Fuzzy Logic Control based Three Phase Shunt Active Filter for Voltage Regulation and Harmonic Reduction

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ABSTRACT
This paper studies a Fuzzy Logic Control Based (FLCB) Shunt Active Filter (SAF) capable of reducing the total harmonics distortion (THD) in Power System (PS). SAF is one of the key controllers in Flexible Alternating Current Transmission System (FACTS) to control the transmission line voltage and can be used in PS to enhance the power transmission capacity and extend the transient stability. In order to improve the power factor, compensate the reactive power and suppress the total harmonic distortion (THD) drawn from a Non-Linear Diode Rectifier Load (NLDRL) of SAF, we propose a Hysteresis Current Pulse Width Modulation (HCPWM) technique which is used as control for the switches of the Voltage Source Inverter (VSI) or SAF. The synchronous reference D-Q frame theory is used to generate the reference compensating currents for SAF. A fuzzy logic based control is developed to regulate the voltage of the DC capacitor. The system with control scheme is implemented in Matlab/Simulink. The simulation results show the effectiveness of the proposed method for harmonic damping and voltage regulation.

KEYWORDS
Power systems, Shunt active filter, Fuzzy logic based control, Voltage regulation, Hysteresis current pulse width modulation, D-Q reference frame theory.

1. INTRODUCTION
Harmonic distortion (HD) is one of the main power quality problems frequently encountered by the utilities. The harmonic problems in the power supply are caused by the non-linear characteristics based loads. The presence of harmonics leads to transformer heating, electromagnetic interference and solid state device malfunctioning. Hence, it is necessary to reduce the dominant harmonics below 5% as specified in IEEE 519-1992 harmonic standard [1].

Harmonic amplification is one of the most serious problems. It is caused by harmonic resonance between line inductance and power factor correction (PFC) capacitors installed by consumers. Active filters for damping out harmonic resonance in industrial and utility power distribution systems have been researched [1]-[5].

Tradionally based, passive L-C filters were used to eliminate line harmonics in [2]-[4]. However, the passive filters have the demerits of fixed compensation, bulkiness and occurrence of resonance with other elements. The recent advances in power semiconductor devices have resulted in the development of Active Power Filters (APF) for harmonic suppression. Various topologies of active filters have been proposed for harmonic mitigation. The shunt APF based on Voltage Source Inverter (VSI) structure is an attractive solution to harmonic current problems. The SAF is a pulse width modulated (PWM) VSI that is connected in parallel with the load. It has the capability to inject harmonic current into the AC system with the same amplitude but opposite phase than that of the load [1]-[2]. The principal components of the APF are the VSI, a DC energy storage device that in this case is capacitor, a coupling transformer and the associated control circuits. The performance of an active filter depends mainly on the technique used to compute the reference current and the control method used to inject the desired compensation current into the line.

There are two major approaches that have emerged for the harmonic detection [2], namely, time domain and the frequency domain methods. The frequency domain methods include, Discrete Fourier Transform (DFT), Fast Fourier Transform (FFT), and Recursive Discrete Fourier Transform (RDFT) based methods. The frequency domain methods require large memory, computation power and the results provided during the transient condition may be imprecise [4]. On the other hand, the time domain methods require less calculation and are widely followed for computing the reference current. The two mostly used time domain methods are synchronous reference (d-q-0) theory and instantaneous real-reactive power (p-q) theory. Synchronous reference (d-q-0) theory is followed in this work.

There are several current control strategies proposed in the literature [5]-[7], [9]-[10], namely, PI control, Average Current Mode Control (ACMC), Sliding Mode Control (SMC) and hysteresis control. Among the various current control techniques, hysteresis control is the most popular one for active power filter applications. Hysteresis current control [6] is a method of controlling a voltage source inverter so that the output current is generated which follows a reference current waveform in this paper.

Generally, PI controller [7] is used to control the DC bus voltage of SAF. The PI controller based approach requires precise linear mathematical model which is difficult to obtain. Also, it fails to perform satisfactorily under parameter variations, non-linearity, and load disturbances. This paper proposes a fuzzy logic controller for D.C bus voltage control [8]. Computer simulations are carried out on a sample power system to demonstrate the effectiveness of the proposed approach in suppressing the harmonics.

