Three Phase NPC Based Multilevel Shunt Active Power Filters and Other Active Power Filters-A Comparison and Effects on Harmonics

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Abstract—Power electronic loads, connected to the distributed power plants through power electronic converters, are the source of harmonics and reactive power, which affects the performance of the power system network. Switching compensators called Active filters brings an effective alternative to the conventional passive LC filters as they can compensate for several harmonic orders, and are unaffected by major changes in network characteristics, avoiding the risk of resonance between the filter and network impedance and are compact and robust compared with traditional passive compensators.

The aim of this work is to compare various designs of shunt active filters to mitigate and alleviate the harmonics and reactive power issues with controller based on different theories under unbalanced and distorted regimes. This paper compares a novel modulation strategy for a neutral-point-clamped converter based power filter with other techniques. The proposed modulation strategy can minimize harmonics for all the operating points and for any kind of loads, even unbalanced and nonlinear loads. The algorithm is based on a carrier-based pulse-width modulation. Nevertheless, it can generate the maximum output-voltage amplitudes that are attainable under linear modulation, such as space-vector modulation. Furthermore, this technique can be implemented with a very simple algorithm and, hence, can be processed very quickly. This balancing strategy is designed, so that it does not further increase the switching frequencies of the devices when it is applied to the converter. The proposed modulation technique is verified by simulation on SIMULINK/MATLAB.

Keywords—*PWM, SVPWM, THD, SAPF, P-Q Theory, Nearest vectors, Neutral-point balance, Nonlinear loads, Space-vector modulation, Three-level inverter.*

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I. INTRODUCTION

Current harmonics is one of the most significant power quality issues which has attracted tremendous research interest. Shunt active power filter (SAPF) is the best solution to minimize harmonic contamination, but its effectiveness is strictly dependent on how quickly and accurately its control algorithms can perform. Proliferation of nonlinear loads resulting from technological advancements in the power electronics field has attracted the attention of researchers, engineers and others who are concerned about harmonic contamination in power systems. Notably, harmonic currents generated by nonlinear loads have caused many significant power quality problems to the power systems. Not only do they degrade the power factor (PF) performance of an operating power system, but they also cause other severe problems, which include overheating of equipment, errors in measuring instruments, failures of sensitive devices and capacitor blowing.The active power filters have become much popular because of excellent performance to diminish the harmonic and reactive power problems.

In order to restrict activity of harmonic currents, IEEE standard 519 (the latest revised version is IEEE 519-2014) has been formulated. It is clearly stated in the harmonic standard that the total harmonic distortion (THD) for current should be at most 5%. Hence, the 5% current THD limit has always been the performance target that all researchers and designers are trying their best to achieve. In order to deal directly with the harmonic problems and to comply with the 5% limits, conventional passive harmonic filters are applied. However, due to their major weaknesses of bulky sizes and fixed mitigation abilities, innovative and efficient harmonic mitigation tools known as active power filters (APFs) are developed to replace them. Besides, the development of APFs is also spurred by the emergence of power semiconductor switching devices such as insulated-gate bipolar transistors (IGBTs) and availability of powerful controllers such as digital signal processors (DSPs).

In an Active Power Filter (APF) we deploy power electronics to introduce current components which removes harmonic distortions incurred by the non-linear load. As shown in Fig.1an active filter sense the harmonic components in the line and then produce and inject an opposing and inverting signal of the detected wave in the system. The two main fields of research in active power filters are the control algorithm for current detection and load current analysis method.

The controller of the active filter is the heart of the filter which notably affects its performance [1]. Control technique depends on the overall system control, such as extraction of reference signal, capacitor voltage balance control and generation of gating signals etc.In general, the controlling techniques are open loop control and closed loop control [2].The closed loop control can further be classified as constant capacitor voltage

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control, constant inductor current control, optimal control and linear voltage control etc [3].

