Harmonic Mitigation using Fuzzy Logic Controller based Shunt Active Power Filter

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ABSTRACT

Power quality problem is t he most sensitive problem in the power system. The objective of the project is to reduce one of the power quality issue called "harmonics" using compensation technique. Shunt Active Power Filter (SAPF) is used to eliminate harmonic current and also it compensates reactive power. In this project, both PI controller and Fuzzy Logic Controller based three-phase shunt active filter is employed for a three-phase four wire systems. The advantage of fuzzy control is that it provides linguistic values such as low, medium, high that are useful in case where the probability of the event to occur is needed. It does not require an accurate mathematical model of the system. A MATLAB/SIMULINK has been used to perform the simulation. Simulink model is developed for three phase four wire system under balanced source condition and three phase four wire system for unbalanced source condition. The performance of both balanced source and unbalanced source is done using Fuzzy Logic Controller and PI controller and their Simulink results is compared. Simulation results obtained shows that the performance of fuzzy controller is found to be better than PI controller.

Keywords

Logic Control, Instantaneous p-q theory, Shunt Active Power Filter.

1. INTRODUCTION

The non-linear characteristics and fast switching of power electronic equipment is the main source of power system problems. . The more the use of special electronic components in the equipment used in the generation and distribution creates new phenomenon which makes interest in the area of power quality. But this newer phenomenon reduces the quality of power. Electric Power quality is the measure of consumer satisfaction in using the equipment of serves the need. Power quality issues are becoming stronger due to the usage of the sensitive equipment that will in turn continuously pollute the system more and more. Both power suppliers and end users are concerned about this power quality problem and compensation techniques. The power electronic equipment includes adjustable speed motor drives, DC motor drives, battery chargers, electronic ballasts all causes a rise in PQ related problems. These controllers are used in HV dc systems and renewable electrical power generation. These are the non-linear loads (NLL) which draws current not linearly with voltage are the prime source of harmonic distortion in a distribution system [11]. The distorted current contains multiples of sine waves at multiples of fundamental frequency. These are called current harmonics. These current harmonics are injected into distribution system at the point of common coupling (PCC). Hence harmonic voltage is produced which combines the pure source voltage cause distortion in source voltage. This is fed to the electrical equipment connected to the same bus. It is a form of electrical pollution which declines the quality of electrical supply. In a three phase systems, they could cause unbalance and draw excessive neutral current. They even disturb the adjacent consumers connected to the bus and cause interference in nearby communication. Harmonic distortion can be reduced by two ways. One is the conventional method of filtering using the reactive storage components like R, L, C components to mitigate harmonics. Basically there are two types of passive filter. Shunt passive which uses L and C in parallel to the grid and the series passive filter which uses L and C in series to the supply. The principle of passive is tuning the filters to the highest dominant frequency and a low impedance path is created for that harmonic frequency. Hence the harmonic current diverts form their normal path and pass through this filter and thereby prevented from flowing back to the source. But this conventional passive filter does not support for dynamic compensation and the physical size is large due to the usage of inductor.

Later power engineers developed a dynamic and adjustable filter to solve the power quality problem is by using Active Power Filters (APF). Active Power Filters are power electronic circuits containing power switching devices and passive energy storage elements. APF uses IGBT technique with the control strategy to reduce the harmonic and make the THD within the acceptable IEEE standards. The basic principle employed is to produce required current to cancel the harmonic current caused by NLL. The main advantage of using APF is that they suppress not only harmonic current but also the reactive current [11]. Modern APF are very efficient in filtering and their physical size is small and is dynamic. The drawback is its cost and operating loss compared to passive filter [1]. The classification of shunt active power filter is shown in fig.1. SAPF is used in the proposed system to mitigate harmonics. The single line diagram of SAPF is shown in Fig. 2.