2. CONTROL METHOD FOR SAF

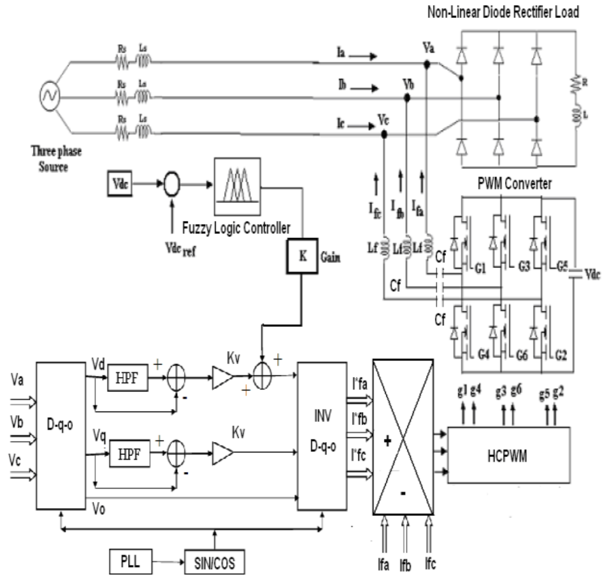

Fig. 1 Active Power Filter with the proposed control technique.

The performance of the active filter mainly depends on the methodology adopted to generate the reference current and the control strategy adopted to generate the gate pulses. The block diagram representation of the proposed control technique for the SAF is shown in Fig.1. The control strategy is implemented in three stages. In the first stage, the essential voltage signals are measured to gather accurate system information. In the second stage, compensating currents are derived based on synchronous reference D-Q theory. In the third stage, the gating signals for the solid-state devices are generated using HCPWM control method.

There are several methods to extract the harmonic components from the detected three-phase waveforms. Among them, the so-called D-Q theory based on time domain has been widely applied to the harmonic extraction circuit of SAF. The detected three-phase voltage is transformed into the D- Q-0 co-ordinates as shown in Fig.1. Two first order digital high pass filters (HPFs) with the same cut off frequency as 20 Hz extract the dc component V_{hd}^*, V_{hq}^* and V_0 which corresponds to the fundamental frequency in the coordinates [7].

In line – voltage regulation part is performed by a feedback control. Two co–ordinates V_d and V_q is compared with harmonic extracted voltage V_{hd}^* and V_{hq}^*. A gain K_V amplifies and to produce current references for harmonic damping I_{hd}, I_{hq}, and I_0 as shown in equation (1), equation (2) and equation (3). The current reference for the voltage – source inverter is the sum of the current references from the three parts, as follows:

$$I^*_{fd}(s) = K_v (G_h V_{hd}^* - V_d) + \text{Preg or } (V_{dc}* - V_{dc})*K \qquad (1)$$

$$I^*_{fq}(s) = K_v (G_h V_{hq}^* - V_q) \qquad (2)$$

$$I^*_0(s) = 1/3\,(V_a + V_b + V_c) \qquad (3)$$

The obtained current reference is converted in to three phase current reference by inverse D – Q transformation I^*_{fa}, I^*_{fb}, and I^*_{fc}. The three phase reference filter current is compared with the active filter compensating current extracted from ac system. Thus three phase filter currents I_{fa}, I_{fb}, and I_{fc} are produced. The obtained reference current is given to a HCPWM scheme, which is used to generate controlled gate signal for SAF.

HCPWM controller derives the switching signals of the inverter power switches in a manner that reduces the current error. The switches are controlled asynchronously to ramp the current through the inductor up and down so that it follows the reference. The current ramping up and down between two limits is illustrated in Fig.2. When the current through the inductor exceeds the upper hysteresis limit a negative voltage is applied by the inverter to the inductor. This causes the current in the inductor to decrease. Once the current reaches the lower hysteresis limit, a positive voltage is applied by the inverter to the inductor and this causes the current to increase and the cycle repeats.

The current controllers of the three phases are designed to operate independently. Each current controller determines the switching signals to the inverter. The switching logic for phase A is formulated as below;

If $i\,fa$ < ($i*\,fa$ -HB) upper switch (G1) is OFF and lower switch (G4) is ON

If $i\,fa$ < ($i*\,fa$ +HB) upper switch (G1) is ON and lower switch (G4) is OFF

In the same fashion, the switching of phase B and C devices are derived.