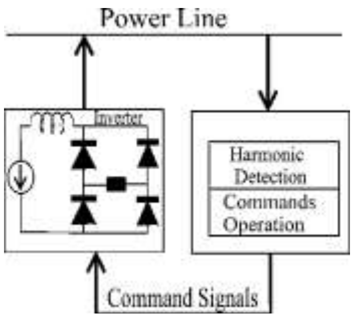

Fig. 1. Conceptual demonstration of active filter

Another important classification is according to the estimation of reference current and voltage control, which can be represented either in time domain control or the frequency domain control that are processed by the open loop or closed loop control[8]. Although, there is a number of control techniques, but the SVPWM technique is the best in terms of percentage of THD of the compensated currents. In terms of efficiency, because this switching technique defines the state of all the inverter IGBTs as one block, it presents better SAPF efficiency [9].In this switching technique the reference signal is compared with the output current in the αβ0 frame as shown in Fig. 2.With this comparison are obtained three errors (e_α, $e_\beta$and e_0). The errors e_α, $e_\beta$and e_0 are the input of two PI controllers.

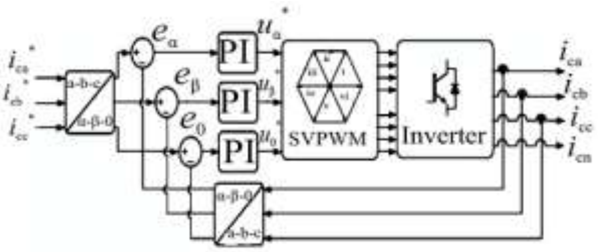

Fig.2. Block diagram of the implemented switching technique: Space Vector PWM (SVPWM)

The outputs of the two PI controllers are then used to determine which vector must be used in the αβ0 frame [7]. This paper presents a design and implementation of suitable control strategy for shunt active power line conditioner[9]. The THD of the source current is reduced to less than 5%, which complies with IEC 61000-3 and IEEE 519 harmonic standards. The modeling of the test electrical system and the passive and active filters has been carried out in the MATLAB/Simulink simulation software.

II. INSTANTANEOUS P-Q THEORY

Instantaneous Reactive Power Theory deploys the Park Transform, given in expression (1), to produce two orthogonal rotating vectors (α and β) from the three phase vectors (a, b and c). This transform is applied to the voltage and current, with the symbol x used to represent v or i. It should be noted that IRPT assumes that the threephase load is balanced[2].

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \qquad (1)$$

The supply voltage and load current are converted into α-β quantities. The instantaneous active and reactive powers, p and q, are calculated from the transformed voltage and current. By observing instantaneous powers, the harmonic content can be visualized as a ripple upon a DC offset representing the fundamental power. By removing the DC offset with a suitable high pass filter [3], and then performing the Inverse Park Transform the harmonic current can be determined [2].

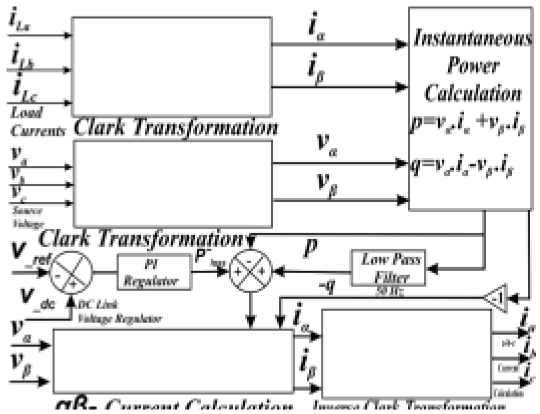

Fig. 3. Shows the resulting algorithm for the calculation of reference currents of the compensator for the constant active power supply

III. SYNCHRONOUS REFERENCE FRAME ALGORITHM

Bhattacharya et al [5],proposed using the DQ transforms, given in (2), which changes the three conventional rotating phase vectors into direct (D), quadrature (Q) and zero (0) vectors. The fundamental component for each is now a dc value with harmonics appearing as ripple [10].The synchronous frame method uses Park's transformation to transform the three phase ac quantities into the synchronous rotating direct, quadrature and zero sequence components which are dc components and easy to analyzed [2].The direct and quadrature components represent the active and reactive powers respectively. Harmonic isolation of the DQ transformed current signal is achieved by removing the DC offset with a high pass filter.