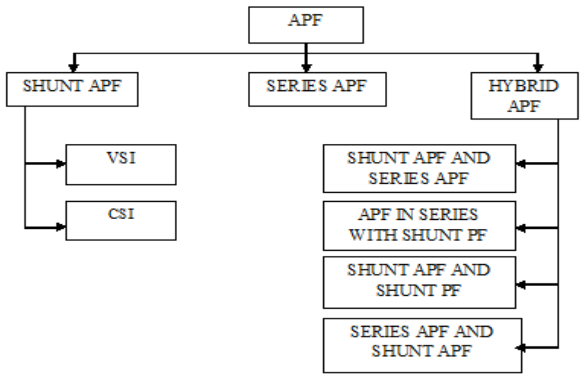

Fig 1: APF Types based on power circuit configurations

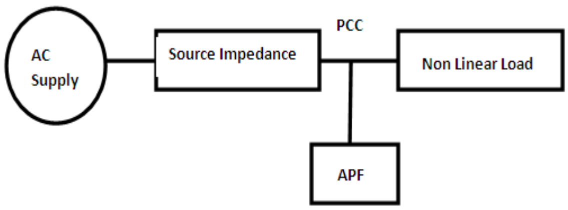

Fig 2: Shunt APF configurations

APF is used to cancel the load harmonic fed to the supply. APF comprises Voltage Source Inverter (VSI) with dc bus capacitor, electronic switches and interfacing inductors. It acts as a current source compensating harmonic current produced due to non- linear load. The basic principle of APF is to generate and inject non sinusoidal compensation current equal in magnitude and opposite in phase to the harmonic produced by NLL at the PCC. This will cancel the harmonic current at PCC [3]. The shape of compensating current is taken care by VSI switches. The reference signal estimation can be done in two modes, Frequency Domain and Time Domain approach. The principle used in frequency domain is Fourier analysis but the drawback is time delay for computing Fourier coefficients. Hence this method is not much suitable for real time applications. Numerous methods were employed in time domain. They are Instantaneous Reactive Power theory (IRP), synchronous detection, synchronous reference frame theory (SFR), PI control theory. The main objective of the paper is to develop the shunt active filter design using MATLAB SIMULINK to mitigate source harmonics. SIMULINK is a MATLAB toolbox used for dynamically simulating linear and non-linear system. This also supports for continuous and discrete time system. MATLAB/SIMULINK is also a GUI tool displays output graphically. The proposed system use IRP theory also called p-q theory for the extraction of harmonic current. p-q theory was introduced by Akagi, Kawakawa and Nabae in 1984 [2]. This theory supports for a three phase system with or without neutral wire. i.e., three phase three wire system or three phase four wire systems. The proposed system uses three phase four wire system using two controllers, conventional PI controller with reference current extraction using p-q method and other is using Fuzzy Logic Controller (FLC) with reference current extraction using p-q theory. Control using PI controller is found to be difficult and time consuming than FLC. The advantages of using FLC are that it does not require accurate mathematical model and they can work even with imprecise inputs. Simulation results show that the harmonic reduction using FLC is better than using PI controller. Block diagram of proposed system is shown in Fig. 3.

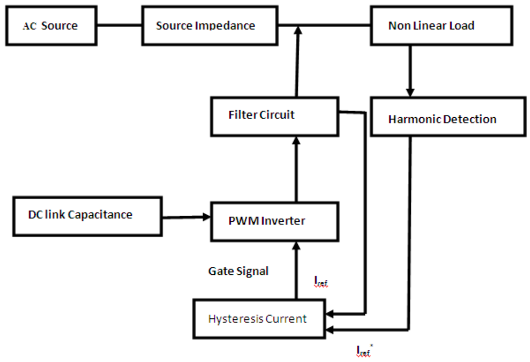

Fig 3: Block diagram of proposed system

The model contains the three phase source connected to the diode bridge rectifier. The source will be used for both balanced and unbalanced condition. Unbalanced source is the case where the three phase source voltage magnitude are unequal or the phase angle subtended is not 120°. This unbalance is also called asymmetrical. The active filter is connected in parallel to the load. The SAPF contains VSI connected in series with an inductor which acts as filter connected to the grid. The inverter uses IGBT because of its high switching frequency. So inverter itself produces high frequency current with low state loss. The inverter circuit triggering depends on the control circuit output. The proposed system use hysteresis current control to produce the pulse to trigger gate of IGBT. Instantaneous p-q theory is used in the proposed system to derive the compensating signal. The compensating current is obtained using the real and reactive power p and q of the nonlinear load. The structure of SAPF for three phase four wire system is shown in Fig. 4.

