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Adaptive –Fuzzy Logic Power Filter for Nonlinear Systems

Yasser A. Elshrief[1], Galal A. Atlam[2], Belal A. Abozalalm[3]
[1,2,3]*(Industrial Electronics And Automatic Control Engineering, Department, FAE.,Menofiua University, Egypt)*

Abstract: *In this paper, Harmonic distortion, lower efficiency and poor power factor caused by nonlinear loads can be compensated and improved by applying Fuzzy Logic Controller (FLC)(Takagi-Sugeno (TS)-type) to a three-phase Shunt Active Power Filter (SAPF).*
Unlike conventional controllers like Proportional-Integral (PI) controller, discussed in many papers, FLCs cover a wider range of operating conditions and does not require any mathematical model of the system.
This controller is used to generate the desired reference current and maintains the dc-side capacitor voltage of the inverter nearly constant.
Further, in this paper, the hysteresis current control mode of operation is implemented as a pulse width-modulation technique for switching signal generation.
Practical design considerations will be presented using MATLAB/SIMULINK showing that the dynamic behavior of the FLC (TS) is better than the conventional (PI) controller as it has a strong robustness to changes in load and other system parameters.
Keywords*: Active Power Filter, Harmonics, hysteresis control, Power Quality, Takagi-Sugeno Fuzzy control*

I. Introduction

In recent years, the widely usage of electronic equipment produces a lot of harmonics in the power distribution systems because of non-sinusoidal currents consumed by non-linear loads, such as inverters, Switching power supplies, diode-rectifiers, thyristors converters, uninterruptible power supplies and adjustable speed drives, etc.

All of these non-linear loads resulting in a lot of Power Quality (PQ) problems such as harmonic distortion of supply current /voltage, low system efficiency, poor power factor, excessive heating in transformers and equipment failure due to over voltages caused by the resonance between the impedance of the equipment and the whole Transmission system [1, 2].

Earlier To avoid these undesirable effects, passive L-C power filters were used, but it has some drawbacks as the limitations of fixed compensation, large size, resonance with the grid and their inability to adapt to network characteristic variation. So the SAPF based on Voltage Source Inverter (VSI) structure is an attractive solution to harmonic Current problems [3-5]. It is connected in parallel with the non-linear load, injecting specific currents components that cancel the harmonic currents components caused by the nonlinear loads [6].

However, the conventional PI controller was used for obtaining a reference current template. It requires precise linear mathematical models of the system, which are difficult to obtain and fails to perform satisfactorily under parameter Variations, nonlinearity load disturbance.

Recently, (FLCs) have generated a good deal of interest in certain applications [7]. The advantages of FLCs over conventional controllers are that they do not need an accurate mathematical model, they can work with linguistics inputs, can handle linearity, and they are more robust than conventional nonlinear controllers [8].

Two types of fuzzy controllers are reported in practice- Mamdani type and Takagi-Sugeno (TS) type. As stated earlier in [9] to the same case Mamdani type fuzzy controllers used for the control of APF gives better results compared with the PI controller [10], but it has the drawbacks of a larger number of fuzzy sets and rules and thus needs to optimize larger number of coefficients, demands large computation time and may not be useful for real time application with small sampling time. On the other side, superiority of TS fuzzy controllers lies in smaller number of fuzzy sets and rules set and hence reduction in computation time.

The performance of APF depends mainly on harmonic detection and current control method used to inject the desired compensation current into the line [10, 11]. Two main approaches are used for reference compensating current estimation: Frequency domain using Fast Fourier Transformation or Time domain with its different techniques. Time domain method (Instantaneous Reactive-power theory) for APF harmonic current references generation will be used because they require less calculation .There are many techniques which are used to generate pulses for APF switches, and we use the Hysteresis band control [12] because of its simplicity of Implementation, fast transient response, suitable stability and high accuracy.

In this paper, the two ways discussed to maintain a DC voltage across the Capacitor of the dc link fixed, are classical PI Controller and Fuzzy logic controller.

At the end of the paper, a comparison between the performance of PI controller and fuzzy controller is performed.

