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Comparison of PI Fuzzy and Neurofuzzy Controller for Shunt Active Power Filter for Enhancement of Power Quality

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Abstract

The Shunt Active Power Filter (SAPF) is one of the key controllers in Flexible Alternating Current Transmission System (FACTS) to control the transmission line voltage and can be used in Power System (PS) to enhance the power quality. This paper compares performance of Cascaded Five-Level Inverter (CFLI) based SAPF in PS with PI, Fuzzy and Neurofuzzy controller. Making use of the CFLI has benefits of low harmonics distortion, reduced number of switches and switching losses. In order to compensate the reactive power, balance the capacitor DC voltage and suppress the total harmonics distortion (THD) drawn from a Non-Linear Diode Rectifier Load (NLDRL) of SAPF, Sub-Harmonics Pulse Width Modulation (SHPWM) technique, and D-Q reference frame theory are proposed in this paper. The SHPWM pattern generation is used as control for the switches of CFLI. The D-Q reference frame theory is used to calculate the reference compensating currents for SAPF. PI controller fuzzy and neurofuzzy controller are used for capacitors dc voltage regulation for SAPF. The results are verified and validated through MatLab/Simulink simulation software with SAPF and without SAPF.

Keywords: Power System, Shunt Active Power Filter, SHPWM, PI controller, Fuzzy Controller Neurofuzzy controller, D-Q theory

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 malfunction. Hence, it is necessary to reduce the dominant harmonics below 5% as specified in IEEE 519-1992 harmonic standard [1].Shunt compensation for medium voltage power systems requires higher rating for voltage source converters (VSCs). Ratings of the semiconductor devices in a VSC are always limited; Therefore for higher rated converters it is desirable to distribute the stress among the number of devices using multilevel topology [2]. Cascaded multilevel configuration of inverter has the advantage of its simplicity and modularity over the configurations of diode-clamped and flying capacitor multilevel inverters. Application of cascaded multilevel converters for shunt compensation of power systems has been described in [3]-[4].

Tradionally based, passive L-C filters were used to eliminate line harmonics in [5]-[7]. 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 [6]-[7]. 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 [5] 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 [7]. 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.

In the conventional methods, the performance of the SAPF degrades when the supply voltage is distorted and unbalanced [5]-[9]. In this paper, PI controller [8]-[9] and fuzzy controller [12]with SHPWM technique [10]-[11] are presented and the source current is maintained sinusoidal even when the supply voltage is distorted and unbalanced. The dc side capacitor voltage of the CFLI is regulated and peak value of the reference source current is obtained. The reference source current is obtained by D-Q reference frame theory.

In Section II, the operation of SAF and control technique with PI controller is presented. The control techniques of SAPF with Fuzzy controller are presented in Section III.

The control techniques of SAPF with neurofuzzy controller are presented in Section IV. Simulation results of system with PI controller, Fuzzy controller, Neurofuzzy controller and without filter are discussed in Section V. The conclusions and future work of system is discussed in Section VI.