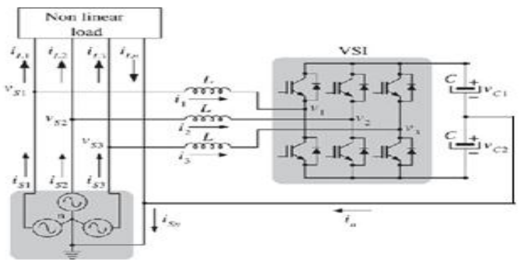

Fig 4: Structure of three phase four wire APF

2. PROPOSED CONTROL STRATEGIES

2.1 Reference Signal Calculation Using Instantaneous Reactive Power Theory (p-q Theory)

Instantaneous reactive power is defined as a unique value of arbitrary voltage or current with all possible distorted waveforms as in [2]. The instantaneous voltages and currents in three phase circuit can be expressed mathematically as instantaneous space vectors. The a,b,c axes in three phase system are 2 π /3 or (120°) apart. The instantaneous voltages are Va, Vb, Vc along a,b.c axes respectively and similarly the currents. This three phase space vectors is converted into two phase co-ordinates as α and β using Clarke transformation.

The active and reactive power of the nonlinear load is calculated from these transformed quantities. This active (p) and reactive power (q) contains both DC and AC component. The AC component is extracted using HPF and reference signal is calculated (V or I) using Inverse Transformation.

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = C \begin{bmatrix} v_a \\ vb \\ v_c \end{bmatrix}; \qquad \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = C \begin{bmatrix} i_{Lc} \\ i_{Lb} \\ i_{Lc} \end{bmatrix}$$

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

Generalized instantaneous power, p (t)

$$p = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} * \begin{bmatrix} i_{la} & i_{lb} & i_{lc} \end{bmatrix} = v_a i_{la} + v_b i_{lb} + v_c i_{lc}$$

The p–q formulation defines the generalized instantaneous power, p(t), and instantaneous reactive power vector, q (t) in terms of the a–b–0 components as

$$p = v_{\alpha\beta0} . i_{\alpha\beta0} = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0$$

$$q = v_{\alpha\beta0} \times i_{\alpha\beta0} = \begin{bmatrix} q_\alpha \\ q_\beta \\ q_0 \end{bmatrix} = \begin{bmatrix} v_0 & v_\alpha \\ i_0 & i_\alpha \\ v_\alpha & v_\beta \\ i_\alpha & i_\beta \\ v_\beta & v_0 \\ i_\beta & i_0 \end{bmatrix}$$

$$q = \|\bar{q}\| = \sqrt{\left(q_\alpha{}^2 + q_\beta{}^2 + q_0{}^2\right)}$$

$$\begin{bmatrix} p \\ q_\alpha \\ q_\beta \\ q_0 \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta & v_0 \\ 0 & -v_0 & v_\beta \\ v_0 & 0 & -v_\alpha \\ -v_\beta & v_\alpha & 0 \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = 1/v^2{}_{\alpha\beta0} \begin{bmatrix} v_\alpha & 0 & v_0 & -v_\beta \\ v_\beta & -v_0 & 0 & v_\alpha \\ v_0 & v_\beta & -v_\alpha & 0 \end{bmatrix} \begin{bmatrix} p \\ q_\alpha \\ q_\beta \\ q_0 \end{bmatrix}$$

Where $v^2{}_{\alpha\beta0} = v^2{}_\alpha + v^2{}_\beta + v^2{}_0$

The reference source current in alpha beta frame is given by

$$\begin{bmatrix} i_{s\alpha} \\ i_{s\beta} \\ i_{s0} \end{bmatrix} = 1/v^2{}_{\alpha\beta0} \begin{bmatrix} v_\alpha & 0 & v_0 & -v_\beta \\ v_\beta & -v_0 & 0 & v_\alpha \\ v_0 & v_\beta & -v_\alpha & 0 \end{bmatrix} \begin{bmatrix} p \\ q_\alpha \\ q_\beta \\ q_0 \end{bmatrix}$$

