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NEURO CONTROLLED SEVEN LEVEL SHUNT ACTIVE POWER FILTER FOR POWER QUALITY ENHANCEMENT

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Abstract

This paper presents a Neuro controlled Hybrid Cascaded Seven-Level Inverter (HCSLI) used in shunt active power filter (SAPF) to improve power quality in medium voltage power system(PS). The HCSLI has merits of less harmonics, reduced number of switches and less loss. The SAPF compensates reactive power, improves power factor and suppresses the total harmonics distortion (THD) due to Non-Liner Diode Rectifier Load (NLDRL).The proposed control strategy for SAPF includes Constant Switching Frequency Multicarrier Sub-Harmonics Pulse Width Modulation (CSFMSHPWM) method for controlling the switches of HCSLI, Neuro Controller (NC) for capacitor DC voltage regulation and d-q theory for obtaining the reference compensation currents for SAPF. The results are validated through MATLAB simulation with SAPF and without SAPF at various load conditions.

Keywords*: S*hunt active power filter, CSFMSHPWM, neuro controller, d-q theory, harmonic distortion.

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 malfunction. Hence, it is necessary to reduce the dominant harmonics below 5% as specified in IEEE 519-1992 harmonic standard. Shunt compensation for medium voltage power system 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 [1]. 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 [2].Traditionally based, passive L-C filters were used to eliminate line harmonics [3]. 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 SAPF 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 [4]. The principal components of the APF are the VSI, a DC energy storage device that in this case is capacitor and the associated control circuits. The performance of an active filter depends mainly on the technique used to compute the reference compensation current and the control method used to inject the desired compensation current waveforms with better harmonic spectrum and attain higher voltage with a limited maximum device rating. Various types of PWM techniques like constant switching frequency, variable switching frequency multicarrier and phase shifted carrier pulse width modulation methods are used for multilevel inverter control methods has been well presented in literature[5]. There are two major approaches that have emerged for the harmonic detection, namely, time domain and the frequency domain methods [3]. 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. SAF can improve the quality of power by mitigating poor load power factor, eliminating harmonic content of load and balancing source currents for unbalanced load operating conditions [6]. The various types of SAPF controllers like Proportional-Integral-Controller (PIC), RST, hysteresis, adaptive control, Fuzzy Logic Controller (FLC) has been well presented in [7]. Neuro Controller (NC) is one of outer loop control used in much power system application has been reported in [8]. The major advantages of NC over traditional control methods are quick settling time and good stability even for large change in line/load variations, and leads to more accuracy and reduced steady state error. The source current is maintained sinusoidal even when the supply voltage is distorted and unbalanced using CSFMSHPWM. The DC side capacitor voltage of the HCSLI is regulated and peak value of the reference source current is obtained by using NC and d-q theory. In Section 2, the operation of HCSLI is presented. The various controller methods for SAPF are presented in Section 3. Simulation results of system with and without filter at both linear and non-linear loads are discussed in Section 4. The conclusions are discussed in Section 5.

2. OPERATION OF THREE PHASE HYBRID CASCADED SEVEN LEVEL INVERTER

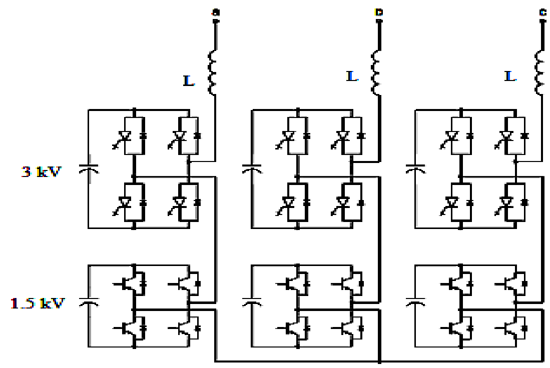

Fig. 1. Simplified schematic of the HCSLI[11]