II. Instantaneous Reactive-Power Theorem (IRPT) Or (P-Q Theory) For Compensation Reference Current Estimation:

Through this method, the compensation reference current is generated from the instantaneous active and reactive power of the non-linear load, which consists of a DC component and an AC component. With the help of HPF, the AC component of the instantaneous active power is extracted. Finally taking inverse transformation to obtain the compensation reference signals as shown in fig.1

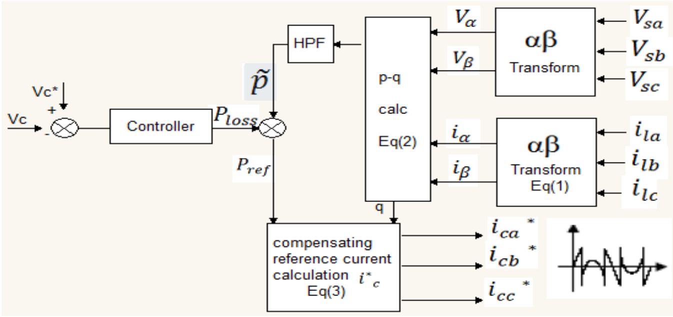


Fig (1) Block diagram of APF based on (p-q) theory

Based on algebraic transformation (Clarke transformation) the p-q theory first transformed three phase voltage and current waveforms from the a-b-c coordinates to α-β-coordinates and then defines instantaneous active and reactive power on these coordinates.

$$\begin{bmatrix} v\alpha \\ v\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} i_{L\alpha} \\ i_{L\beta} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \qquad (2)$$

Using eq (1), (2) to calculate The instantaneous active and reactive powers p and q

$$\begin{bmatrix} p = \overline{p} + \tilde{p} \\ q = \overline{q} + \tilde{q} \end{bmatrix} = \begin{bmatrix} v\alpha & v\beta \\ -v\beta & v\alpha \end{bmatrix} \begin{bmatrix} i\alpha \\ i\beta \end{bmatrix} \qquad (3)$$

The compensating reference currents are calculated by taking the inverse of Eq. (3) after the process of filtering of the instantaneous active power (p) by H.P.F to pass only the AC components

$$\begin{bmatrix} i^*c\alpha \\ i^*c\beta \end{bmatrix} = \frac{1}{v^2{}_\alpha + v^2{}_\beta} \begin{bmatrix} v\alpha & -v\beta \\ v\beta & v\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} + p_{loss} \\ q \end{bmatrix} \qquad (4)$$

Taking inverse transformation for eq (4)

$$\begin{bmatrix} i^*ca \\ i^*cb \\ i^*cc \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i^*c\alpha \\ i^*c\beta \end{bmatrix} \qquad (5)$$

III. Proposed Fuzzy Control Scheme

FLCs are an excellent choice when precise mathematical formula calculations are impossible.
In order to implement the control algorithm of a SAPF in a closed loop, the dc capacitor voltage(V_{dc}) is sensed and then compared with the reference value(V_{dcref}) .In case of a fuzzy logic control scheme, the error ($e = V_{dcref} - V_{dc}$) and integration of error signal $\int e$ are used as inputs for fuzzy processing.
The output of the FLC limits the magnitude of peak reference current I_{max} .This current takes care of the active power demand of the non-linear load and losses in the distribution system.
The schematic diagram of the fuzzy control scheme is shown in fig.2

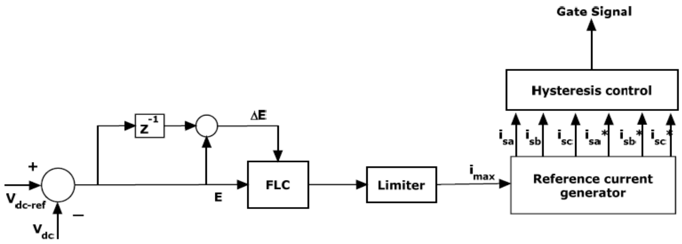


Fig (2) Fuzzy Based Hysteresis Current Controlled (SAPF)

IV. Design Of Ts Fuzzy Control Algorithm

A fuzzy controller consists of stages: fuzzification, knowledge base, interference mechanisms and defuzzification as shown in fig.3

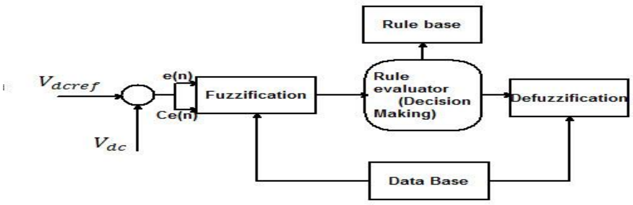


Fig (3) Fuzzy Logic Controller

1) Fuzzification:

Fuzzy logic uses linguistic variables instead of numerical variables. In a control system, In this case the inputs are fuzzified with two fuzzy sets P(positive) and N(negative).The process of fuzzification converts numerical variable (real number) to a linguistic variable (fuzzy number).

