source condition. The model for the Shunt active power filter (SAPF) system was simulated using MATLAB/Simulink environment.

Keywords: ANFIS, Deadbeat Control, $i_d - i_q$ method, p-q theory, Shunt active power filter (SAPF), Sinusoidal PWM.

Introduction

The increase use of power electronics based loads like three phase diode rectifier, adjustable speed drives and domestic appliances etc. highly non-linear characteristics. The power quality distortion has become serious problem in electrical power system because of drawing non sinusoidal current and excessive burden of neutral current in three phase four wire system [1]. This leads to reduce the efficiency and interference of distribution system with the nearby communication networks generally capacitors are used to improve the efficiency, which also leads to the improvement of power factor of the mains. Traditionally Passive filters are employed to eliminate harmonics current and to improve the power factor of the AC mains. However the limitations of passive filters are large size, tuning problems, series and parallel resonance. To overcome the drawbacks of passive filter using active power filter (APF).

The realization of SAPF using different topologies for three phase four wire system like Voltage source converter (VSI) based split-capacitor type and four leg SAPF. There are many number of current control concepts and methods of active power filters have been reported in the literature [2][3]. They are two methods of control in SAPF: one is frequency and another method is time domain, most popular are the time domain methods such as the notch filter, the instantaneous reactive power theory (p-q)[6], and the synchronous reference frame theory(d-q)[4][7]. The main advantage of these time domain control methods compared to the frequency domain methods based on the fast Fourier transform (FFT) is the fast response, whereas the frequency domain methods provide an individual selective harmonic detection which is not the case in time domain methods.

In previous research work, there are many control techniques[5] for producing pure sinusoidal input currents with low THD and fast dynamic responses. The hysteresis controller based PI controller used in p-q and i_d-i_q current control method [9] need precise linear mathematical models which are tough to get accurate results under parameter variations[8]. Nowadays, the soft computing (fuzzy logic controller (FLC) and Adaptive neuro fuzzy inference system (ANFIS)) based analysis of SAPF gives outstanding performance under various voltage condition [14]. The main feature of the fuzzy logic controller compared to conventional controllers is that they do not need an accurate mathematical model, can work with imprecise inputs, can handle non-linearity, and are more robust than conventional controllers. The Mamdani type of fuzzy controller used for the control of APF gives better results compared with the PI controller, but it has the drawback of a huge number of fuzzy sets and rules. This increases the complexity of the controller; hence, this demands large computational time. To overcome the drawback of FLC using ANFIS controller and its gives less THD value in source and neutral current.

In this paper presents a deadbeat control based SAPF with p-q and $i_d - i_q$ control strategies for line and neutral current harmonic mitigation in three phase four wire system using PI and ANFIS controller under different source voltage condition.

The work is organized as follows, section two described the SAPF configuration, section 3 described the control strategies of p-q and i_d-i_q method, section 4 discussed the dc link voltage control using PI and ANFIS controller, section 5 deadbeat control based SPWM section 6 described the simulation result and discussion.

System Configuration

The basic system configuration of shunt active power filter is shown in fig. 1. There are two types of topologies were used in three phase four wire distribution system one is split capacitor type and another four leg VSI based inverter[10]. The Shunt active filter is connected in parallel with the non linear loads of three phase diode rectifier and two single phase diode rectifier. The basic operating principle of active power filter is that a non sinusoidal waveform at a PCC can be corrected to sinusoidal by injecting current of proper magnitude and waveform.

The four leg shunt active power filter consists of eight switches; three of its legs are used for phase current harmonic compensation and the fourth leg is connected to the load neutral and the supply neutral for neutral current harmonic compensation through an interface reactance. This requires only one dc storage unit. The four leg SAPF is used to reduce harmonics presents both three phase source current and neutral current.

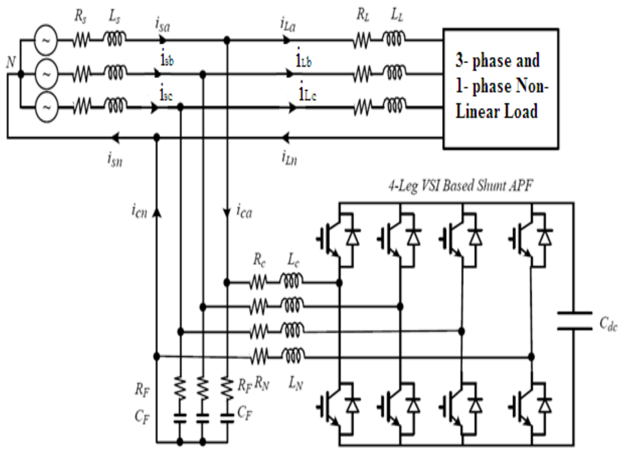


Fig. 1. Schematic diagram of four leg SAPF with non-linear load

Control Strategies

A. Instantaneous real and reactive power (p-q) theory

Akagi et. Al. proposed a theory based on instantaneous values in three phase power system with or without neutral wire. Reactive (p-q) power theory which consists of an algebraic transformation (Clarke transformation) of the three-phase voltages in the *a-b-c* coordinates to the *α-β-0* coordinates [6], followed by the calculation of the p-q theory instantaneous power components. In Fig. 2 describe the block diagram of p-q theory using Clarke and inverse Clarke transformation to obtain the reference currents of i_a, i_b and i_c.