This paper presents a SAPF in PS application implemented with multiple single-phase cells connected in series combination arrangements as shown in Fig. 1. Each cell is composed by a DC capacitor and a full H-bridge. Using this type of topology, higher voltage levels can be generated, making the proposed topology suitable for compensation of medium and high voltage power system applications. A three-phase reactor is connected between the line and SAPF for isolation purpose. Each power cell can be operated at different DC voltage and constant switching frequency for improving the performance characteristics of proposed HCSLI system. The proposed control schemes are used for the correct operation of each H-bridge cell and compensation demands. The current reference required can be obtained allowing the generation of the total compensating current and the absorption of the needed active power to compensate system losses and to keep the capacitor DC voltages maintained almost stable. The voltage capability of the semiconductor devices like Insulated Gate Bipolar Transistors (IGBT) and the switching speed of high voltage device like Integrated Gate Commutated Thyristors (IGCT) used in the proposed system will define the number of total cells that must be connected in series in each phase to compensate the harmonic currents for a given medium voltage PS [9]. The voltage at which each cell must operate depends on the number of cells and the total voltage that must be delivered by the modular inverter. It may be verified that with a combination of 3 kV and 1.5 kV DC bus voltages in this topology, it is possible to synthesize stepped waveforms with seven voltage levels via. -4.5 kV, -3 kV, -1.5 kV, 0, 1.5 kV, 3 kV, 4.5 kV at the each phase leg output.

As shown in Fig. 1, the higher voltage levels (± 3kV) are synthesized using GTO inverters while lower voltage levels (± 1.5kV) are synthesized using IGBT inverters. But it is well known that switching capability of GTO thyristors is limited at high frequencies [10]. Hence a hybrid strategy which incorporates stepped synthesis in conjunction with variable pulse width of the consecutive steps is proposed. The number of output phase voltage levels “m” in a cascaded multilevel inverter is defined by m=2s+1, where s is the number of separate DC sources. The SAPF topology proposed in this paper is shown in Fig. 1. The principal characteristic of the cascaded (modular) topology is suitable for high voltage PS applications.

SAPF or HCSLI compensate the current harmonics by injecting equal-but-opposite harmonic compensating current. In this case, the HCSLI 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 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.

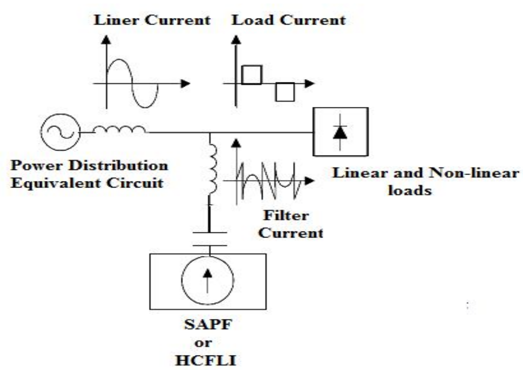

Fig. 2. Principle of SAPF[11]

3. CONTROL STRATEGY OF SAF

It includes d-q theory for reference compensation current estimation, Neuro controller for DC bus voltage control and Constant switching frequency subharmonic pulse width modulation for generating control signals to VSI.

3.1 d-q theory based Reference Current Generation

In d-q theory 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 35Hz extract the dc component V_{hd}^* V_{hq}^* and V_0 which corresponds to the fundamental frequency in the coordinates. The line voltage regulation part is performed by a feedback control. Two co – ordinates V_d and V_q are compared with harmonic extracted voltage V_{hd}^* and V_{hq}^*. Again K_V amplifies to produce current references for harmonic damping I_{hd}, I_{hq}, and I_0 as shown in equations (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

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

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

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

The obtained current reference is converted to three phase current reference by using inverse d-q transformation I^*_{ca}, I^*_{cb}, and I^*_{cc}. The three-three phase reference compensating current is compared with the HCSLI compensating current extracted from AC system. Thus three phase compensating current I^*_{ca}, I^*_{cb}, and I^*_{cc} are produced.

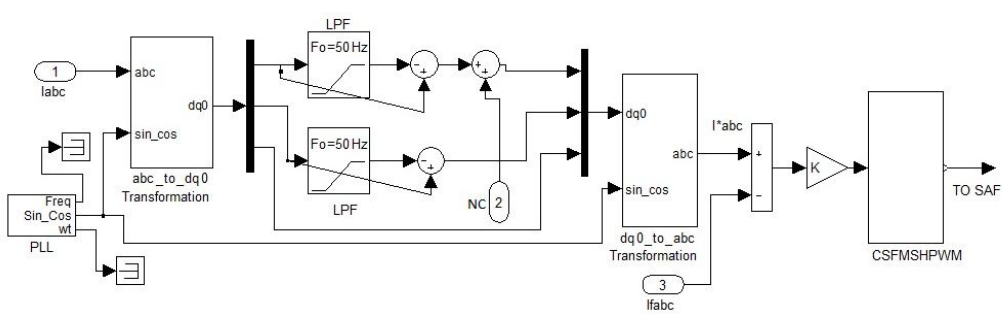

Fig.3. Block diagram of d-q theory

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, as given in eqns.(4),(5) and (6).