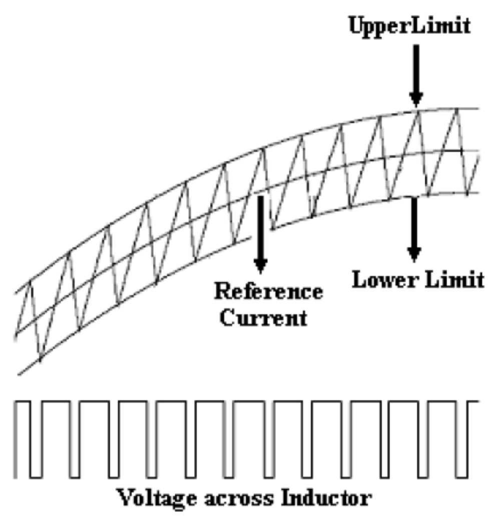

Fig.2. Hysteresis Current PWM Control Operation Waveform.

The DC side of the inverter is connected to a capacitor. The DC capacitor provides a constant DC voltage and the real power necessary to supply the losses of the system. In the steady state, the real power supplied by the source should be equal to the real power demand of the load plus a small power to compensate the losses in the active filter. Thus, the DC capacitor voltage can be maintained at a reference value. However, when the load condition changes the real power balance between the mains and the load will be disturbed. The real power difference is to be compensated by the DC capacitor. This changes the DC capacitor voltage away from the reference voltage. A fuzzy logic controller is applied to maintain the constant voltage across the capacitor by minimizing the error between the capacitor voltage and the reference voltage.

Fig. 3 shows the simplified circuit of distribution system under no-load conditions. In the feeder simulator, harmonic is generated by a NLDRL connected at the bus which produces an amount of harmonic voltage. When a lossless line is assumed, the characteristic impedance of the feeder simulator can be calculated as shown in equation (4).

$$Z_O = \sqrt{\frac{L}{C}} = 0.8\ \Omega \tag{4}$$

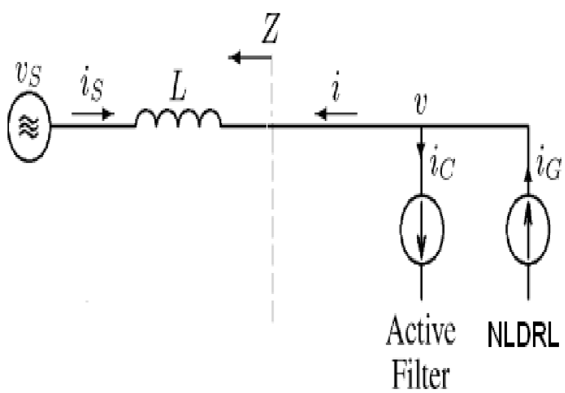

Fig. 3. Simplified circuit of the distribution system.

3. DESIGN OF DC BUS FUZZY LOGIC CONTROLLER

To design the FLC, variables which can represent the dynamic performance of the plant to be controlled should be chosen as the inputs to the controller. It is common to use the output error (e) and the rate of change of error (e') as controller inputs. In the case of the fuzzy logic based DC voltage control, the capacitor voltage deviation and its derivative are considered as the inputs of the FLC and the real power (Preg) requirement for voltage regulation is taken as the output of the FLC. The input and output variables are converted into linguistic variables. In this case, seven fuzzy subsets , NL(Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PL (Positive large) have been chosen. Membership functions used for the input and output variables used here are shown in Fig.4. As both inputs have seven subsets, a fuzzy rule base formulated for the present application is given in **Table 1**.

Table 1. Fuzzy Control Rule

e / de	NL	NM	NS	ZE	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	ZE
NM	NL	NM	NM	NM	NS	Z	PS
NS	NL	NM	NS	NS	ZE	PS	PM
ZE	NL	NM	NS	ZE	PS	PM	PL
PS	NM	NS	ZE	PS	PS	PM	PL
PM	NS	ZE	PS	PM	PM	PM	PL
PL	ZE	PS	PM	PL	PL	PL	PL
PL	ZE	PS	PM	PL	PL	PL	PL

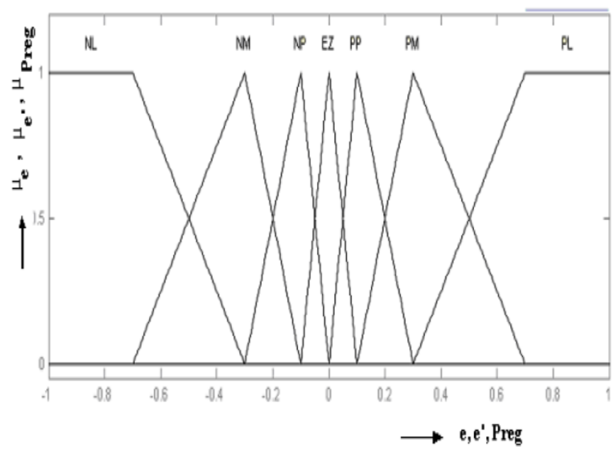

Fig. 4. Memberships function for the input and output variables.