For the positive set, the membership function for input $Y_{1\&}Y_2$ is respectively given by:

$$\mu_P(y_i) = \begin{cases} 0 & y_i < -L \\ \frac{y_i + L}{2L} & -L \le y_i \le L \\ 1 & y_i > L \end{cases} \qquad (6)$$

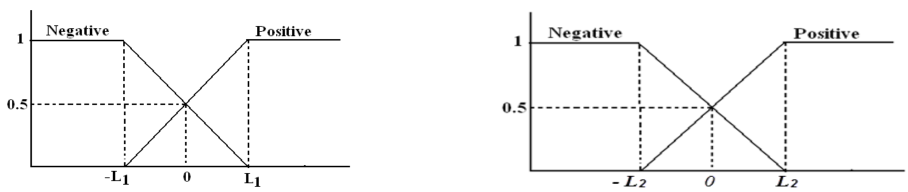
On the other hand, the membership function of the negative set for input $Y_{1\&}Y_2$is respectively given by:

$$\mu_N(y_i) = \begin{cases} 1 & y_i < -L \\ \frac{-y_i + L}{2L} & -L \le y_i \le L \\ 0 & y_i > L \end{cases} \qquad (7)$$

Where $y_i = [y_1, y_2]$

Y_1 (k) =e (k) =V_{dcref} -V_{dc} , Y_2 (k) =∑e (k)

Fig.4 (a, b) shows the membership function for positive and negative sets for input $y_{1\,\&}y_2$ respectively



(a) **(B)**

Fig (4) Membership function for Y_1 and Y2 respectively

2) Design of control rules:

TS fuzzy controller uses the four simplified rule as:

R1: If y_1 (k) is P and y_2 (k) is P then u_1 (k) =a_1.y_1 (k) +a_2 .y_2 (k)

R2: If y_1 (k) is P and y_2 (k) is N then u_2 (k) =u_1 (k)

R3: If y_1 (k) is N and y_2 (k) is P then u_3 (k) =K_3u_1 (k)

R4: If y_1 (k) is N and y_2 (k) is N then u_4 (k) =K_4u_1 (k)

Where u_1, u_2, u_3, u_4 represent the consequent of the TS fuzzy controller.

3) Defuzzification:

Using Zadeh's rule for AND operation and the general defuzzifier, the output of the TS fuzzy controller is:

$$U(k) = \frac{\sum_{J=1}^{4}(\mu_J)^{\gamma} U_j(K)}{\sum_{J=1}^{4}(\mu_j)^{\gamma}} \qquad (8)$$

However, for γ=1, we get the centroid defuzzifier with u (k) given by:

$$U(k) = a\ y_1(K) + b\ y_2(K) \qquad (9)$$

Where $a = a_1K$& b=a_2K

And $k = \frac{\mu_1+k_2\mu_2+k_3\mu_3+k_4\mu_4}{(\mu_1+\mu_2+\mu_3+\mu_4)}$ (10)

As **K** is the operating condition dependent on the effective value of control gain varies widely during the control process.

V. Adaptive Hysteresis Current Control (AHCC)

Hysteresis current control with variable band can be implemented to generate the switching pattern for APF.

