

FUZZY LOGIC CONTROLLER BASED ACTIVE POWER LINE CONDITIONERS FOR COMPENSATING REACTIVE POWER AND HARMONICS

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Abstract

This article explores a novel fuzzy logic controller (FLC) based three-phase shunt active power line conditioners (APLC) for power quality improvements due to the non-linear loads. The fuzzy logic controller is Mamdani-type and linguistic description, so it does not necessitate a mathematical model of the system. The FLC controller is capable of controlling harmonic current and dc-side capacitor voltage of the inverter to improve the performance of the active power filter. Hysteresis current controller (HCC) is used to generate the switching signals from the comparison of reference current and actual current for driving the current controlled voltage source inverter (VSI). Extensive simulation executed and tested under different non-linear load conditions. The simulation results reveal that the APLC with fuzzy logic controller is a perfect candidate for current harmonics and reactive power compensation.

Keywords:

Active Power Line Conditioners (APLC), Power Quality, Fuzzy Logic Controller (FLC), Hysteresis Current Controller (HCC)

1. INTRODUCTION

Distribution power system feeds different variety of linear and non-linear loads. The non-linear loads produce current harmonic and reactive power problems in the utility system network [1-2]. The harmonics and reactive power are primary concern for poor power factor and these loads distort the power supply at the point of common coupling (PCC). This distortion is mainly due to the line impedance or the transformer leakage inductance. Traditionally Passive filters are used to compensate the power factor and harmonic currents, but there are definite drawbacks such as resonance, large size, weight and limited compensation. So the alternative solution is an active power line conditioners (APLC) or active power filter (APF) that provides an efficient solution for reactive power and current harmonics suppression produced by the non-linear loads [3-5].

The controller plays a significant role in the functioning of the active power line conditioners and recently lot of research is being explored. Conventional PI and PID controllers have been used to extract the fundamental component of the load current thus facilitating reduction of harmonics; in addition it also controls the dc capacitor voltage on the dc side of the PWM-inverter of the shunt APF [6-7]. However, the conventional PI and PID controller requires exact linear mathematical calculation of the system, which is difficult to obtain under parameter variations, nonlinearity and load disturbances. Another drawback of this system is that the proportional, integral and derivative gains are to be selected heuristically. Recently, fuzzy logic controllers (FLC) are used in power electronic systems, variable speed motor drives and power quality applications. The advantages of fuzzy logic controller over the conventional controllers are: it does not require accurate numerical

calculation; it can work with imprecise inputs; it can handle nonlinearity, and it is more robust than conventional nonlinear controllers [1-5].

This paper describes the possibility and feasibility of fuzzy logic control schemes for harmonic current reduction and reactive power mitigation by shunt APLC. The FLC controller is capable of maintaining dc side capacitor voltage (of the inverter) nearly constant which in turn helps to improve the power quality. The performance of fuzzy logic controller is evaluated through computer simulation under different non-linear load conditions. The results clearly indicate that the proposed active power filter with fuzzy logic controller is capable of providing sinusoidal source current(s) with low harmonic distortion and the current is in phase with the line voltage that amend the power factor correction.

2. DESIGN OF APLC SYSTEM

Active power filter comprises six IGBTs along with freewheeling diodes, a dc capacitor, and RL-filter. The choice of capacitor is governed by the amount of ripple that can be allowed on the dc side capacitor without affecting the performance. The RC-filter facilitates suppressing the higher order harmonic currents caused by the switching function of the power transistor devices. Reduction of current harmonics is achieved by injecting equal but opposite current harmonic components at the point of common coupling, there by canceling the original distortion and improving the power quality. The block diagram of the proposed APLC is shown in Fig.1. The APLC consists of a gating signal generator, current reference generator and dc voltage controller that are implemented using fuzzy logic controller. The three phase distribution grid connected to the non-linear load; here the instantaneous source current is measured and given as

$$i_s(t) = i_L(t) - i_c(t) \quad (1)$$

From the equation (1), the harmonic or filter current can be obtained by subtracting the fundamental component currents from the load currents. The instantaneous supply voltage can be written as

$$v_s(t) = V_m \sin \omega t \quad (2)$$

The non-linear load current contains the fundamental current component and higher order harmonic components, which can be represented as