The objective of the p-q theory is to supply only the power needed by the load from the source

P_s (t) = P_{L0} (t) +P_{Lab}(t)

The another condition is that the source power does not deliver any zero sequence current

i.e., $i_{s0re}f = 0$

Now the reference source current is given by

$$\begin{bmatrix} i_{s\alpha ref} \\ i_{s\beta ref} \\ i_{s0ref} \end{bmatrix} = 1/v^2{}_\alpha + v^2{}_\beta \begin{bmatrix} v_\alpha & 0 & v_0 & -v_\beta \\ v_\beta & -v_0 & 0 & v_\alpha \\ 0 & v_\beta & -v_\alpha & 0 \end{bmatrix} \begin{bmatrix} \bar{p}_{L\alpha\beta} + \bar{p}_{L0} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

2.2 DC Link Control Using PI Controller

PI controller is added to maintain the DC link voltage. This PI controller will maintain the active power flowing in the APF and the current controller regulates this current to maintain the DC link voltage. This can be done by controlling the active power flowing into the controller equal to the losses inside the filter. This can be done by comparing the measured dc link voltage and the reference voltage set by the control circuit. The voltage difference is fed to the PI controller and this voltage difference (e) is the required active current needed to maintain the dc link voltage. This current is used as the part of the reference current (I_{sa}*,I_{sb}*,I_{sc}*) to the current controller which controls the inverter to provide the required compensation current as in [10]. This is shown in "Figure 5".

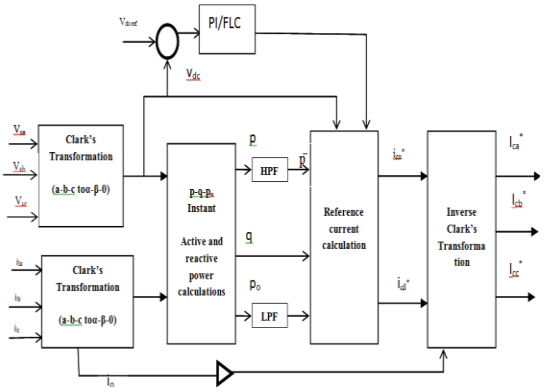

Fig 5: Reference current controller with pq method using PI

2.3 DC Link Control Using FLC

Fuzzy Logic Tools introduced in 1965 is a mathematical tool for predicting uncertainties. The FLC can provide linguistic components like low, high and medium. Fuzzy control system is very useful when the processes to be controlled are complex using the conventional controller. The conventional method of controlling involves more mathematical calculation and the traditional method best suits for crisp events that either occur or not occur. But for the event which includes uncertainties can be eliminated using FLC as it does not need accurate modeling. Fuzzy Logic Tool is based on relative graded membership function. These membership functions possess the degree of membership between the real values [0, 1]. The FLC system comprises mainly of four components the fuzzifier, the rule base, the inference engine and the defuzzifier.

2.3.1 Fuzzification

The process of converting numerical variable to linguistic variable is done in fuzzification. Here seven triangular shaped membership functions are used and their linguistic variables are Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero Error (Z), Positive Small (PS), Positive Medium (PM) and Positive Big (PB).

Each membership function is defined using three vertices {a,b,c} which represents the values corresponding to the left minimum, peak and right minimum of a triangle representing the membership function. This is shown in "Figure 6".

2.3.2 Fuzzy Rule Base

The rule base store the linguistic control rule base need by rule evaluator. Large errors in transient state need coarse control and in small errors need fine control in steady state. Based on these elements, 49 rules of the rule table used in the paper are shown in Table I as in [5].