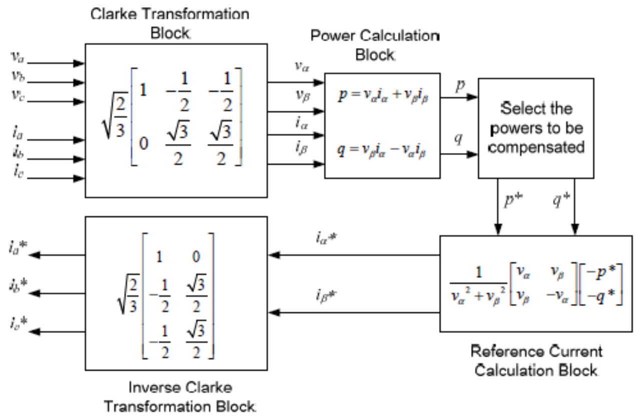


Fig. 2. Block diagram of p-q theory

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = C \begin{bmatrix} v_a \\ v_\alpha \\ v_\beta \end{bmatrix} \quad \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = C \begin{bmatrix} i_{Lc} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{1}$$

$$C = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \tag{2}$$

In equation (1) describe the Clarke transformation and equation (2) denotes the transformation matrix. The main objective of the p-q theory is to supply only the power needed by the load from the source that was described in equations (3) and (4).

$$P_s(t) = P_{L0}(t) + P_{Lab}(t) \tag{3}$$

$$\begin{bmatrix} i_{s\alpha ref} \\ i_{s\beta ref} \\ i_{s0ref} \end{bmatrix} = \left(p_{L\alpha\beta} + p_{L0}\right) \big/ \left(v^2_\alpha + v^2_\beta\right) \begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} \tag{4}$$

B. Instantaneous current component (i_d-i_q) method

The instantaneous current component (i_d-i_q) method is based on set of rotating direct and quadrant power defined in time domain method and it is valid for both steady state and transient state. This theory is very efficient and flexible for designing shunt active filter under non sinusoidal voltage condition. The three phase voltages and load currents (abc) are converted into dq0 synchronous rotating reference frames [7][10]. The park and inverse park transform of three phase currents are given by,

$$\begin{bmatrix} i0 \\ i\alpha \\ i\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} \tag{5}$$

$$\theta = tan^{-1}\frac{V\beta}{V\alpha} \quad (6)$$

Where 'θ' is the transformation angle

$$\begin{bmatrix} id \\ iq \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \quad (7)$$

The three phase compensated reference current calculated by inverse park transform is given by,

$$ica\ ref = id \sin(wt) + iq \cos(wt) \quad (8)$$

$$icb\ ref = id \sin\left(wt - \frac{2\pi}{3}\right) + iq\cos\left(wt - \frac{2\pi}{3}\right) \quad (9)$$

$$icb\ ref = id \sin\left(wt + \frac{2\pi}{3}\right) + iq\cos\left(wt + \frac{2\pi}{3}\right) \quad (10)$$

$$icn\ ref = ica\ ref + icb\ ref + icc\ ref \quad (11)$$

where ia, ib, ic is three phase current, i_α, i_β is stationary reference current, i_d, i_q is rotating reference current. The θ is independent frequency. The compensating three phase currents are i_{ca}, i_{cb}, i_{cc} and neutral current i_{cn}.

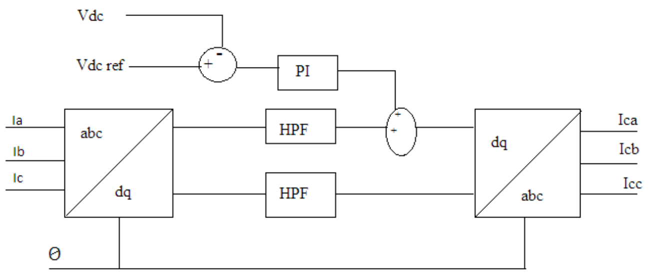


Fig. 3. Reference Current Calculation using Id –Iq method

The block diagram of the reference current calculation of instantaneous current component (i_d-i_q) method is shown in Fig. 3. The three phase current is converted into synchronously rotating reference frame and feed to high pass filter (HPF), it attenuate lower order harmonics and then compute the compensated reference current using inverse Park transformation. In that reference dc voltage (V_{dc} ref) and actual dc link voltage (V_{dc}) compared and is given to the dc voltage is regulated using PI / ANFIS controller.