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \Phi_n) \quad (3)$$
$$= I_1 \sin(\omega t + \Phi_1) + \left(\sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \right)$$

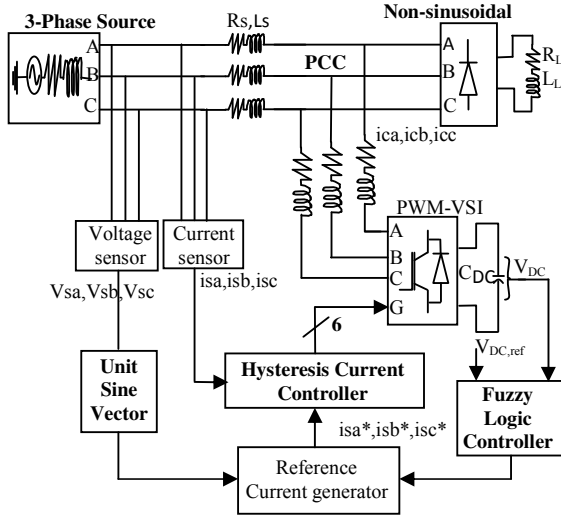


Fig. 1. Shunt APLC implemented with PWM-VSI in the distribution ac network

The instantaneous load power can be multiplied from the source voltage and current and the calculation is given as

$$\begin{aligned}
 p_L(t) &= i_s(t) * v_s(t) \\
 &= V_m \sin^2 \omega t * \cos \phi_1 + V_m I_1 \sin \omega t * \cos \omega t * \sin \phi_1 \\
 &\quad + V_m \sin \omega t * \left(\sum_{n=2}^{\infty} I_n \sin(n\omega t + \Phi_n) \right) \\
 &= p_f(t) + p_r(t) + p_h(t)
 \end{aligned} \quad (4)$$

This load power contains fundamental or real power, reactive power and harmonics power. From this equation only the active (fundamental) power drawn by the load is

$$p_f(t) = V_m I_1 \sin^2 \omega t * \cos \phi_1 = v_s(t) * i_s(t) \quad (5)$$

From this equation, the source current drawn from the mains after compensation should be sinusoidal; this is represented as

$$i_s(t) = p_f(t) / v_s(t) = I_1 \cos \phi_1 \sin \omega t = I_{sm} \sin \omega t \quad (6)$$

where,

$$I_{sm} = I_1 \cos \phi_1 \quad (7)$$

The total peak current supplied by the source is

$$I_{sp} = I_{sm} + I_{sl} \quad (8)$$

If the active power filter provides the total reactive and harmonic power, $i_s(t)$ will be in phase with the utility voltage and would be sinusoidal. At this time, the active filter must provide the compensation current:

$$i_c(t) = i_L(t) - i_s(t) \quad (9)$$

Therefore, the APLC extracts the fundamental component of the load current; that can be used for compensating the harmonic current and reactive power simultaneously. The desired source currents, after compensation, can be written as

$$i_{sa}^* = I_{sp} \sin \omega t \quad (10)$$

$$i_{sb}^* = I_{sp} \sin(\omega t - 120^\circ) \quad (11)$$

$$i_{sc}^* = I_{sp} \sin(\omega t + 120^\circ) \quad (12)$$

Where $I_{sp} = I_{sm} + I_{sl}$ is the amplitude of the desired source current, while the phase angle can be obtained from the source voltages [3]. This peak value of the reference current I_{max} has been estimated by regulating the DC side capacitor voltage of the voltage source inverter using fuzzy logic controller.

3. PROPOSED CONTROL SCHEME

The proposed control system consists of reference current generator using unit sine vector technique with fuzzy logic controller and pulse width modulation voltage source inverter switching signals are derived from hysteresis band current modulator.