Operation of Three Phase Cascaded Five Level Inverter

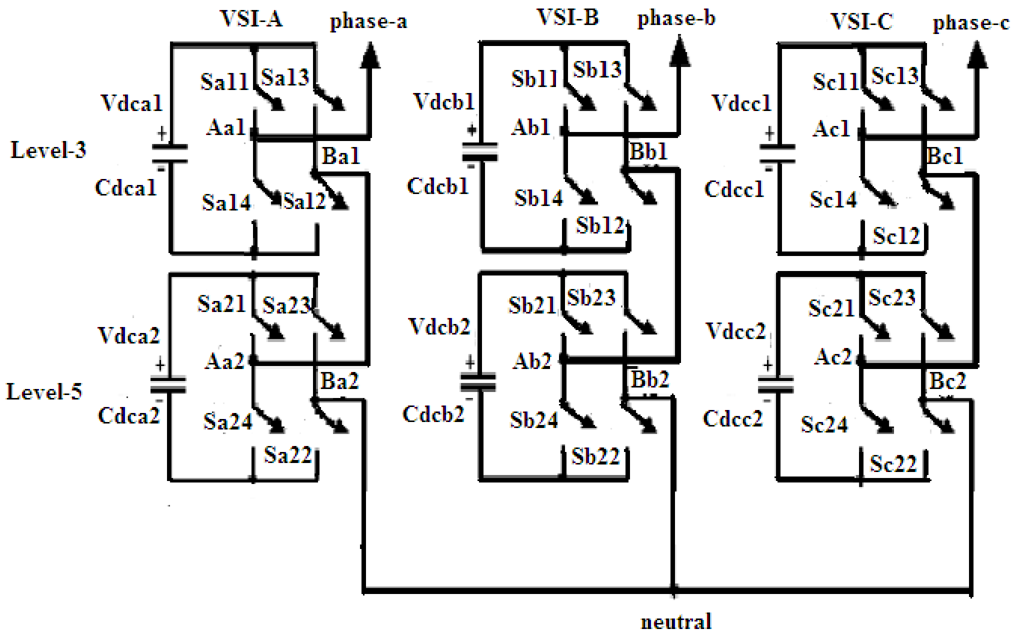

Figure 1: Simplified schematic of the Cascaded Five Level Inverter

The schematic diagram of three phase cascaded five level inverter is illustrated in Fig.1. Each dc source is connected to an inverter. Each inverter level can generate three different voltage outputs, +Vdc, 0, and –Vdc using various combinations of the four semiconductor power switches. The ac outputs of the various full bridge inverter levels are connected in series such that the synthesized voltage waveform is obtained by using the sum of the inverter outputs. The number of output phase voltage levels "m" in a cascaded inverter is defined by m=2s+1, where s is the number of separate dc sources. This CFLI is used as a SAPF in this paper.

Basic Principle and Control Method of SAPF with PI Controller

SAPF or CFLI compensate current harmonics by injecting equal-but-opposite harmonic compensating current. In this case the CFLI operates as a current source injecting the harmonic components generated by the load but phase shifted by 180^o. This principle is applicable to any type of load considered a harmonic source. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor. In this way, the power distribution system sees the non- linear load and the active power filter as an ideal resistor. The current compensation characteristic of the SAPF is shown in Fig.2.

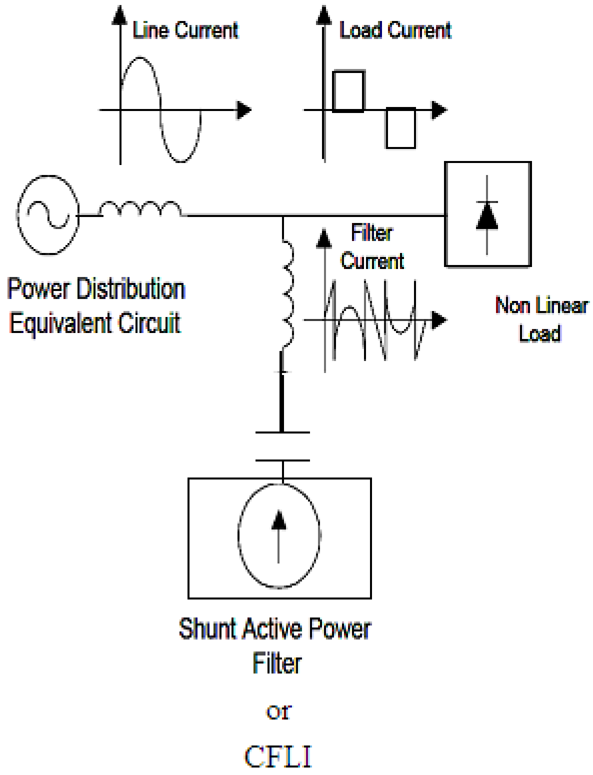

Figure 2: Principle of SAPF

SAPF or CFLI compensate current harmonics by injecting equal-but-opposite harmonic compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180^o. This principle is applicable to any type of load considered a harmonic source. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor. In this way, the power distribution system sees the non linear load and the active power filter as an ideal resistor. The current compensation characteristic of the shunt active power filter is shown in Fig.2.

D-Q Reference Current Generation

There are several methods to extract the harmonic components from the detected three-phase waveforms [7]. Among them, the so-called p - q theory based on time domain has been widely applied to the harmonic extraction circuit of active filters. The detected three-phase voltage is transformed into the D – Q coordinates as shown in Fig. 3. The second order digital high pass filters (HPFs) with the same cut off frequency as 40Hz extract the dc component Vhd*, Vhq* and V0 which corresponds to the fundamental frequency in the coordinates. 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 (1), (2) and (3). The current reference for the voltage – source inverter is the sum of the current references from the three parts, as follows

$$I^*_{cd}(s) = K_v (G_h V_{hd}^* - V_d) + (V_{dc}^* - V_{dc}) \quad (1)$$

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

$$I^*_0(s) = 1/3 (V_{sa} + V_{sb} + V_{sc}) \quad (3)$$

The obtained current reference is converted to three phase current reference by inverse D–Q transformation I^*_{ca}, I^*_{cb}, and I^*_{cc}. The three-three phase reference compensating current is compared with the SAPF compensating current extracted from ac system. Thus three phase compensating current I_{ca}, I_{cb}, and I_{cc} are produced.