DC Link Voltage Regulation

A. Deadbeat based PI Controller with SPWM

In order to maintain and regulate the dc link voltage of the four leg SAPF using deadbeat based PI controllers with sinusoidal pulse width modulation (SPWM) switching control scheme is proposed and shown in fig. 4.. The reference voltage (V_{dc} ref) and actual dc link voltage (V_{dc}) is compared and the error signal is passed to PI controller in which the *Kp* value is 8. 5 and *Ki* value is 0. 685 shown in fig 4.. The coefficient values of *Kp* and *Ki* are computed using a heuristic tuning method, i. e. the Ziegler–Nichols method. In general, the deadbeat controller plays the important role of producing the output voltage to the steady state in finite time steps or dead time after the input signal is applied to the system. Generally, deadbeat control is a digital feedback strategy designed to control the pulse width so that the output of the VSI can track the reference at every sampling instant. Hence, the past modulation index will be sampled after a delay time of 0. 04s in the model. Subsequently, the modulation index generated by the PI controller will summate with the previous modulation index and send this to the reference sine wave generator [12]. Next, the product of the modulation index and the three sinusoidal signals, which are 180degree out of phase from each other, will be compared with the triangular signal carriers in order to produce the SPWM switching waveforms used to trigger the eight IGBTs, S1, S2, S3, S4, S5, S6, S7 and S8 of the VSI based four leg Shunt active power filter.

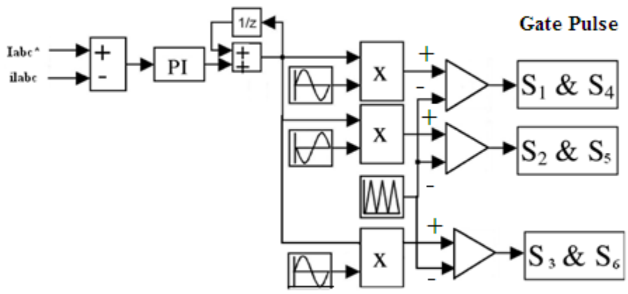


Fig. 4. Block Diagram of the Deadbeat-Based PI Controller with SPWM Switching Technique

The control scheme consists of a PI controller, a limiter, and a modified d-q theory for reference current calculation and deadbeat current based SPWM used to generate the switching pulses. The maximum value of the reference currents is determined by regulating the DC link voltage.

The peak or maximum value of the current (I_m) is obtained by multiplying the unit sine vectors in phase with the respective source voltages to obtain the reference compensating currents. These estimated reference currents (I_a*, I_b*, and I_c*) and the sensed actual filter currents (I_a, I_b, and I_c) are compared to a deadbeat controller, which gives the error signal for the modulation technique [11]. This error signal decides the operation of the converter switches. In this current control circuit configuration, the load currents I_{Labc} are made to follow the sinusoidal reference current I_{abc}*.

B. ANFIS Controller

The design of adaptive neuron fuzzy inference system learning techniques is very simple. Adaptive Neuro-Fuzzy Inference system is the combination of artificial neural networks and fuzzy inference systems. It consists of three elements namely auxiliary, compatible and integrative [13]. The main aim of ANFIS controller is to automatically realize the fuzzy system by using the neural networks. It permits the

combination of numerical and linguistic data and it has the ability to obtain fuzzy number from real number.
To express the ANFIS controller structure, thereare two fuzzy if-then rules under Takagi-Sugeno (TS) model are given as follows:
Rule 1: If (x is A1) and (y is B1) then f1 = p1x+q1y+r1
Rule 2: If (x is A2) and (y is B2) then f2 = p2x+q2y+r2

Where x and y are the inputs, A_1 and B_1 are the fuzzy sets, fi, i = 1, 2 are the output fuzzy system, and pi, qi and ri are the design parameters which are determined during the training process[14].
In fig. 5. shows the internal structure of ANFIS controller. The ANFIS controller system realizes TS rules in 5 layers by using multi-iteration learning procedure and hybrid learning algorithm. In the block structure of ANFIS, there are two adaptive layers (Layers 1 and 4). Layer 1 has three adjustable parameters related to input membership functions (A*i*, B*i* and Ci). These parameters are pioneer parameters. Layer 4 has three adjustable parameters (*ri, pi, qi*) related to first degree polynomial. These parameters are called result parameters [13].

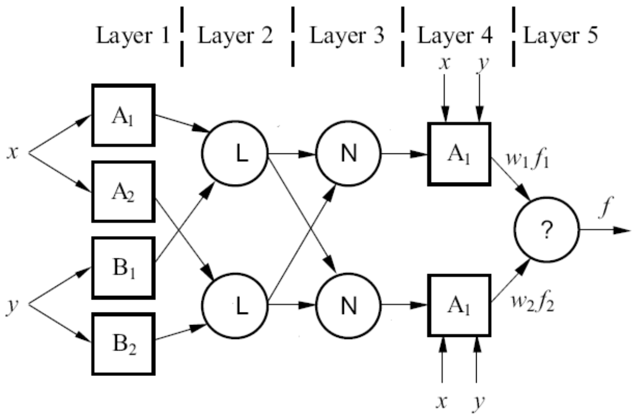


Fig. 5. Structure of ANFIS Controller

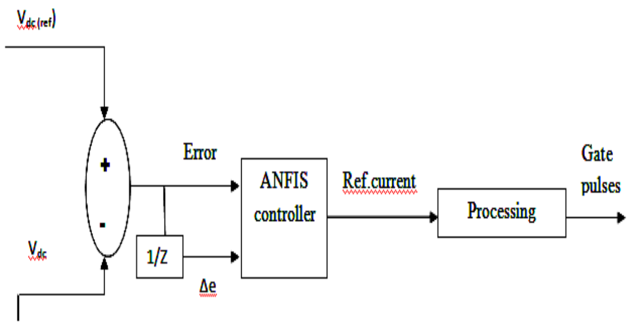


Fig. 6. Switching pulse generation using ANFIS controller

The bock diagram of ANFIS controller used to regulate the dc link voltage is shown in fig. 6 [13]. The back propagation algorithm is used to training of neutral network and fuzzy logic controller used to generate FIS. For implementing the current system ANFIS is coded in MATLAB environment.