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

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

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

Finally, each voltage reference of the SAPF is compared with a multicarrier triangular waveform (1500 Hz) to generate the switching patterns for the HCSLI.

3.2 Neuro Controller

In this paper, NC algorithms are implemented to regulate the DC capacitor voltage of proposed SAPF in order to improve the dynamic performance. The input-output data necessary for the off-line training of the neural network have been found in the proposed work using the DC capacitor voltage error of the HCSLI. The data set value is made sufficiently rich to ensure stable mode operation since no additional learning will take place after training. A back-propagation algorithm [12] is used for training of the created network. The LEARNGDM function which has a gradient descent with momentum weight / bias learning is used in this work. Learning occurs according to the learning parameters: learning rate=0.01 and momentum constant t = 0.9. MSE is the performance criteria used in this work that evaluates the network according to the mean of the square of the error between the target and computed output. The minimum MSE that can be achieved in this work is 1e-6. For a back-propagation training algorithm, the derivative of the activation function is essential. Therefore, the activation function selected must be differentiable. The sigmoid function satisfies this requirement and it is the commonly used soft-limiting activation function. It is also quite common to use linear output nodes to make learning easier and using a linear activation function in the output layer does not 'squash' (compress) the range of output. Hence, a bipolar sigmoid activation function and a linear activation function are used for the hidden and output layers respectively. Trials have been carried out to obtain maximum accuracy with a minimum number of neurons per layer.

The feed forward neural network developed consists of one neuron in the input layer, four neurons in the hidden layer and one neuron in the output layer. The optimum number of neurons for the hidden layer is selected as four (TABLE I) since the number of epochs for training the neural network is reduced considerably. The tansig function is found to be better than the logsig activation function for the hidden layer since the logsig function takes (TABLE II) approximately 200 more epochs than the tansig function. The input to the NC is DC capacitor voltage error (e) of SAPF (Fig. 3). The output of the NC is the corrected reference signals.

Table 1: Choice of hidden neurons

Number of hidden neurons	Number of epochs for training the network
1	Performance goal not met
2	Performance goal not met
3	≈ 400
4	**≈ 100**
5	≈ 320
6	≈ 360
7	≈ 400
8	≈ 420

Table 2: Choice of bipolar sigmoid transfer function as activation function for hidden layer

Number of hidden neurons	Number of epochs with tansig activation function	Number of epochs with logsig activation function
1	Performance goal not met	Performance goal not met
2	Performance goal not met	Performance goal not met
3	≈ 400	≈ 410
4	**≈ 100**	**≈ 200**
5	≈ 320	≈ 420
6	≈ 360	≈ 460
7	≈ 400	≈ 480
8	≈ 420	≈ 485

3.3 Constant switching frequency multicarrier pulse width modulation

Fig.4 shows CSFSHPWM technique with (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 A_m, the frequency f_m, 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 carrier is switched off.

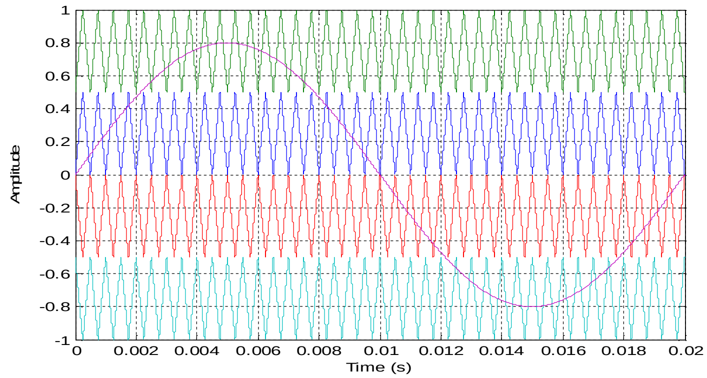

Fig. 4. Constant switching frequency multicarrier sub harmonic Pulse width modulation

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

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

$M_f = f_c\ / f_m$ (8)

4. SIMULATION RESULTS AND 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 at linear and non-linear loads. 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 III. The MATLAB/SIMULINK is used to simulate the test power system with and without the proposed SAPF at various load conditions.