4. SIMULATION RESULTS

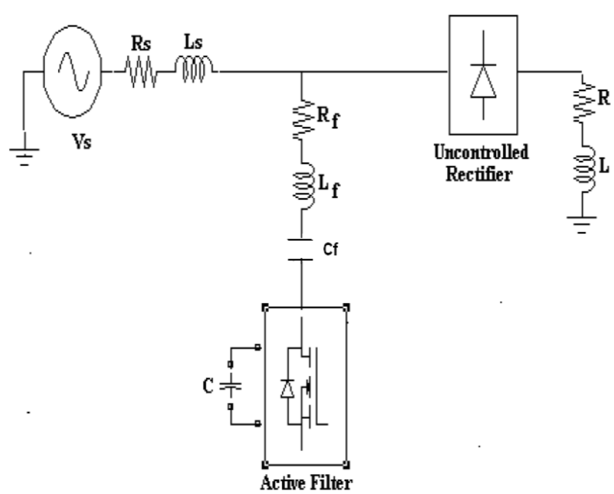

Fig. 5. Test Power System.

Table 2. Circuit parameters used for the SAF.

Parameters name	Numerical Value
Source voltage Vs	2.828 kV , 50 Hz (line r.m.s)
DC Capacitors	4700 μF
D.C capacitor reference voltage	400V
switching frequency	1kHz
Diode rectifier Non- linear Load resistance and inductance	20 Ω , 0.1 mH
Filter inductance, resistance and capacitor	2mH, 0.1 ohm and 100 μF
Source resistance and inductance	1mH, 0.1 ohm

This section presents the details of the simulation carried out to demonstrate the effectiveness of the proposed control strategy for the SAF to reduce the harmonics. Fig.5 shows the test system used to carry out the analysis. The test system consists of a three phase voltage source, and an uncontrolled rectifier with RL load. The active filter is connected to the test system through an inductor L_f and Capacitor C_f . The values of the circuit elements used in the simulation are listed in **Table 2**. The Matlab/Simulink is used to simulate the test power system with and without the proposed SAF.

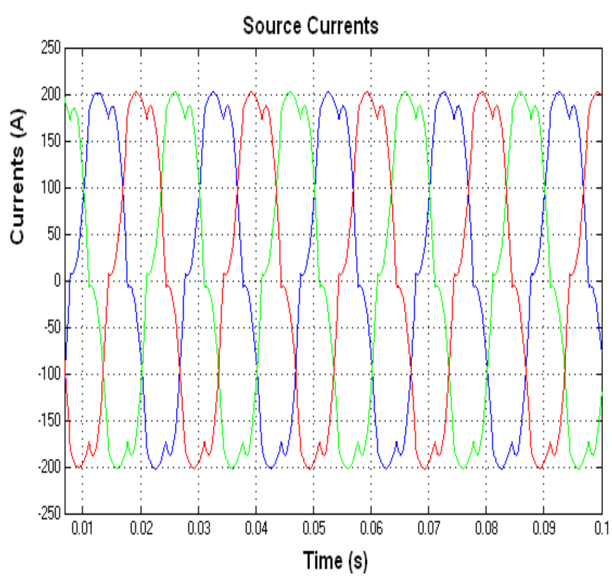

Fig.6. Three phase source currents of test power system without SAF.

Figs. 6 and 7 show the three phase source voltages and currents of test power system without SAF. It can be seen that the harmonic has severely disturbed the voltages as well as currents. Fig. 8 shows the harmonic spectrum of phase–a source current without SAF. It can be found that the THD is 26.35 % for proposed test system.