3.1 FUZZY LOGIC CONTROL

Fuzzy logic control is derived from fuzzy set theory introduced by Zadeh in 1965. In fuzzy logic concept, the transition is derived between membership and non-membership functions. Therefore, boundaries of fuzzy sets can be undefined and ambiguous, making it useful for approximate systems. FLC's are an attractive choice when precise mathematical formulations are impossible to utilize. Fig.1 shows the active power filter compensation system with fuzzy logic control scheme. In order to implement the control algorithm of shunt active power line conditioners in a closed loop, the dc capacitor voltage V_{DC} is sensed and then compared with the reference value $V_{DC,ref}$. In case of a fuzzy logic control scheme, the error signal ($e = V_{DC,ref} - V_{DC}$) allows only the fundamental components using Butterworth 50 Hz low pass filter (LPF) and integration of error signal ($\int e$) are used as inputs for fuzzy processing shown in Fig.2. The output of the fuzzy controller after a limit is considered as 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 switching signals for the PWM inverter are obtained by comparing the actual source currents (i_{sa}, i_{sb}, i_{sc}) with the reference current templates ($i_{sa}^*, i_{sb}^*, i_{sc}^*$) using the hysteresis band current controller.

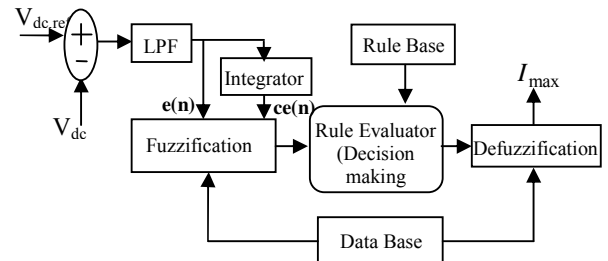


Fig. 2. Block diagram of Fuzzy logic controller

The proposed fuzzy logic controller characteristics are; (1) Seven fuzzy sets for each input and output variables. (2)Triangular membership function is used for simplicity (3) Implication using mamdani-type min operator (4) Defuzzification using the height method.

The non-linear load current contains the fundamental current component and higher order harmonic components, which can be represented as

Fuzzification:

Fuzzy logic uses linguistic variables instead of numerical variables. In a control system, error between reference signal and output can be labeled as negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), positive big (PB). The processes of fuzzification is numerical variable (real number) convert to a linguistic variable (fuzzy number), shown in Fig.3.

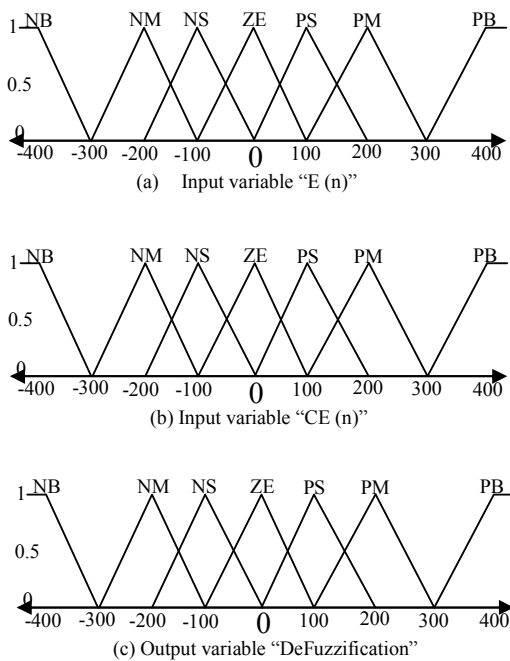


Fig.3. FLC membership functions (a) the input variables error e(n) (b) change of error ce (n) and (c) output variable defuzzification

Rule Elevator:

In conventional PI and PID controllers, we have control gains or control laws which are combination of numerical values. In FLC, the equivalent term is rules and they are linguistic in nature. A typical rule can be written as follows;

$$R_k : \text{If } e(n) \text{ is } A_i \text{ and } ce(n) \text{ is } B_i \text{ then output is } C_i$$