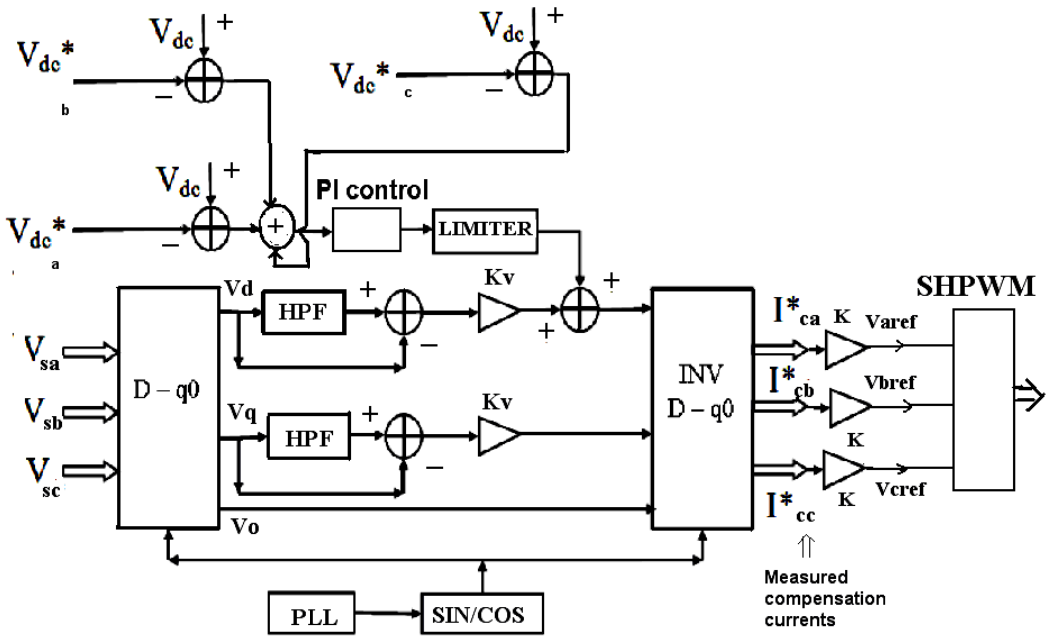

Figure 3: Block diagram of the SAPF control scheme using PI controller

Each phase of the compensating currents is amplified by a gain K in order to produce the three AC voltage references of the feedback loop, given by:

$$V_{aref} = K^* (I^*_{ca} - I_{mca}) \quad (4)$$

$$V_{bref} = K^* (I^*_{cb} - I_{mcb}) \quad (5)$$

$$V_{cref} = K^* (I^*_{cc} - I_{mcc}) \quad (6)$$

Finally, each voltage reference of the SAPF is compared with a multicarrier triangular waveform (1000 Hz) to generate the switching patterns for the CFLI.

DC Bus Voltage Control

A DC bus controller is required to regulate the DC bus voltage V_{dc} and to compensate the inverter losses in Fig. 3. The measured DC bus voltage Vdc of each phase is compared with its reference value V_{dc}*. Similarly, the remaining phases and added all the error signals. The resulting error is applied to a PI regulator. The proportional and integral gains are set to 0.14 Ω^{-1} and .012 Ω^{-1} s^{-1} respectively [11]. Moreover, the SAPF can build up and regulate the DC capacitor voltage, the electrical quantity to be controlled in the dc-voltage feedback loop is (V_{dc}^* - V_{dc}).

Constant Switching Frequency Multicarrier Pulse Width Modulation

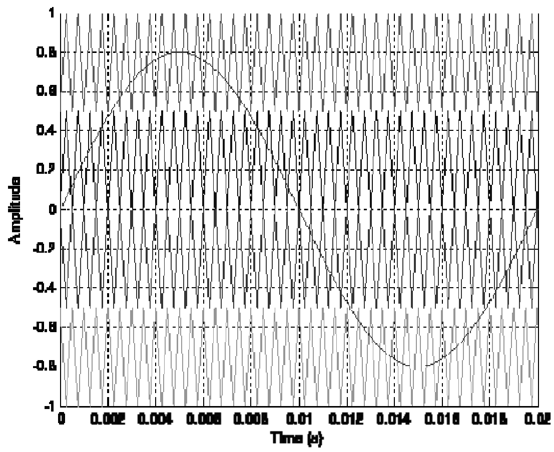

Figure 4: Constant switching frequency multicarrier subharmonic Pulse width modulation

Fig.4 shows an m-level inverter, m-1 carriers with the same frequency f_c and the same amplitude A_c are disposed such that the bands they occupy are contiguous. The reference waveform has peak to peak amplitude Am, the frequency fm, and its zero centered in the middle of the carrier set. The reference is continuously compared with each of the carrier signals. If the reference is greater than “s” carrier signal, then they active device corresponding to that carrier is switched off.