Simulation Results and Discussion
The simulations have been conducted to evaluate the proposed system in three phase four wire system. The proposed system is simulated with PI and ANFIS controller based 4leg shunt active power filter using MATLAB/SIMULINK. The system parameters were tabulated in table 1.

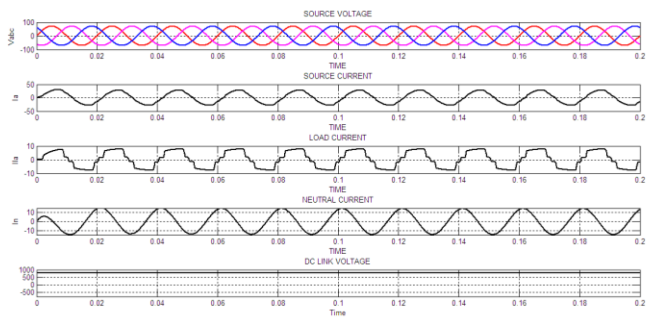
TABLE 1. The system parameters used in simulation

Parameters	Value
Source	
Voltage (V_{sabc})	70. 7V-Phase-nuetral
Frequency	50Hz
Resistor Rs	0. 1Ω
Inductance Ls	1mH
Four leg SAPF	
DC link oltage(V_{dc})	800V
DC Capacitor (C_{dc})	3000µF
Switching frequency	20kHz
AC side filter(Rc, Lc)	0.01 Ω, 0. 04mH
(R_f, C_f)	1 Ω, 10µF
Load	
Three Phase Load	10 Ω, 60mH
Single Phase Load	30 Ω, 40mH

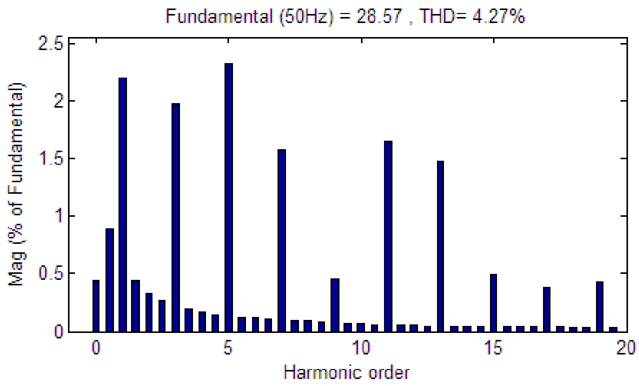
A. Ideal main voltage condition
Figure 7, 8, 9 and 10. Shows the simulation results for 4leg shunt active power filter with PI and ANFIS controller under balanced source condition using pq and I_d – Iq theory. Also shows the percentage THD value of source and neutral current.

B. Unbalanced main voltage condition
For this case, the simulation results of unbalanced 3 phase voltages are shown in fig. 11 and 12. The compensated, source and neutral current results are shown in fig. 11. (a) and (d) using PI and ANFIS controller with pq theory. Fig. 12. Shows the simulation results compensated source and neutral current of shunt active power filter.

C. Balanced and unbalanced load condition
Fig. 13 and 14. illustrates the comparison chart with total harmonic distortion value for source and neutral current of the various source and load condition using PI and ANFIS controller. The barchart shows the Simulation results of source current and neutral current under balanced and unbalanced source and load condition with FFT analysis of source and neutral current.



(a)