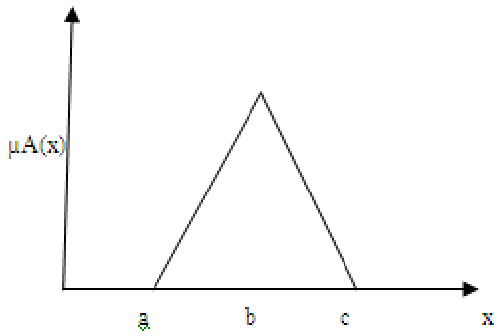

Fig 6: Triangular membership function

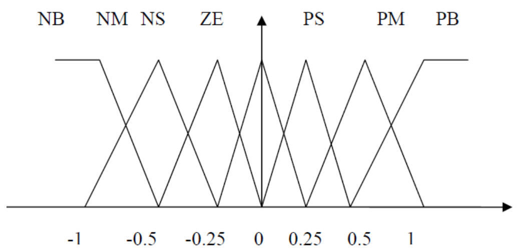

Fig 7: Membership function of fuzzifier input variables e, Δe and defuzzifier output variable $\mu_a(x)$

2.3.3 Inference Engine and Defuzzification

To determine a specific or crisp value, the rule base has to be used with an inference method or engine followed by defuzzification. Mamdani's fuzzy implication and max-min composition rule are used for inference. Centroid method is used for defuzzification.

This fuzzy rule can be design based on experience. Here the error (e) and change in error (Δe) are considered as input to FLC and the output of FLC is the control current $I_{max.}$ This is the required active current needed to maintain the dc link voltage. This current is used as the part of the reference current (I_{sa}*,I_{sb}*,I_{sc}*) to the current controller which controls the inverter to provide the required compensation current.

This estimated reference current (I_{sa}*,I_{sb}*,I_{sc}*) and the actual sensed current (I_{sa},I_{sb},I_{sc}) are compared in the hysteresis current controller and the error signal controls the operation of the converter switches as in [10]. Each switch of the converter is controlled independently.

Table 1 Fuzzy Rule Base

e / Δe	**NS**	**NM**	**NB**	**Z**	**PS**	**PM**	**PB**
NB	**PB**	**PM**	**PS**	**PS**	**PS**	**PS**	**Z**
NM	**PM**	**PS**	**PS**	**PS**	**PS**	**Z**	**NS**
NS	**PS**	**PS**	**PS**	**PS**	**Z**	**NS**	**NS**
Z	**PS**	**PS**	**PS**	**Z**	**NS**	**NS**	**NS**
PS	**PS**	**PS**	**Z**	**NS**	**NS**	**NS**	**NS**
PM	**PS**	**Z**	**NS**	**NS**	**NS**	**NS**	**NM**
PB	**Z**	**NS**	**NS**	**NS**	**NS**	**NM**	**NB**

3. SIMULATION RESULTS

The specification for the simulation is given "Table 2". "Figure 8" and "Figure 9" show the waveform of source voltage, source current, load current and DC link voltage.

Table 2 Simulation Parameters

System parameters	Values
Source voltage (V_s)	325V(peak)
System frequency	50Hz
Source impedance(R_s,L_s)	0.07Ω, 1mH
Filter impedance (R_c,L_c)	0.01Ω,0.1mH
Load impedance (R_L,L_l)	20Ω,20mH
Reference DC link voltage(V_{dcref})	780V
DC link capacitance	2000μF