In multilevel inverters, the amplitude modulation index “M_a” and the frequency ratio “M_f” are defined as

$$M_a = A_m / (m\text{-}1)\ Ac \quad (7)$$

$$M_f = f_c / f_m \quad (8)$$

Basic Principle and Control Method of SAPF With fuzzy Controller

Fig.5. shows the Block diagram of the SAPF control scheme using Fuzzy controller. In our study we consider the output error (e) and its derivative as inputs. In Fuzzy logic control of our system the capacitor voltage deviation and its derivative are

considered as the inputs .The real power requirement for voltage regulation is taken as the output of the FLC. We take seven fuzzy subsets , NL(Negative Large), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive

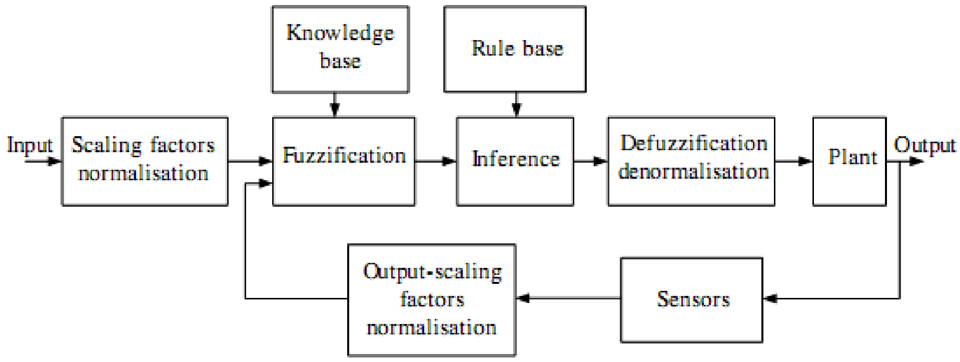

Figure 5: Block diagram of the SAPF control scheme using Fuzzy controller

Small), PM (Positive Medium) and PL (Positive large) have been chosen 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	ZE	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

Basic Principle and Control Method of SAPF With Neuro fuzzy Controller

Control of Shunt Active Filter

The typical components of an active power filter system are the mains supply, a nonlinear load, a reference current estimator, a PWM current controller and a voltage source inverter with an interface reactor. The information regarding the harmonic current generated by a nonlinear load is supplied to the reference current estimator together with information about other system variables. The reference signal from the current estimator, as well as the other signals provides the control for the PWM current controller. The output of the PWM current controller controls the voltage source inverter via a suitable interface Reactor.

The main components of an active power filter system with the proposed hierarchical neuro-fuzzy current controller are shown in Fig. 6. Circuit shows two Fuzzy controllers (1 & 2) to regulate the switching signals (T1 – T6) for converter.

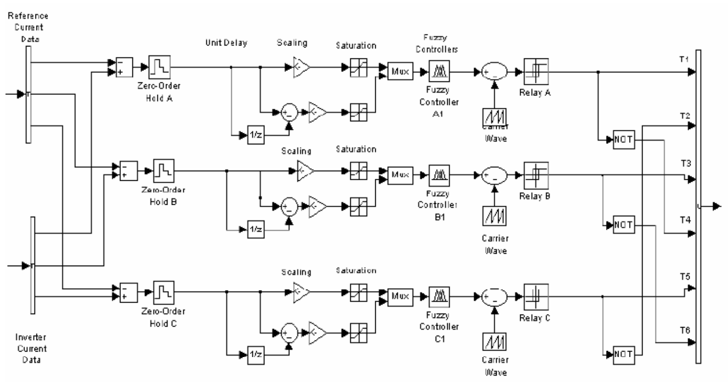

Figure 6: Basic block diagram for SAF.

The fuzzy controllers for the single fuzzy controller scheme are characterized as follows:

- 3 fuzzy sets for each of the 2 inputs.
- 3 fuzzy sets for the output.
- Triangular and trapezoidal membership functions.
- Implication using the "min" operator.
- Mamdani fuzzy inference.
- Defuzzification using the "centroid" method.