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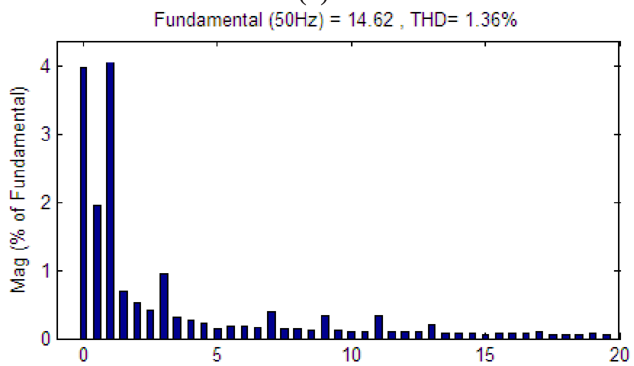
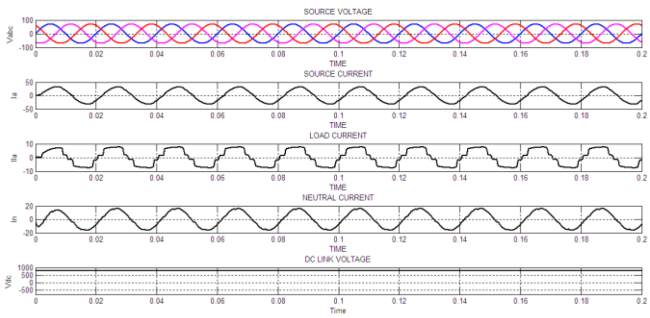
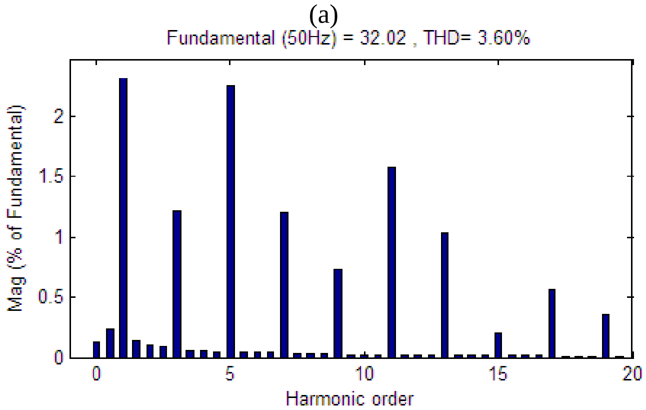


(c)

Fig. 7. Simulated results of pq theory based 4 leg SAPF under balance supply condition using PI controller (a) supply voltage, source current, load current, neutral current and DC voltage (b) & (c) %THD value for source and neutral current.



(a)



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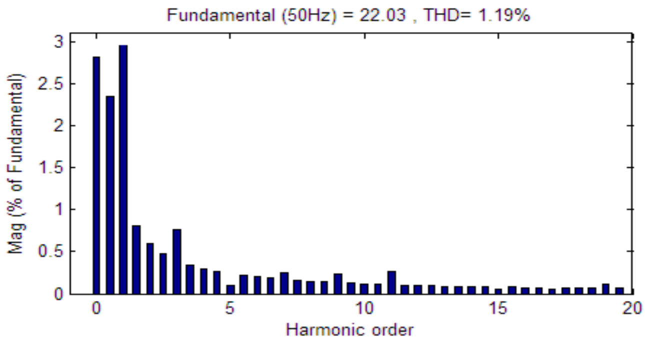
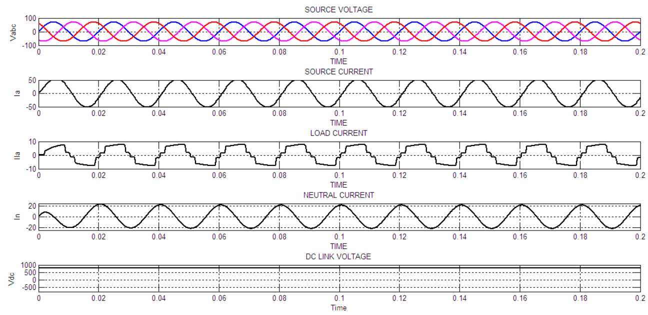
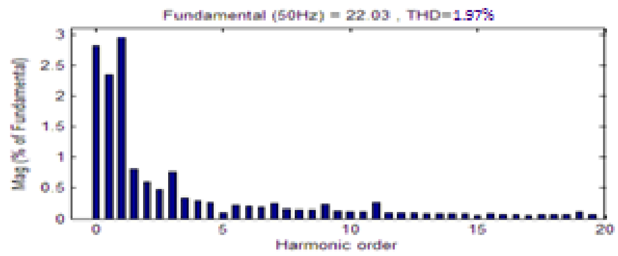


(c)

Fig. 8. Simulated results of pq theory based 4 leg SAPF under balance supply condition using ANFIS controller (a) supply voltage, source current, load current, neutral current and DC voltage (b) & (c) %THD value for source and neutral current.



(a)