Table 3: Specifications of PS With Shunt Active Power Filter

Parameters name	Numerical Value
Source voltage and frequency	4.5 kV(line r.m.s) , 50 Hz
DC Capacitors	3000 uF
D.C capacitor reference voltage (each phase)	4.5 kV
Switching frequency	1.5kHz
Non- linear Diode rectifier 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

4.1 PS without SAPF :

Fig. 5 show the three phase source currents of power system without SAPF. It can be seen that the harmonic pollution is severely affected in source currents due to reactive power demand of NLDRL. Fig. 6 shows the harmonic spectrum of phase–a source current without SAPF. It could be observed that the THD_i is 12.23% for proposed test system without SAPF.

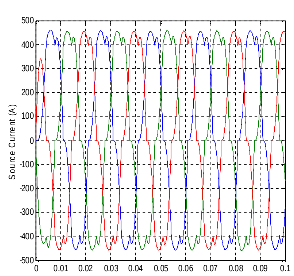

Fig.5. Three phase source currents of test power system.

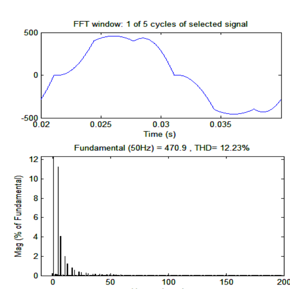

Fig.6. Harmonic spectrum of source current for phase - a

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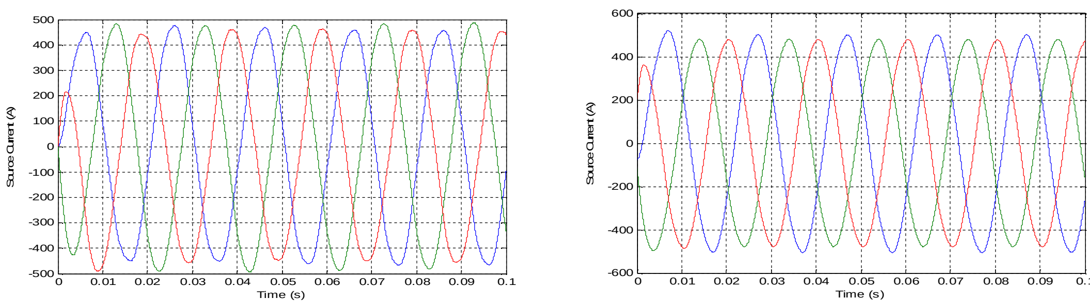
4.2 PS with SAPF using Linear and Non-liner Loads:

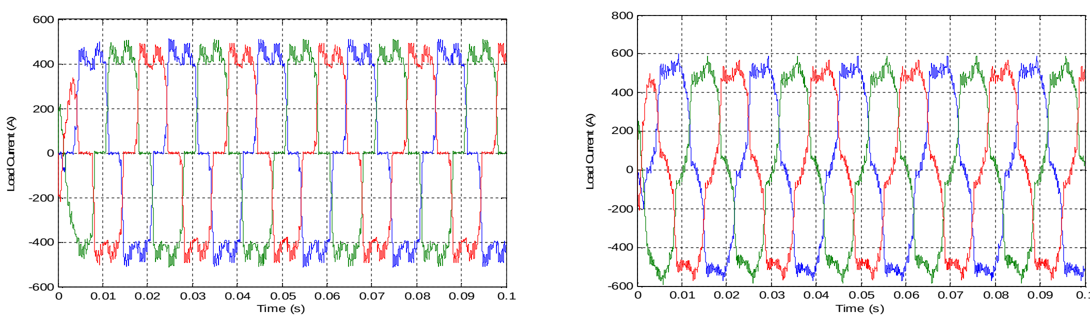
Fig. 7 shows the three phase source currents of PS with SAPF using both linear and non-linear loads. From this figure, it is clearly found that the waveform shapes of the source currents are almost pure sinusoidal for SAPF for both loads. Fig. 8 shows the load currents for the compensated system in the presence of SAPF with both linear and non-linear loads. It can be seen that SAPF using linear and non-linear loads has same results.

The shunt current tracking response for SAPF using both linear and non-linear loads is shown in Fig. 9. From this figure, it is clearly observed that an error of about 1 to 2 A (peak value) in the tracking of the fundamental component. Also, from the Figs. 7 to 9, it is clearly observed that a source/ load and measured shunt compensated currents of the proposed system has a negligible overshoot and quick settling time under the start-up transient and steady state operating condition at both loads.