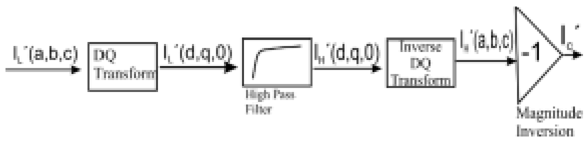

Fig.4. Block diagram of the SRF based active filter controller.

$$\begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \cos(\omega t) & \cos\left(\omega t - \frac{2}{3}\pi\right) & \cos\left(\omega t + \frac{2}{3}\pi\right) \\ -\sin(\omega t) & -\sin\left(\omega t - \frac{2}{3}\pi\right) & -\sin\left(\omega t + \frac{2}{3}\pi\right) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

Fig.4, illustrates the block diagram of the DQ active filter. One of the main differences of this method from p-q theory is that the d-q method requires the determination of the angular

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position of the synchronous reference of the source voltages; for this a PLL algorithm is used [8].

IV. SVPWM TECHNIQUE

The SVPWM method is mostly used in vector controlled applications to generate reference voltage when current control is deployed. The SVPWM technique is more preferable over conventional technique because of its excellent features [7].

- Efficient use of DC supply voltage.
- 15% greater output voltage than conventional modulation.
- Total Harmonic distortion (THD) is very low.

A model of a three-phase inverter is shown on the basis of space vector representation in Fig. 5.

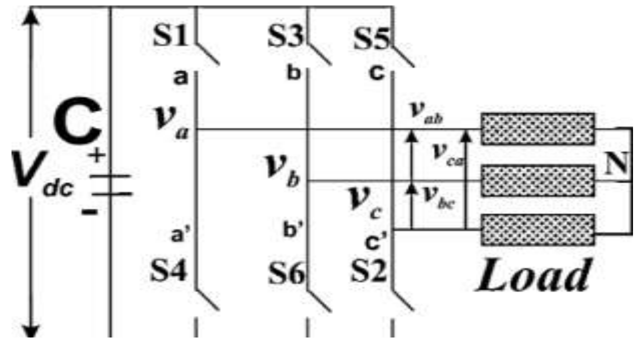

Fig.5. Power circuit of a three-phase VSI

The relationship between the switching variable vector [a b c]^T and line-to-line voltage vector $[V_{ab,}\ V_{bc,}\ V_{ca}]$ is given by (3) in the following:

$$\begin{bmatrix} V_{ab} \\ V_{bc} \\ V_{ca} \end{bmatrix} = V_{dc} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} \quad (3)$$

The graphic voltage vector representation in two axis system can be denoted in Fig.6.In SVPWM we deploy a special switching sequence of the upper power switches of a three-phase power inverter [5].

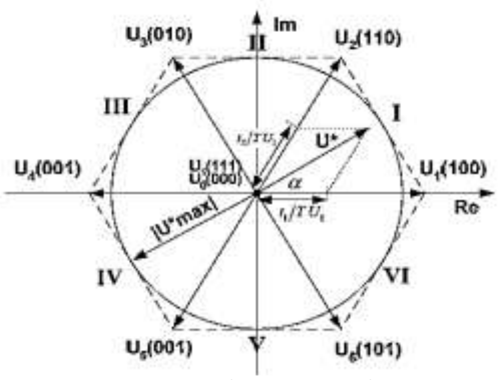

Fig. 6 Graphical representation of voltage vector for each switching state

For the switching time at each sector, a MATLAB code is developed for generating the SVPWM pattern pulses.