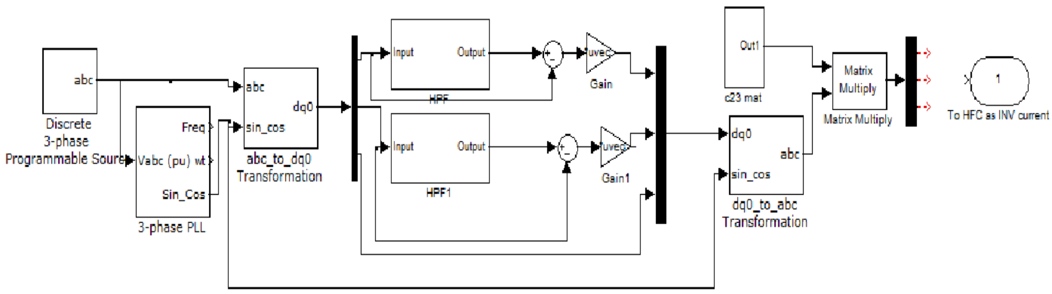

Figure 7: Getting Ia, Ib, Ic currents for HFCPWM input.

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.

1. The control strategy is implemented in three stages.
2. The essential voltage signals are measured to gather accurate system information.
3. Compensating currents are derived based on synchronous reference D-Q theory.
4. The gating signals for the solid-state devices are generated using HFCWM 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.7.

Fuzzification of Inverter Current with Reference Load Current

Triggering of Mosfet's With (T1-T6) Controlled By Flc (2)

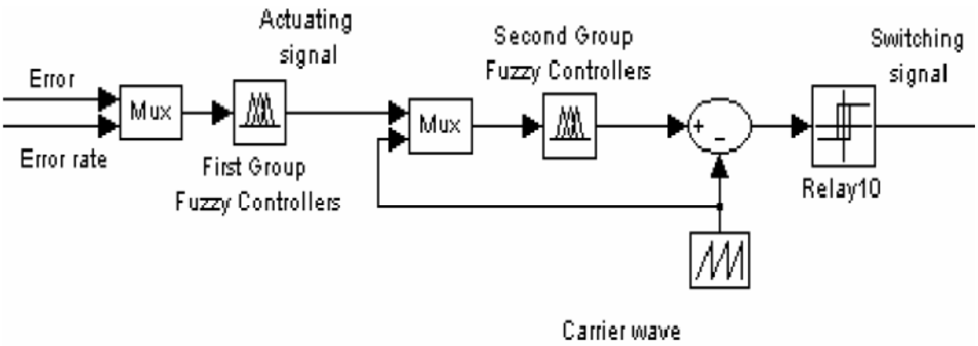

Figure 8: FLC (2) giving switching signals.

Fig. 8 explains the generation process of switching signals in the model. The output of the fuzzy controller is the actuating signal and this output is compared with a carrier signal. The relay element is set to give output when the input of itself is greater than 0. The output of the fuzzy controller is set to take values between –0.622 to 0.622. The carrier signal is set to take values between –0.55 to 0.55.

The important point here is that the second group controllers employed in the model are Adaptive Neuro Fuzzy Inference Systems. They are developed by using the ANFIS tool of the MATLAB Fuzzy Logic Toolbox. They are employed to correct error points of the first group controllers. As explained before, without controlling the carrier signal, it may not be known, what the switching signals are, if the error or error rate is not high enough to make the output value high enough to pass the carrier signal. To correct this, a training data has been developed that includes the input/output data pairs of the neuro-fuzzy controllers in the second group. This training data is based on the input-output characteristics of the first group fuzzy controllers. In this training data, at the error points, by using the reference signal input, the correct output values are trained to neuro-fuzzy controllers.

Simulation and its Results in Matlab/Simulink
Simulation Results Discussions

This section presents the details of the simulation carried out to demonstrate the effectiveness of the proposed control strategy for the SAPF to reduce the harmonics. The test power 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 II. The MatLab/Simulink is used to simulate the test power system with PI controller, Fuzzy controller and without the proposed SAPF.

Table II: Specifications of SAF

Parameters name	Numerical Value
Source voltage Vsk	4.5 kV , 50 Hz (line r.m.s)
DC Capacitors	3000 uF
D.C capacitor reference voltage (each phase)	4.5 kV
switching frequency	1kHz
Diode rectifier Non- linear Load resistance and inductance	20Ω, 0.1 mH
Shunt inductance , capacitor and resistance	100 uF 2mH, 0.1 ohm
Source resistance and inductance	1mH, 0.1 ohm