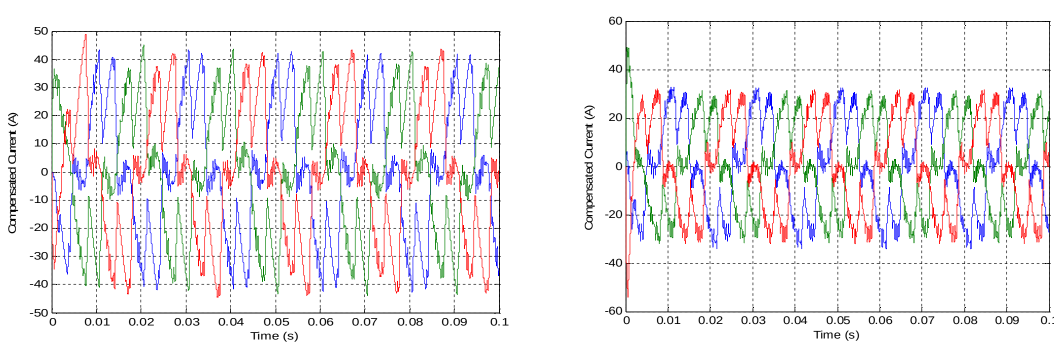
(a) (b)

Fig.7. Three phase source currents of test power system with SAPF (a) Non-linear load, (b) Linear load



(a) (b)

Fig.8. Distorted three phase load currents of test power system with SAPF (a) Non-linear load, (b) Linear load



(a) (b)

Fig. 9. Three phase compensated current of SAPF for test power system with **(**a) Non-linear load, (b) Linear load

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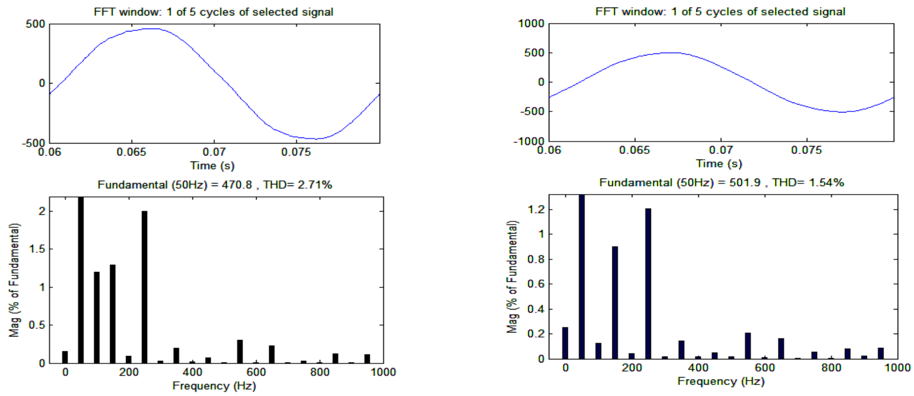
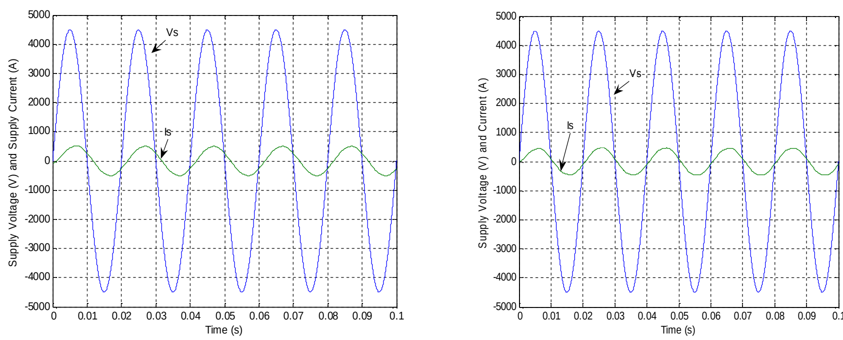


(a) (b)

Fig.10. Harmonic spectrum of phase-a source current of test power system with SAPF
(a) Non-linear load, (b) Linear load

Fig.10 shows the harmonic spectrum analysis of the source current in phase-a waveform with SAPF using both linear and non-linear loads. It is clearly found that the THD of the source current in phase-a for a SAPF using linear load has 1.54%, where as THD for the same system with non-linear load has 2.71%. From Figs. 6 and 10, the THD with SAPF is very low compared to without SAPF. Fig. 11 shows the source of current is in phase with the source voltage with SAPF using both linear and non-linear load (for phase-a-only). From this figure, it is clearly found that the proposed SAPF implies a near unity power factor operation in PS.
The seven-level inverter output voltage for the phases-a, b and c using non-linear load is shown in Fig. 12. Fig. 13 show the inverter output voltage of phase-a. From these figures, it is clearly observed that the proposed PWM control method for SAPF showed better output response.