V. SAPF'S WITH MULTILEVEL INVERTERS

Multilevel inverters have received tremendous attention, especially in medium and high voltage applications, due to their appealing features in providing high quality output voltage with negligible distortion, minimum harmonic contents and minimum switching losses [12]. Nowadays, it is very difficult to apply a single power semiconductor switch directly to high or even medium voltage networks. Therefore, multilevel inverters which possess the capability to generate higher output voltages without depending on transformer are recognized as cost-effective solutions in higher voltage applications. Typically, the structure of a multilevel inverter consists of an array of power semiconductor switches and DC capacitors. The unique commutation of power semiconductor switches allows the addition of capacitor voltages, producing stepwise waveform with small increase in voltage steps to reach a higher output voltage, while the power switches withstand only reduced voltages.

These unique features allow the usage of power semiconductor devices with smaller ratings, and thus reduce the implementation cost. Therefore, other than higher voltage applications, it will be interesting to apply them at low voltage side as they allow the use of lower voltage-rated devices. Besides, despite the types of applications (low or high voltage applications), multilevel inverters possess the unique capability in generating output waveform with higher voltage level, and thus reduces harmonic distortion in the output voltage waveform. In other words, multilevel inverters are able to generate output voltages of better quality (less harmonic distortion) as compared to two-level inverters. This is an important quality of multilevel inverters which makes them ideal for SAPF applications. In fact, applications of multilevel inverters at low voltage side have been reported in and are proven to exhibit better performance and economical features as compared to two-level VSIs.

For SAPF applications, the most attractive advantages of using multilevel inverters over a standard two-level inverter are;

- They produce output voltages with negligible harmonic distortion, thereby improving the mitigation performance of SAPFs.
- They significantly reduce voltage stresses across the power semiconductor switches, which allows the usage of lower voltage-rated semiconductor devices, and thus improves the economical features of the SAPF.
- They are not only suitable for low voltage applications, but also can fulfil the higher output voltage requirements which are needed for medium and high voltage applications.
- They are able to work with both fundamental switching frequency and high switching frequency pulse-width modulation (PWM). Note that, operating with lower switching frequency provides lower switching losses and higher efficiency.

VI. Nearest Three Vector Modulation

Three level or neutral point clamped converters shown in Fig. 7, are seeing increased application in industrial high power drive systems as they allow the use of lower voltage devices in higher voltage applications, provide reduced output voltage THD and can develop low common mode voltage[4].The NTV algorithm chooses states exclusively based on their proximity to the reference vector position, disregarding any other criterion, which leads to the lowest ripple at the terminals and the best THD [6].

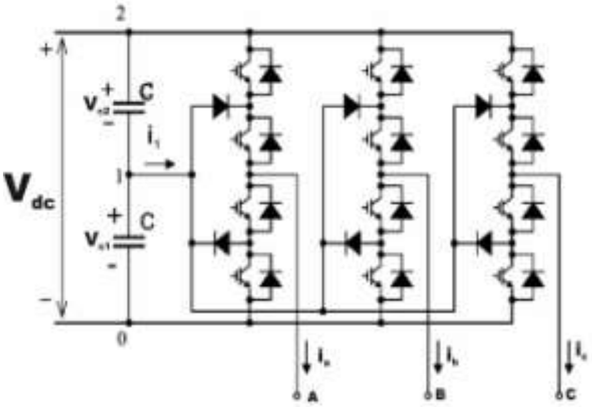

Fig. 7. A Neutral Point Clamped Converter

In Fig.8. the SV diagram of the three- level converter is shown which is divided into sextants, which is again divided into four triangular regions to depicting vectors nearest to the reference which must be generated for each modulation period [4].

VII. Power Filter 1 Based on P-Q Theory

The inputs to the p-q controller are the currents from the non-linear load and the source voltages [5].