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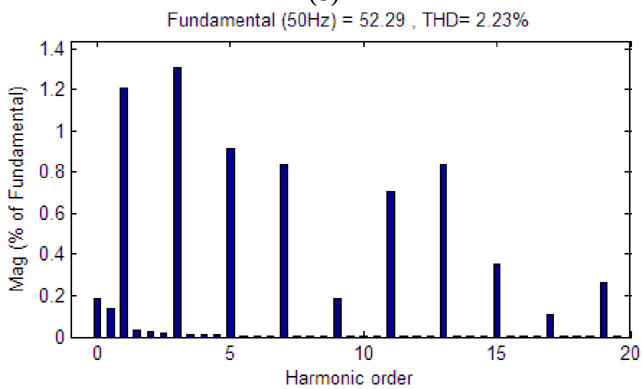
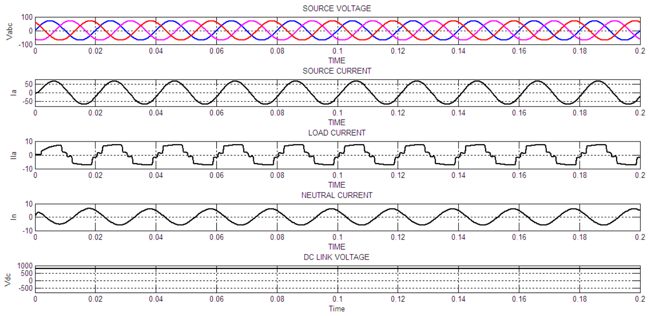
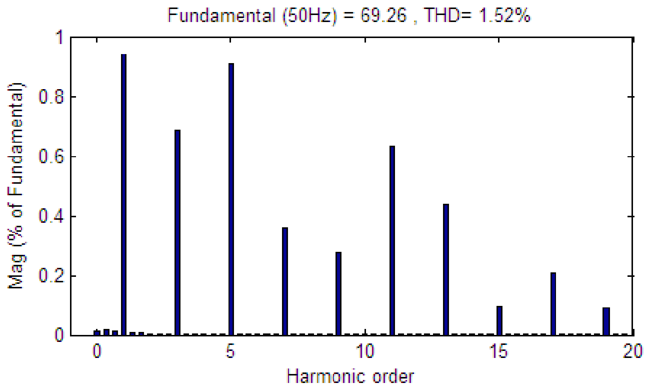


(c)

Fig. 9. Simulated results of I_d – Iq theory based 4 leg SAPF under balance supply condition using PI controller (a) supply voltage, source current, load current, neutral current and DC voltage (b) & (c) %THD value for source and neutral current.



(a)



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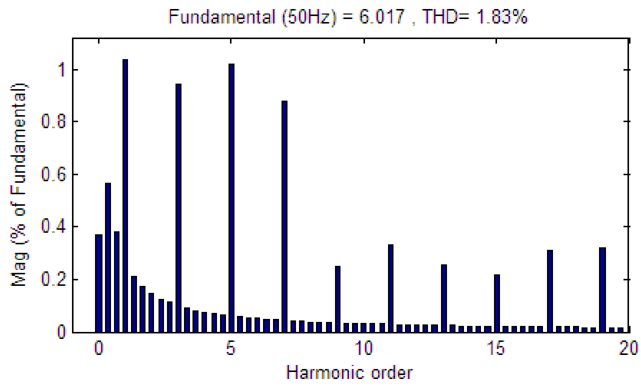
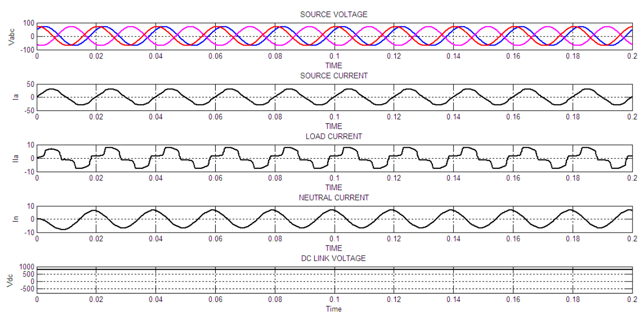


(c)

Fig. 10. Simulated results of I_d – Iq theory 4 leg SAPF under balance supply condition using ANFIS controller (a) supply voltage, source current, load current, neutral current and DC voltage (b) & (c) %THD value for source and neutral current.



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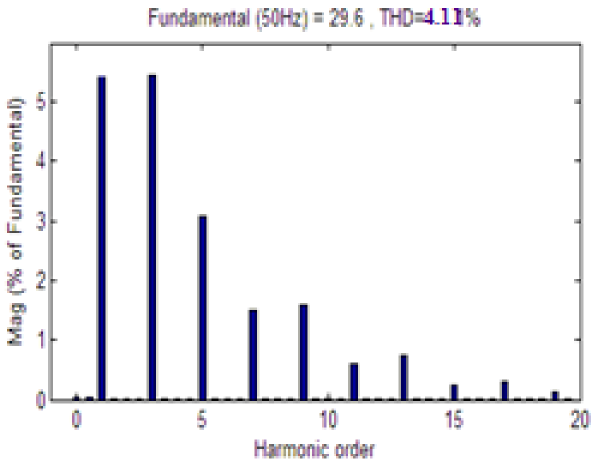

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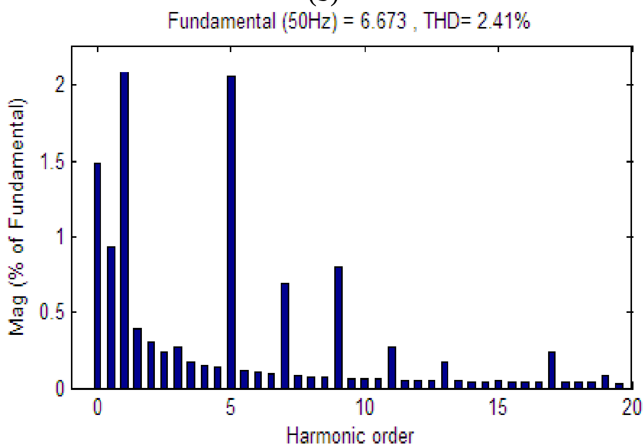