(a) (b)

Fig. 11. In-phase source current with supply voltage of phase-a for test power system with SAPF
(a) Non-linear load, (b) Linear load

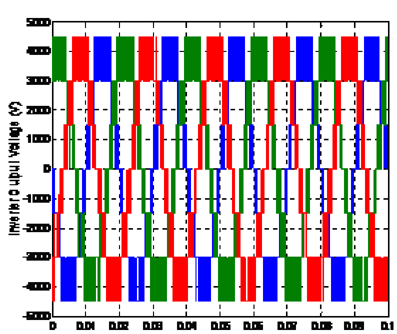


Fig. 12. Three phase seven level inverter output voltages

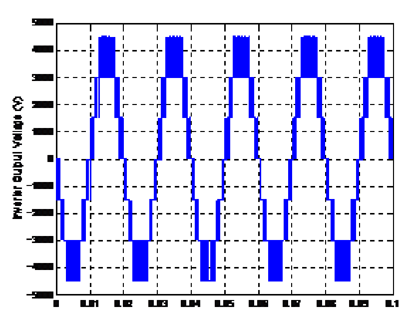


Fig.13. Seven level inverter output voltage for phase –a

Figs. 14 and 15 shows the DC-link capacitors voltage of the cascaded HCSLI-bridges with non-linear load for the phase-a. It can be found that the DC capacitor voltage has small ripple voltage of about 0.5 V and quick settling time with designed NC (lower cell unit and upper cell unit).

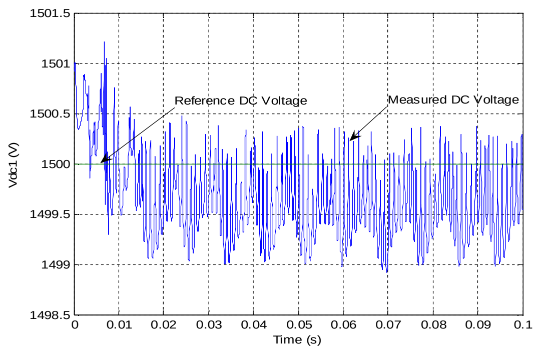


Fig.14. DC Capacitor voltage of SAPF (lower cell)

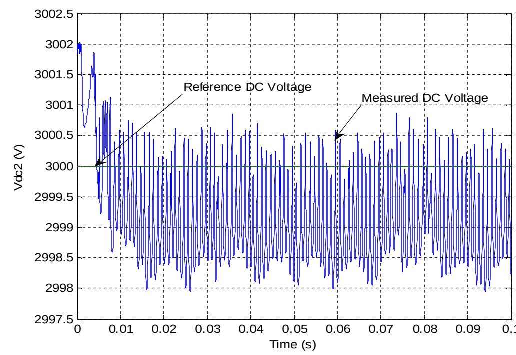


Fig.15. DC Capacitor voltage of SAPF (upper cell)

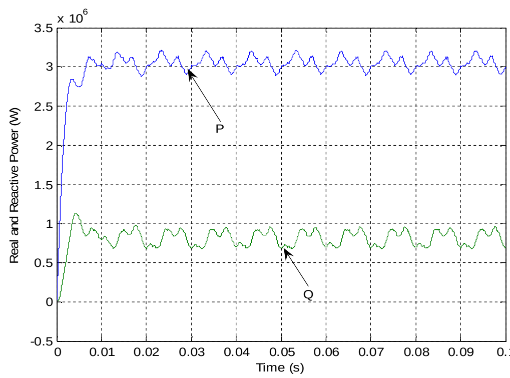


Fig.16. Real power(P) and reactive power (Q) flow with SAPF.

Fig. 16 shows the real power (P) and reactive power (Q) of the proposed system using non-linear load. From this figure, it is clearly observed the real/reactive power has to be enhanced or reduced with SAPF in PS.

5. CONCLUSION

The SAPF using HCSLI was simulated and its performance was analyzed in a test power system with a source and a linear and non-linear loads using MATLAB/SIMULINK. The simulated d-q theory produced required compensating current to suppress the harmonic current and improve the power factor. The CSFMSHPWM method has been successfully suppressed the harmonics and improved the power factor in supply source side for PS. The neuro controller maintained DC bus capacitor voltage constant. The simulation results showed the effectiveness of the designed NC in regulating a stable capacitor DC voltage for HCSLI.

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