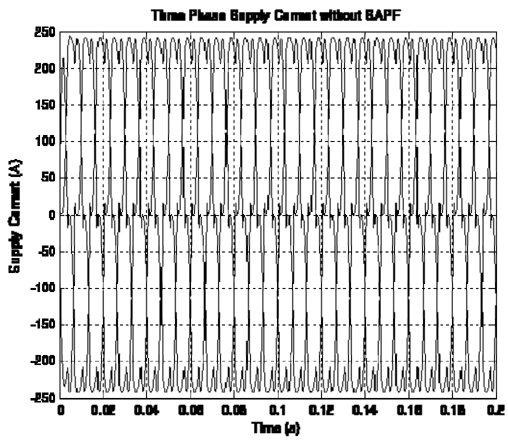

Figure 9: Three phase source currents of test power system without SAPF

Fig. 9 show the three phase source currents of test power system without SAPF. It can be seen that the harmonic is severely disturbed in source currents. Fig. 10 shows the harmonic spectrum of phase–a source current without SAPF. It can be found that the THD of 26.35 % for proposed test system without SAPF. Fig. 11 shows the three phase supply currents of test power system with SAPF. It could be found that the wave shapes of the supply currents are pure sinusoidal form.

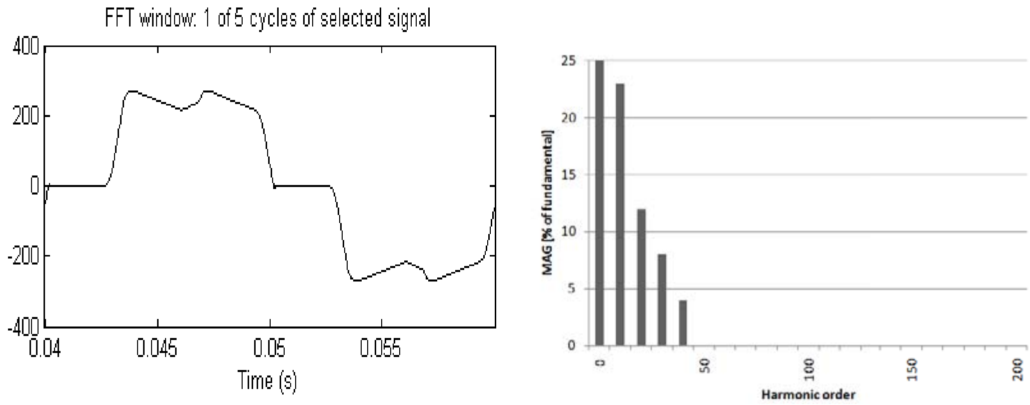

Figure 10: Harmonic spectrum of phase a source current without SAPF

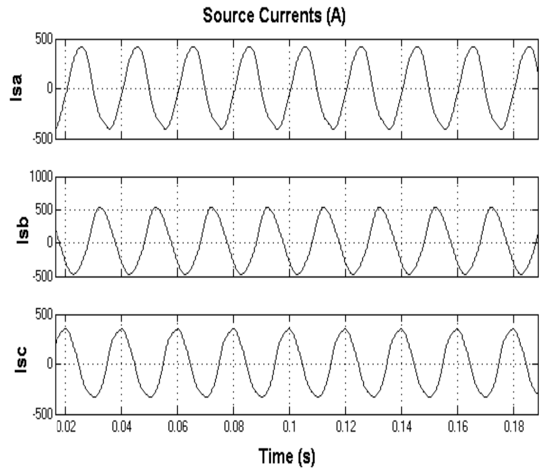

Figure 11: Three phase source currents of test power system with SAPF

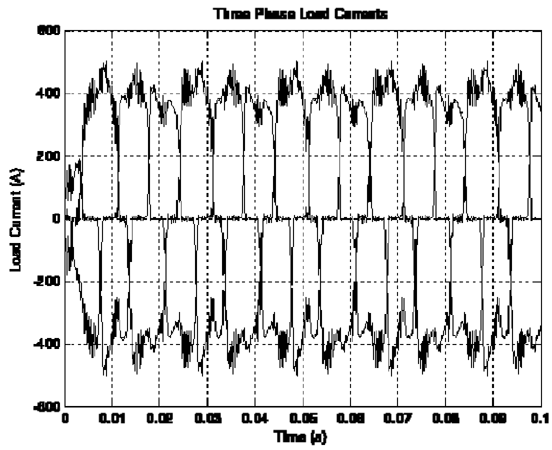