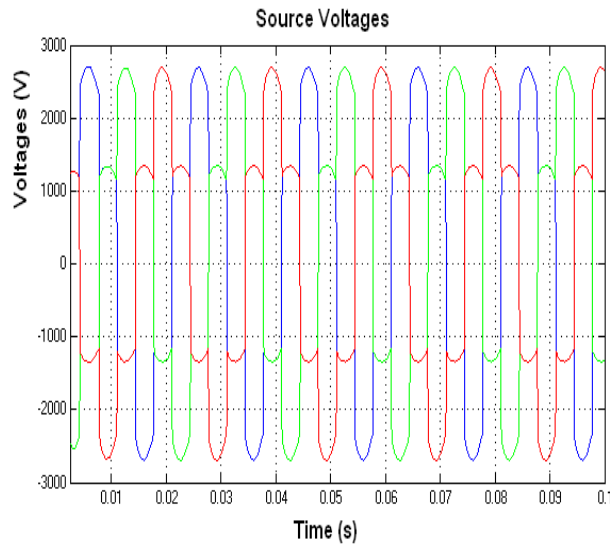

Fig.7. Three phase supply voltages of test power system without SAF.

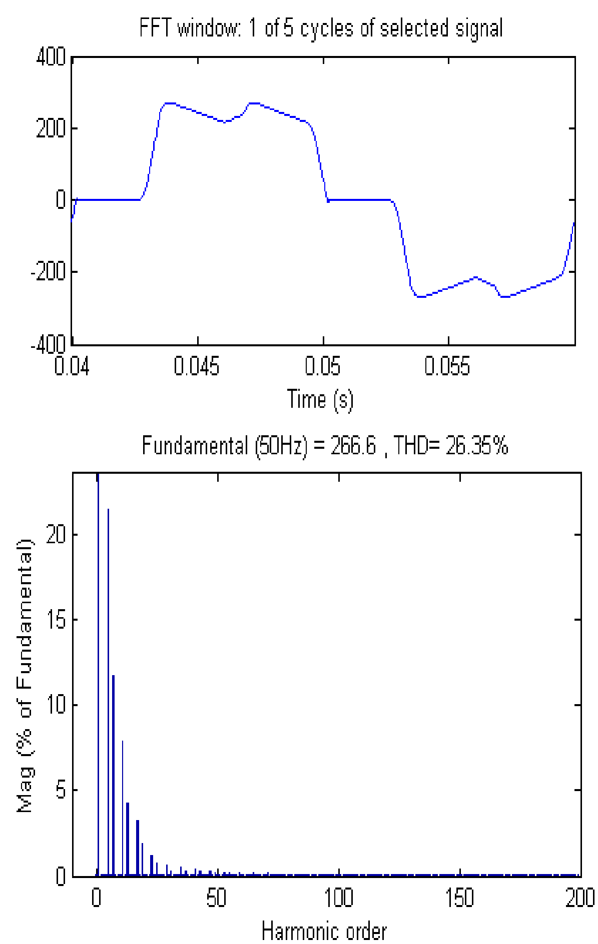

Fig.8. Harmonic spectrum of phase a source current without SAF.

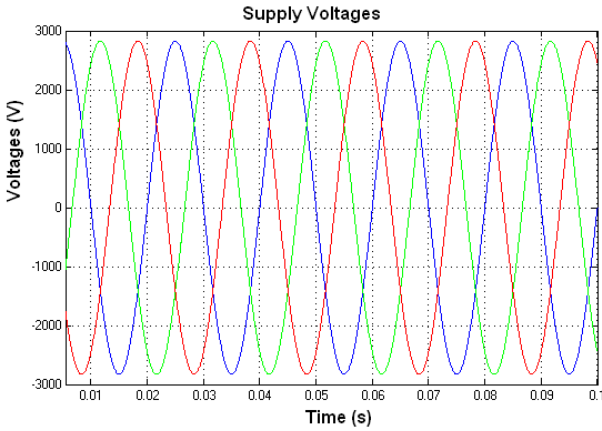

Fig.9. Three phase supply voltages of test power system with SAF.