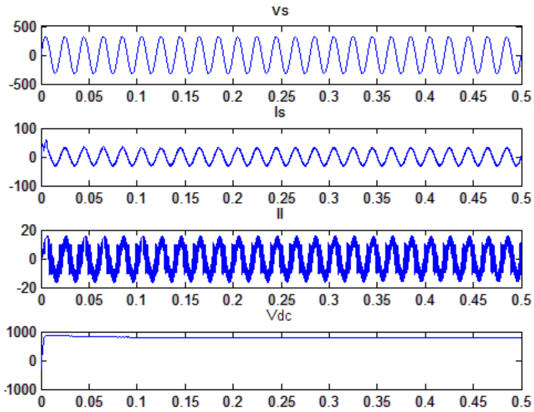

Fig 8: Simulation Waveform using pq with PI

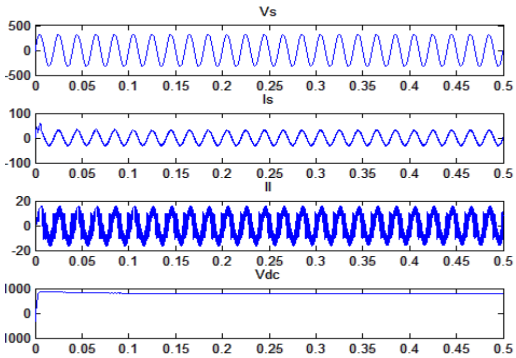

Fig 9: Simulation Waveform using pq with FLC

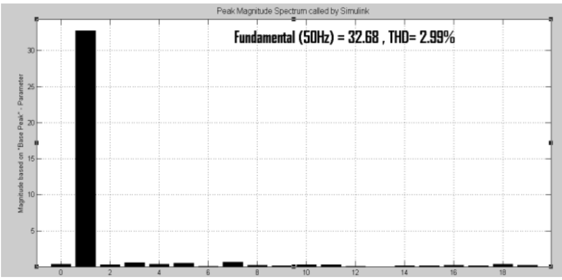

Fig 10: Harmonic Spectrum of Is using PI for balanced source

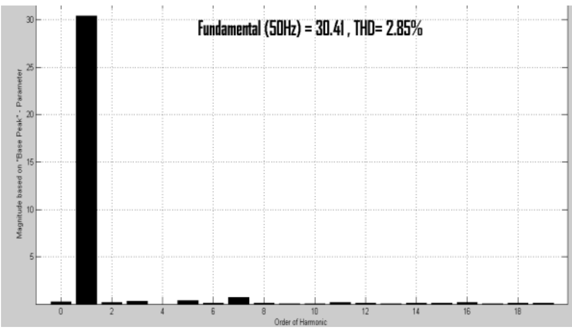

Fig 11: Harmonic Spectrum of Is using FLC for balanced source

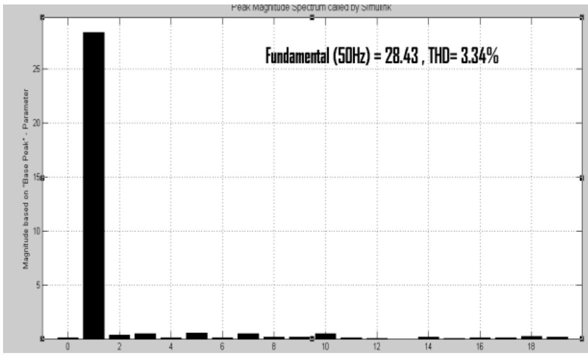

Fig 12: Harmonic Spectrum of Is using PI for unbalanced source

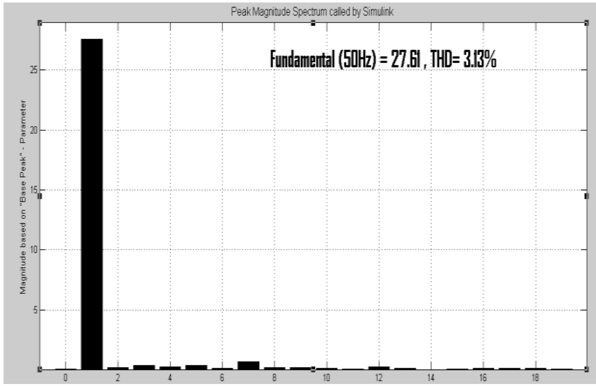

Fig. 13 Harmonic Spectrum of Is using FLC for unbalanced source

4. CONCLUSION

The comparative analysis of a three phase four wire system using SAPF for reducingTHD of source current is done.The analysis uses the control of compensating current using PI controller and FLC is done for both balanced and unbalanced source condition. The harmonic spectrum shows the THD of both balanced and unbalanced source condition using PI and FLC. It is found that the harmonic reduction using FLC is found to produce better result than PI controller.

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