Figure 12: Distorted three phase load currents of test power system with SAPF

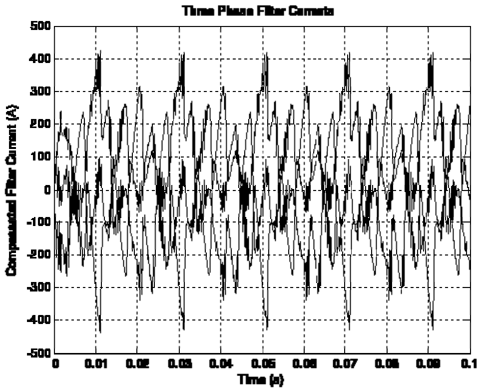

Figure 13: Three phase Filter currents of test power system with SAPF

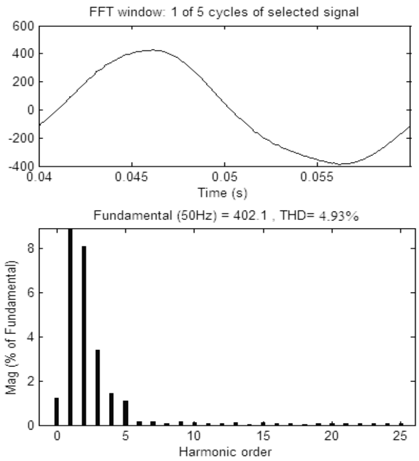

Figure 14: Harmonic spectrum of phase-a source current of test power system with PI controller

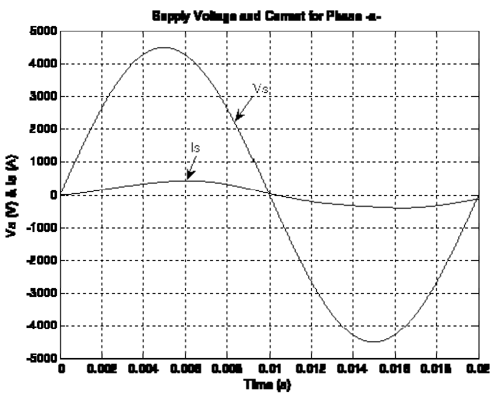

Figure 15: In-phase source current with supply voltage of phase-a for test power system with SAPF

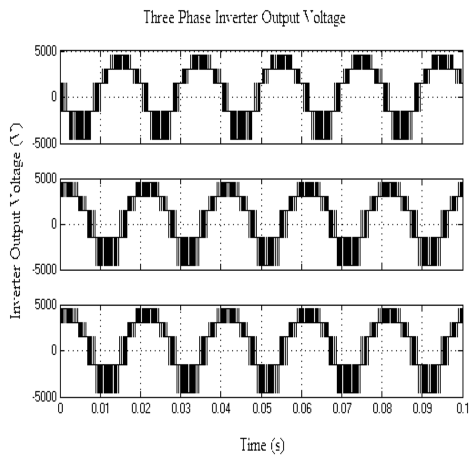

Figure 16: Inverter output voltage for three phases

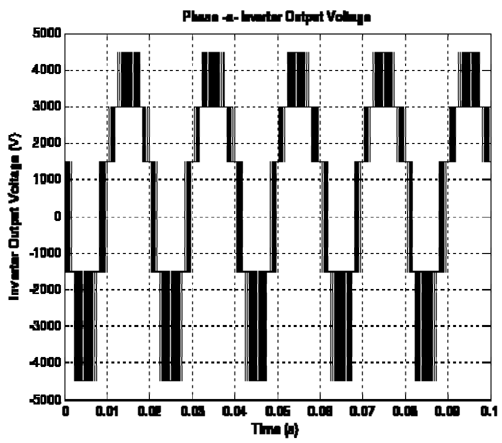

Figure 17: Inverter output voltage for phase - a.

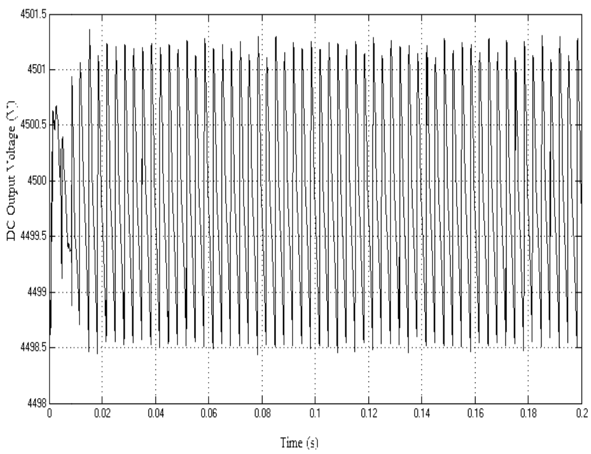

Figure 18: DC Capacitor voltage of SAPF

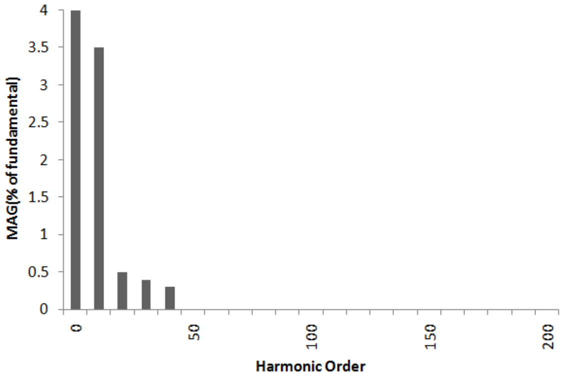

Figure 19: Harmonic spectrum of phase-a source current of test power system with fuzzy controller