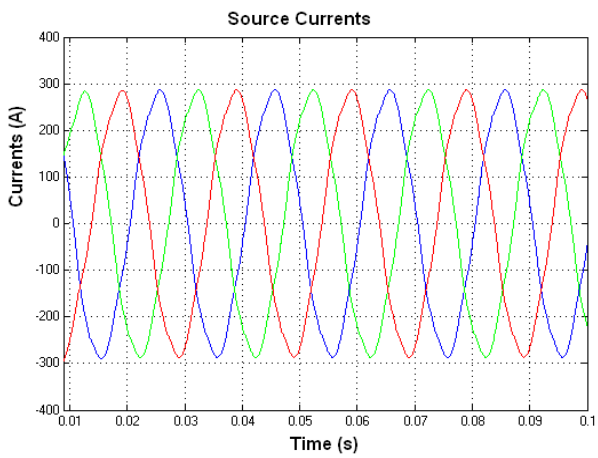

Fig.10. Three phase source currents of test power system with SAF.

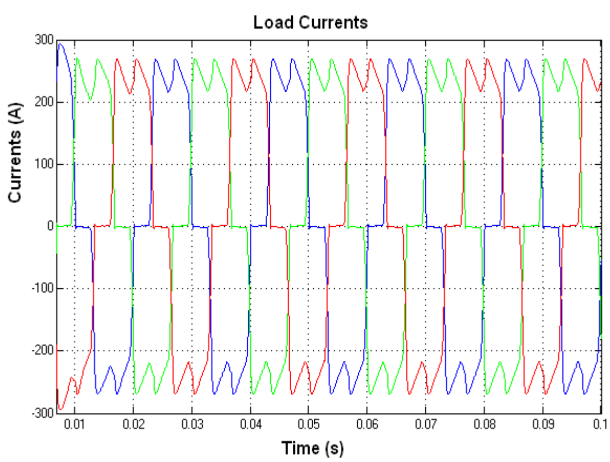

Fig.11. Distorted three phase load currents of test power system with SAF.

Figs. 9 and 10 show the three phase voltages and currents of test power system with SAF. It could be found that the wave shapes of the voltages and currents are in pure sinusoidal form.

The three phase load current waveforms in the presence of the filter are shown in Fig. 11 and the three phase compensated or filtered currents for SAF are shown in Fig. 12.

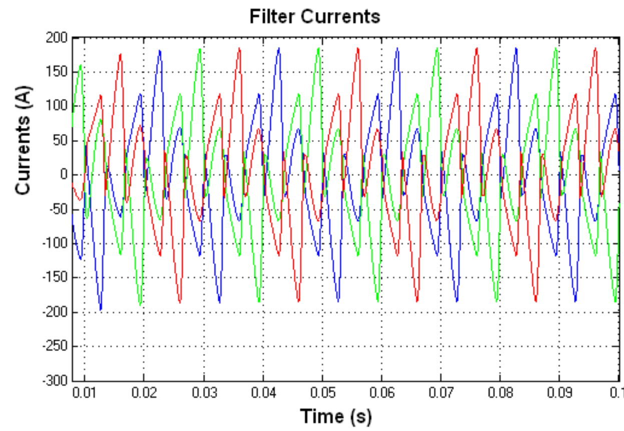

Fig. 12. Three phase Filter currents of test power system with SAF.

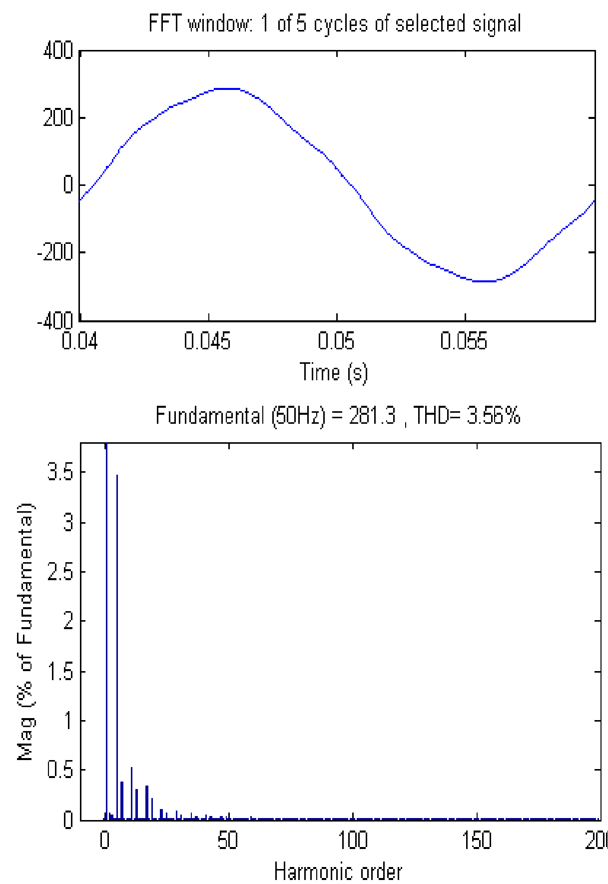

Fig.13. Harmonic spectrum of phase-a source current of test power system with SAF.