Where A_i, B_i, C_i are the labels of linguistic variables of error $e(n)$, change of error $ce(n)$ and output respectively. Here $e(n), ce(n)$ and the output represents degree of membership. The basic fuzzy set operations needed for evaluation of rules are $AND(\cap), OR(\cup)$ and $NOT(-)$

$$AND \text{-Intersection: } \mu_{A \cap B} = \min[\mu_A(X), \mu_B(x)]$$

$$OR \text{-Union: } \mu_{A \cup B} = \max[\mu_A(X), \mu_B(x)]$$

$$NOT \text{-Complement: } \mu_A = 1 - \mu_A(x)$$

Defuzzification:

The rules of fuzzy logic generate demanded output in a linguistic variable, according to real world requirements, linguistic variables have to be transformed to crisp output (Real number). The choices available for defuzzification are numerous. So far the choice of strategy is a compromise between accuracy and computational intensity.

Database:

The Database stores the definition of the membership function involved by fuzzifier and defuzzifier. Storage arrangement is a compromise between available memory and microprocessor stages of the digital controller chip.

Rule Base:

The Rule base stores the linguistic control rules required by rule evaluator (decision making logic). The rules used in this paper are shown in table 1.

Table.1 Rule base table

ce(n) \ e(n)	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

3.2 UNIT SINE VECTOR

The source voltages are converted to the unit sine current(s) while corresponding phase angles are maintained. The unit current is defined as

$$i_a = \sin \omega t, i_b = \sin(\omega t - 120^\circ) \text{ and } i_c = \sin(\omega t + 120^\circ)$$

The amplitude of the sine current is unit or 1 volt and frequency is in phase with the source voltages. This unit current multiplies with peak value of fuzzy logic control output for generate the desired reference current.

3.3 HYSTERESIS BAND CURRENT CONTROL

Hysteresis current control is the softest control method to implement [5-6]. An error signal $e(t)$ is used to control the switches in an inverter. This error is the difference between the desired current $i_{ref}(t)$ and the actual current $i_{actual}(t)$.

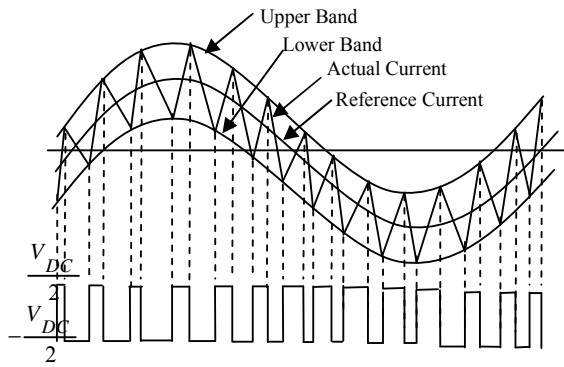


Fig.4. Hysteresis current control

If the error current crosses the upper limit of the hysteresis band ($h=0.5$), the upper switch of the inverter leg is turned OFF and the lower switch is turned ON, shown in Fig.4. As a result, the current starts to decrease. If the error current exceeds the lower limit of the hysteresis band ($h=-0.5$), the lower switch of the inverter leg is turned OFF and the upper switch is turned ON. As a result, the current gets back into the hysteresis band. The range of the error signal $e(t)$ directly controls the amount of ripple in the output current from the inverter. The PWM-voltage source inverter provides compensating harmonic current at the point of common coupling to eliminate the harmonic content.

4. SIMULATION RESULT AND ANALYSIS

The performance of the proposed fuzzy logic control strategy is evaluated through digital simulation using SIMULINK toolbox in the MATLAB. This software is used in order to model and test the system under non-linear load conditions. The system parameters values are;

- Line to line source voltage is 440 V,
- System frequency (f) is 50 Hz,
- Source impedance of R_s, L_s is $1 \Omega; 0.1 \text{ mH}$,
- Filter impedance of R_c, L_c is $1 \Omega; 1 \text{ mH}$ respectively,
- Diode rectifier R_L, L_L load: $20 \Omega; 200 \text{ mH}$ respectively,
- DC side capacitance (C_{DC}) is $1300 \mu\text{F}$
- Reference voltage ($V_{DC,ref}$) is 400 V
- Power devices used are IGBTs with anti parallel diodes.