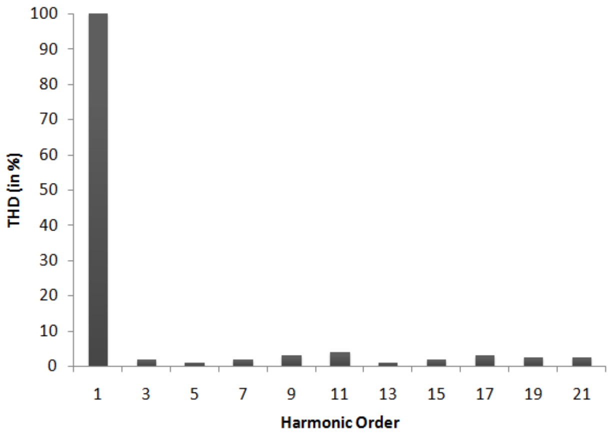

Figure 20: Harmonic spectrum of phase-a source current of test power system with neurofuzzy controller

Fig. 12 shows the load currents for the compensated system in the presence of filter. The shunt current tracking characteristic is shown in Fig13. In an error of about 28A (rms) is observed in the tracking of the fundamental component. Fig.14 shows the harmonic spectrum of the supply current in phase-a waveform with PI controller. The THD of the supply current in phase-a- is 4.93%. From Figs. 6 and 11, the THD for with SAF is very low compared to without filter. 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. The 5-level inverter output voltage for the phases-a, b and c is shown in Fig. 16. Fig. 17 show for the a-phase inverter output voltage. An average switching frequency of 1000 Hz is observed for all the switches. Fig. 18 shows the convergence of the dc-link voltage of the cascaded CFLI-bridges for the phase-a. Fig.19 shows the harmonic spectrum of the supply current in phase-a waveform with fuzzy controller. The THD of the supply current in phase-a- is 3.56%.

Fig.20 shows the harmonic spectrum of the supply current in phase-a waveform with neurofuzzy controller. The THD of the supply current in phase-a- is 2.9%.

Fig. 21 shows the comparison of source current using both SHPWM and hysteresis current controller PWM methods. From this figure, it is clearly observed that THD of proposed system with neurofuzzy controller has best performance in comparison with a PI and fuzzy controller.

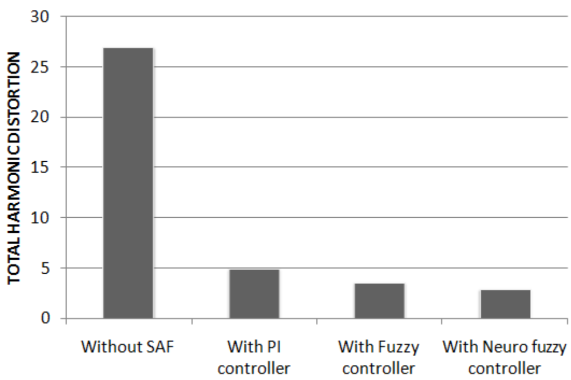

Figure 21: Comparison of source current THD without SAF and with PI & Fuzzy controller

From the Table III THD with neuro fuzzy controller based SAF is very low compared to without controller ,PI controller and fuzzy.

Table III

Parameters	Source current I_s			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 %
SAF with PI controller	4.93%	4.93%	4.93 %	5.4 %	5.4 %	5.4 %
SAF with Fuzzy controller	3.56%	3.56%	3.56%	3.9 %	3.9 %	3.9 %
SAF with Neuro fuzz Fuzzy controller	2.9%	2.9%	2.9%	3.6%	3.6%	3.6%

Comparison of source current THD without SAF and with PI & Fuzzy controller

Conclusion

This paper compares the performance of SAF without controller and with PI,fuzzy &neurofuzzy controller. The Total Harmonic Distortion is proved to be very less with neurofuzzy controller. The SAPF was simulated and its performance was analyzed in a sample power system with a source and a NLDRL. The constant switching frequency SHPWM control has been successfully eliminated the harmonics and improved the power factor in supply side. The simulation results showed the effectiveness of the designed Fuzzy controller in maintaining constant capacitor DC voltage for CFLI.

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