Fig .13 shows the harmonic spectrum of the supply current waveform in phase-a. The THD of the supply current in phase-a is 3.56%. From

Figs. 8 and 13, the THD with SAF is very low compared to without SAF.

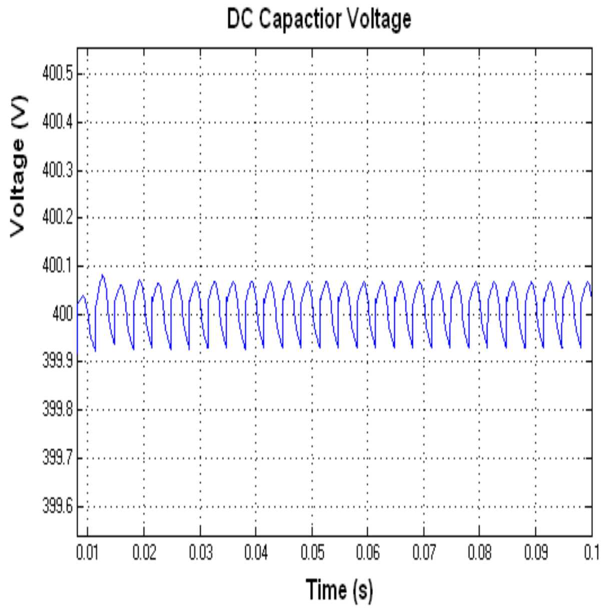

Fig.14. DC Capacitor voltage of SAF.

Fig. 14 shows the constant and small ripple dc capacitor voltage of SAF. It can be found that the DC capacitor voltage of SAF has without startup-transient overshoot with proposed FLCB.

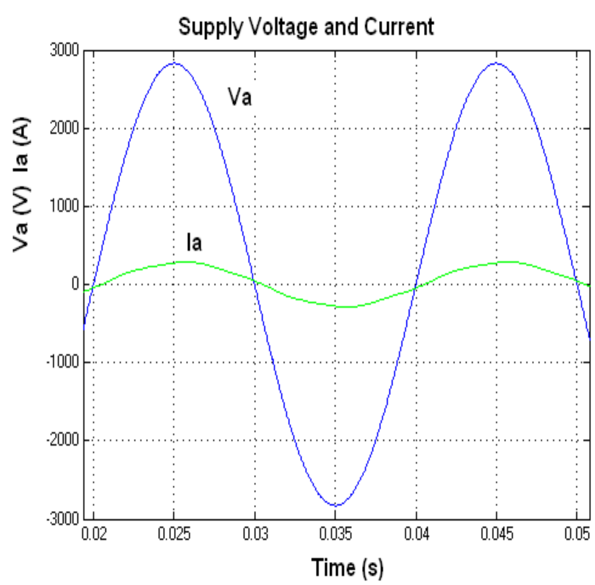

Fig. 15 In-phase source current with supply voltage of phase-a for test power system with SAF.

The source current is in phase with the source voltage as shown in the Fig. 15 (for phase-a only). This implies a near unity power factor operation.

Tables 3 shows the THD analysis of supply currents and voltages r with and without SAF. From the Table 3, THD with SAF is very low compared to without SAF.

Table 3. Total harmonic distortion Analysis of Test Power System.

Parameters	Source current Is			Voltage V		
	I_a	I_b	I_c	V_a	V_b	V_c
Without SAF	26.35%	26.35 %	26.35 %	25%	25%	25 %
With SAF	3.56 %	3.56 %	3.56 %	3.9%	3.9%	3.9 %

5. CONCLUSIONS

This paper presented a FLCB and an HCPWM technique for SAF has been successfully demonstrated in MatLab/Simulink. The SAF was simulated and its performance was analyzed in a sample power system with a source and a NLDRL. The HCPWM control has successfully eliminated the harmonics and improved the power factor in supply side. The simulation results show the efficiency of the fuzzy logic controller in maintaining the DC voltage set point. Future work, the neuro control technique can be applied to study the proposed system further.

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