Fuzzy logic controlled APLC system comprises of a three-phase source with six pulse diode rectifier non-linear load and a voltage source inverter with an inductive filter. The simulation time is counted from $T=0$ to $T=0.1s$. The source current after compensation is presented in Fig.5 (a) that indicates the source current becomes sinusoidal. The non-linear load current is shown in Fig.5 (b). The each phase is shifted by 120° and we have considered a balanced load. The actual reference currents derived from fuzzy logic controlled value multiply with unit sine vector current, shown in Fig.5(c). The APLC supplies the compensating current that is shown in Fig.5(d). The current after compensation is as shown in (a) which would have taken a shape as shown in (b) without APLC. It is clearly visible that this waveform is sinusoidal with some high frequency ripples.

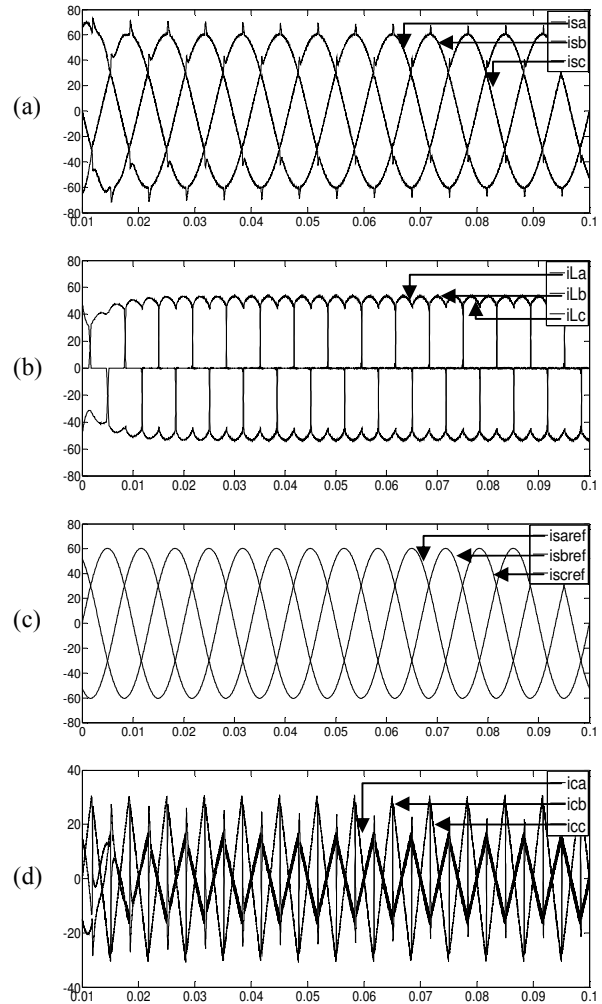


Fig.5.Simulation results for three-phase active-power-line conditioners under non-linear load condition (a) Source current after APLC compensation, (b) Non-linear load current or source current before APLC (c) reference current and (d) Compensation current by APLC.

The proposed fuzzy logic controller achieves power factor correction as shown in Fig.6, represents a-phase voltage and a-phase current are in phase.

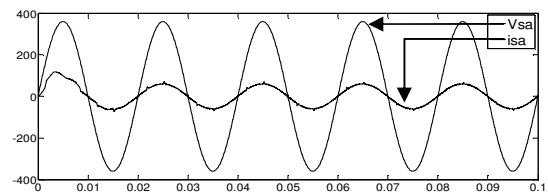


Fig.6. Simulation results for unit power factor

The dc side capacitance voltage (C_{dc}) and its settling time are controlled by fuzzy logic controller (FLC). This controller reduces the ripple voltage to certain level and makes settling time to a low value in the non-linear load condition ($t= 0.123s$) and it is plotted in Fig.7.