AHCC is the method that builds variable hysteresis bandwidth which is calculated instantaneously, hence the switching speed becomes smooth and the frequency switching will be fixed considerably.
The adaptive Hysteresis Band(HB) should be derived instantaneously using eq (11) during each sample time to keep the Switching frequency constant

$$HB = \left\{\frac{0.125\ V_{dc}}{F_c L}\left[1 - \frac{4L^2}{V_{dc}^2}\left(\frac{V_s}{L} + \frac{di_c^*}{dt}\right)^2\right]\right\} \qquad (11)$$

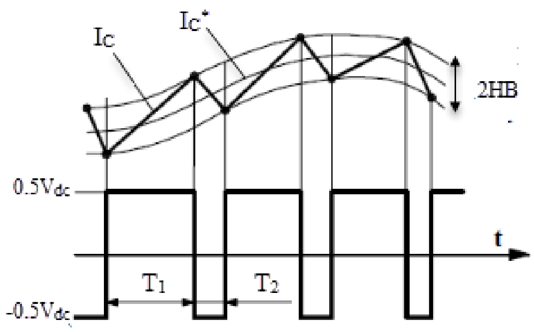


Fig (5)adaptive hysteresis current controller

VI. Simulation And Results

To examine the performance of the proposed APF, 3phase, 3wire system is considered. The parameters used for the simulation are:

System parameters	Values
Source voltage (V_s)	220V (rms)
System frequency (f)	50 HZ
Source impedance (R_s; L_s)	0.5 mΩ ; 15 μH
Filter impedance (R_c; L_c)	1.5 mΩ ; 1200 μH
Load impedance (R_l; L_l)	1.2 mΩ ; 50 μH
Reference Dc Link Voltage (V_{dcref})	700 V

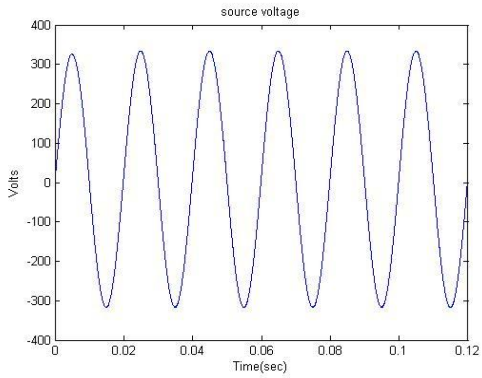


Fig (6)AC source voltage (for phase a)

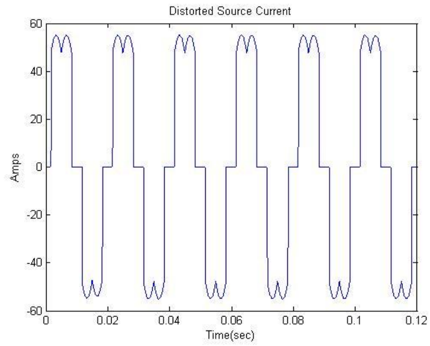


Fig (7)Distorted source current (for phase a)

a) Under action of APF &PI controller:

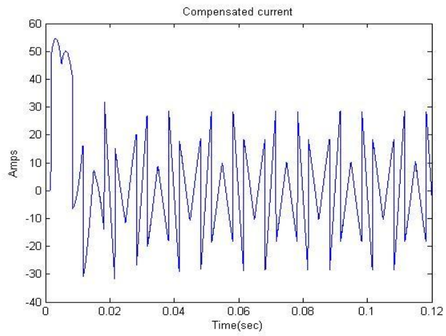


Fig (8) Compensating current *(for phase a)*

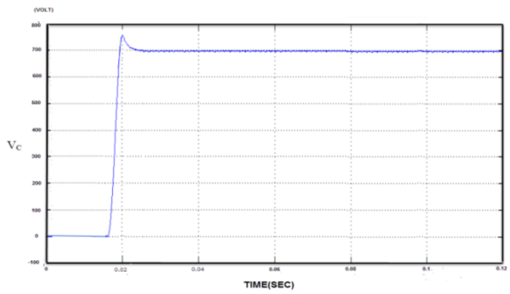


Fig (9) DC bus Voltage

The line current and its spectrum after compensation using active power filter with PI controller are represented in Figure (10) and figure (11)

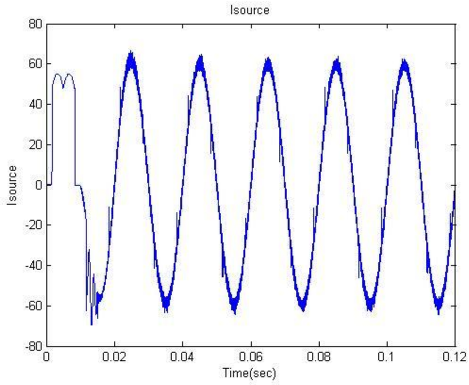


Fig (10) Source current after compensation (for phase a)