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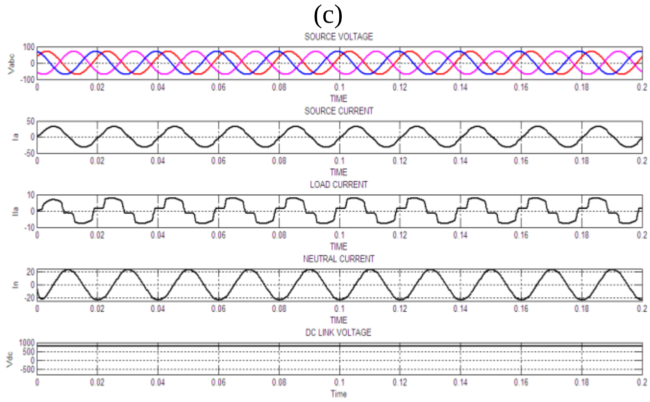

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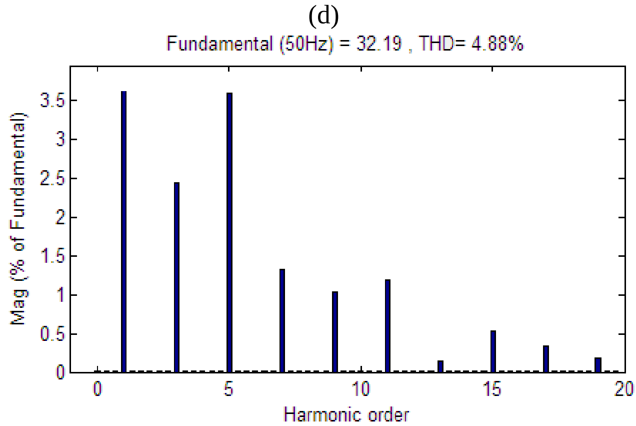

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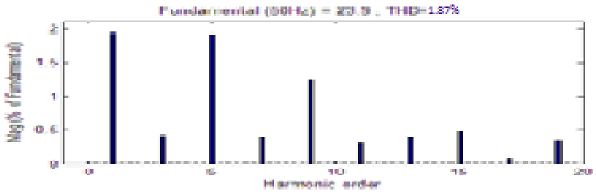
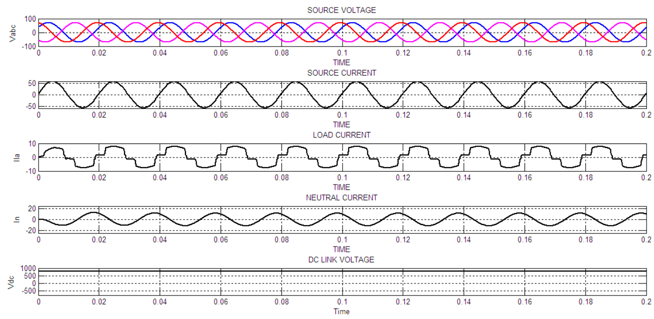
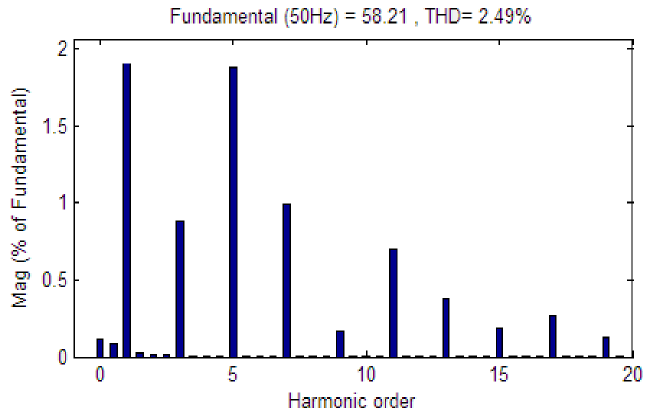


(f)

Fig. 11. (a) & (d) Simulated results of pq theory based 4 leg SAPF under unbalance supply condition using PI and ANFIS controller, (b), (c), (e) & (f) %THD value for source and neutral current.



(a)



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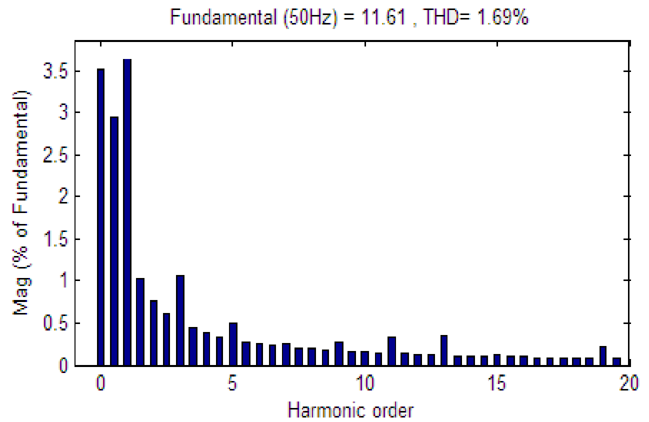