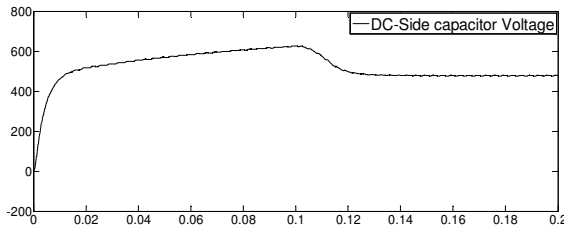


Fig.7. The DC side capacitor voltage settling time controlled by fuzzy logic controller (t= 0.123s)

The Fourier analysis of the fundamental frequency with order of harmonics is plotted in Fig.8 for source current. The Fourier can be calculating the magnitude and the harmonic component of the signal f (t) is given as,

$$f(t) = \frac{a_0}{2} + \sum_{n=1,2,3,..}^{\infty} a_n \cos(n\omega t) + b_n \sin(n\omega t) \quad (13)$$

Where n represents the order of the harmonics, this order of the harmonics plotted under non-linear load condition using fuzzy logic controller based shunt APLC system.

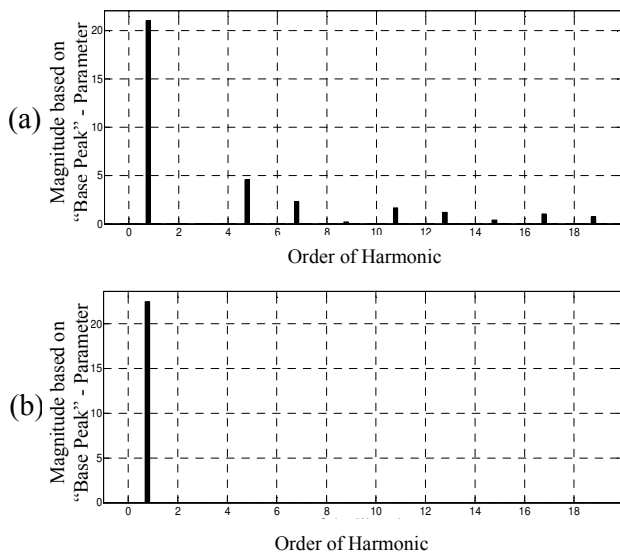


Fig.8. Order of harmonics under the non-linear load condition, (a) the source current without APLC (THD=26.94%), (b) with APLC (THD=2.27%)

Total Harmonic distortion (THD) of the source current measured and verified without APF and with APF using fuzzy logic controller algorithm, see in Table 2.

Table.2 Comparison of without/with active power filter in non-linear load condition

Measurement	Without APLC	With APLC
THD	26.94%	2.27%
Power factor	0.913	0.999

The proposed controller based compensator filter made balance responsibility in the non-linear load conditions. FFT

analysis of the active power line conditioners brings the THD of the source current less than 5 % into compliance with IEEE-519 standards harmonic limits.

5. CONCLUSION

A novel fuzzy logic controller has been implemented for three phase shunt active power filter to control the dc-link capacitor voltage and estimate the peak value of desired reference current. This facilitates to improve the power quality parameters such as current harmonics and reactive power due to non-linear loads. The FLC output of peak current multiplied with unit sine vector currents generates reference currents. Hysteresis current controller is used for generating switching signals of the voltage source inverter. The performance of a fuzzy logic controlled shunt active power is verified under various non-linear load conditions. The obtained results indicate that DC capacitor voltage and the harmonic current control can be adapted easily. The THD of the source current after compensation is 2.27% which is less than 5%; the harmonic limit imposed by the IEEE-519 and IEC 61000-3 standards. The fuzzy logic controller is a good candidate for controlling APLC to solve power quality problems. This proposed fuzzy logic control algorithm based APLC system can be implemented using field programmable gate array (FPGA) devices that would be attempted as a future work.

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