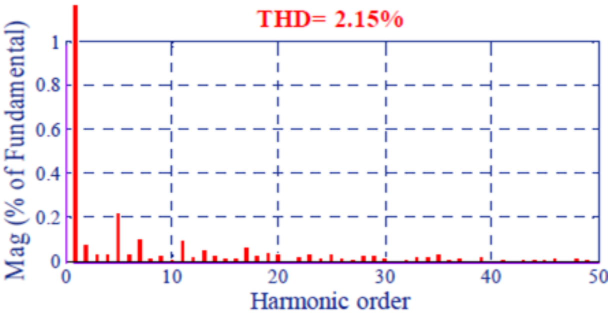


Fig (11)Harmonic Spectrum of Source Currents

B) Under action of APF & TS-fuzzy controller

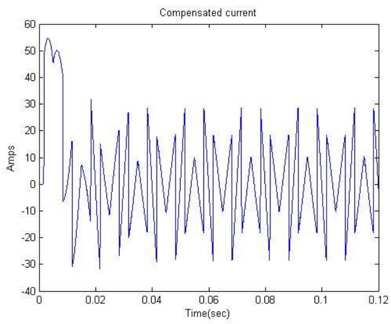


Fig (12)Compensating current *ic(for phase a)*

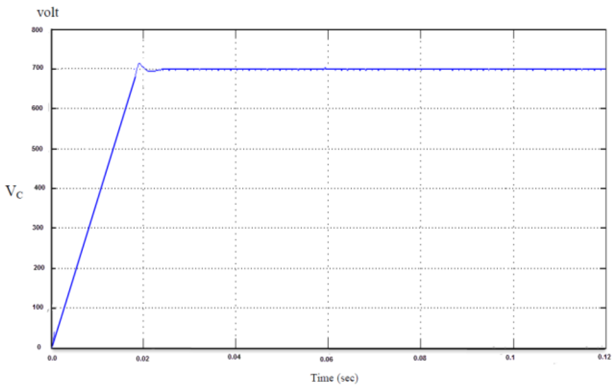


Fig (13) DC bus Voltage

The line current and its spectrum after compensation using active power filter with TS fuzzy controller are represented in Figure (14) and figure (15)

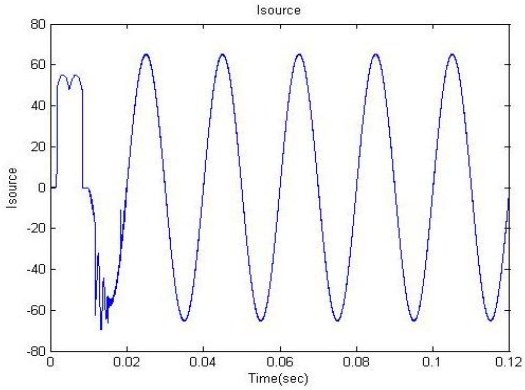


Fig (14) Source current after compensation

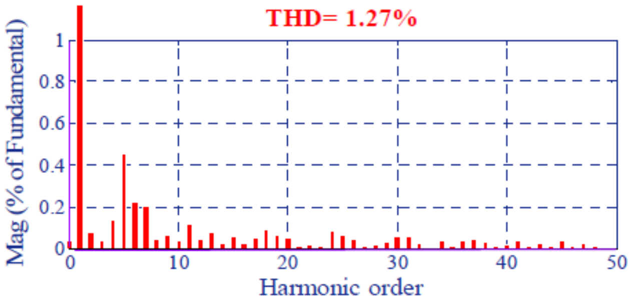


Fig (15) Harmonic Spectrum of Source Currents

VII. Conclusion

In this paper, A TS fuzzy controller is applied to balanced three phase system. by comparing the performance of TS&PI controllers. By visualizing all Figures of current source, we can conclude a successful operation of harmonics compensation using the proposed shunt active power filter based on TS Fuzzy controller. it is noticed the TS Fuzzy Logic controller shows some dynamic performance over Conventional PI controller, and The performances of the proposed shunt active filter based on Fuzzy current controller in terms of harmonics elimination is better than PI controller, in addition, fast dc link voltage response over conventional PI controller,

The total harmonic distortion (THD) values of the supply current with the proposed controllers well below 5% [13] that respect IEEE standard Norms (THD ≤5%).

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