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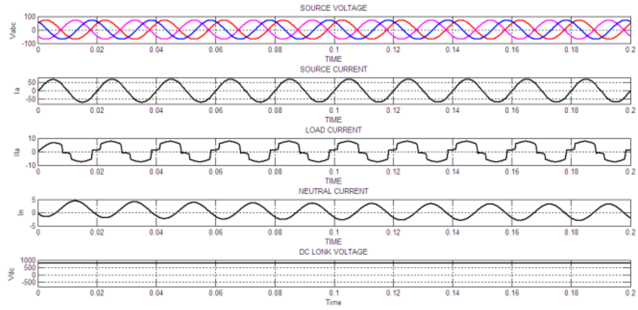

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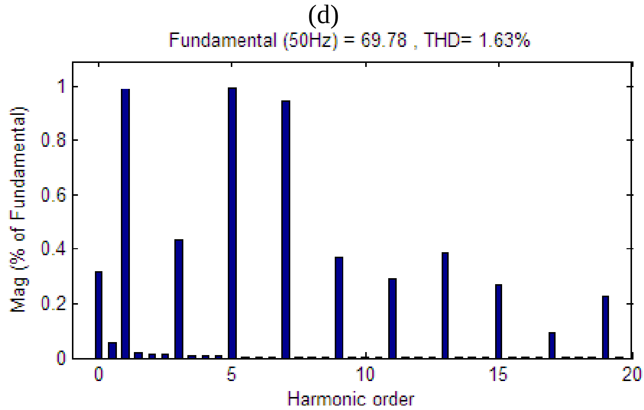

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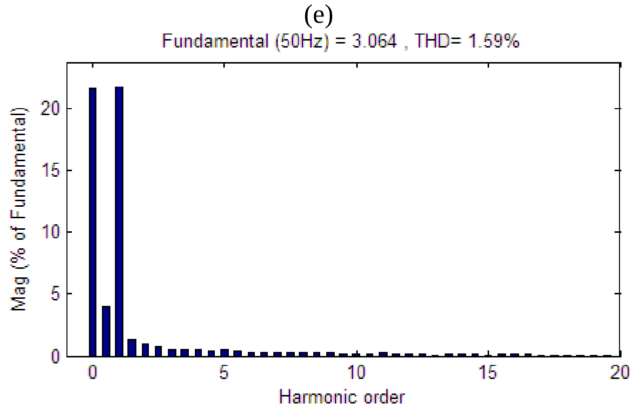

(f)

Fig. 12. (a) & (d) Simulated results of $I_d - Iq$ theory based 4 leg SAPF under unbalance supply condition using PI and ANFIS controller and (b), (c), (e) & (f) %THD value for source and neutral current.

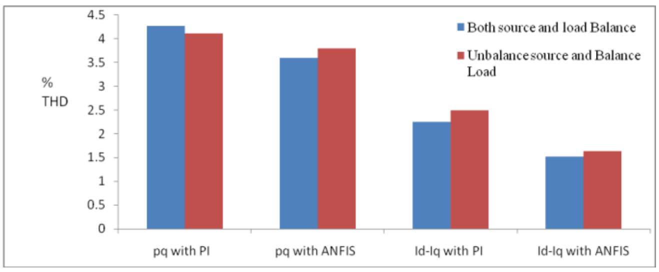

Fig. 13. THD Value of source current for pq and $i_d - i_q$ control methods with PI and ANFIS Controller

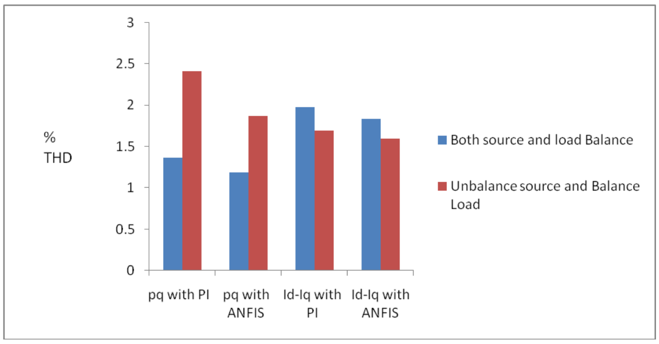

Fig. 14. THD Value of Neutral current for pq and $i_d - i_q$ control methods with PI and ANFIS Controller

Conclusion

In this paper, a three-phase four-wire four leg shunt active filter based on PI and ANFIS controller using two control strategies is proposed to compensate source and neutral current harmonics. The two controllers use the instantaneous real and reactive power (pq) theory and instantaneous current component ($I_d - I_q$) strategy. The dc-link voltage is regulated using a proportional integral voltage controller with fast dynamic response in case of load current variation. The Simulation results obtained show the robustness and the effectiveness of the ANFIS controllers compared to PI controller. After compensation the source current is balanced, sinusoidal and in phase with line voltage source. The harmonic spectrum for source current shows that the THD value is very acceptable and respect IEEE standard Norms.

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