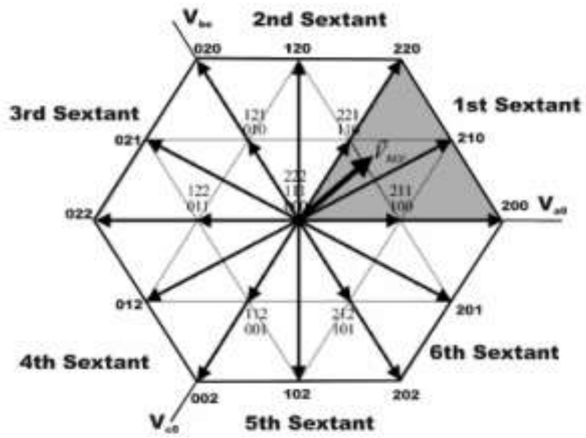

Fig.8. Space-vector diagram of the NPC converter.

The outputs are the three phase reference currents that are send to the hysteresis current controller where these currents are compared with the actual currents of the active filter to get the driving pulses of the inverter. The load currents and the source voltages are converted to αβ frame using (3). These currents and voltages in αβ frame are used to find the instantaneous powers and are modeled in Fig. 9.

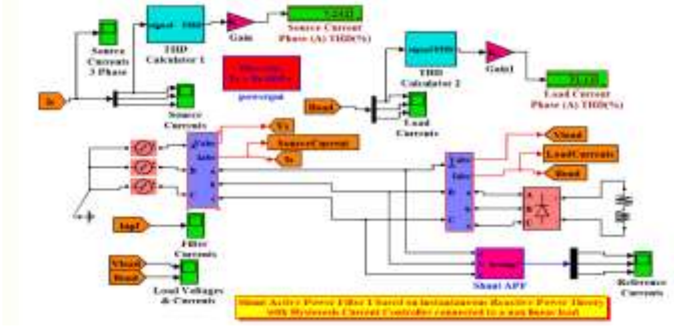

Fig. 9. Simulink Model of Shunt Active Power Filter 1 based on Instantaneous Reactive Power Theory with Hysteresis Current Controller connected to a non – linear load

VIII. Modelling of Shunt Active Power Filter 2 Based on PWM Technique

In discrete PWM technique based hybrid filters, the reference current can be calculated by'd-q' transformation. The basic structure of SRF controller consists of direct (d-q) and inverse (d-q)-1 park transformations as shown in Fig.10. These are useful for the evaluation of a specific harmonic component of the input signals [8].

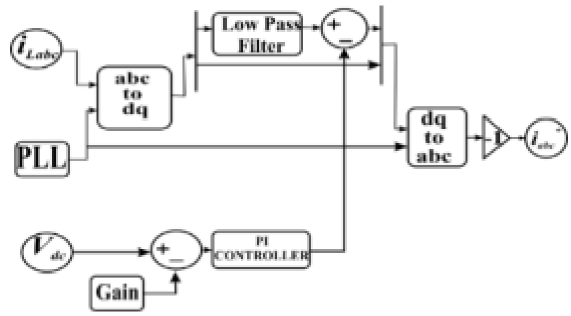

Fig.10. Synchronous d-q-0 reference frame based compensation algorithm

Fig.11 shows MATLAB/ Simulink model of a shunt active power filter 1 connected to the network.

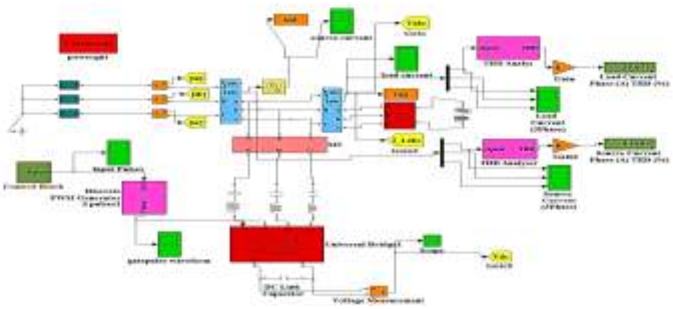

Fig. 11. Simulink Model ofShunt Active Power Filter 2 based on PWM technique connected to a non -linear load.

IX. Modelling of Shunt Active Power Filter 3 Based on SVPWM Technique

The heart of the APF shown in Fig.12, is a forced-commutated VSI connected with a dc capacitor.

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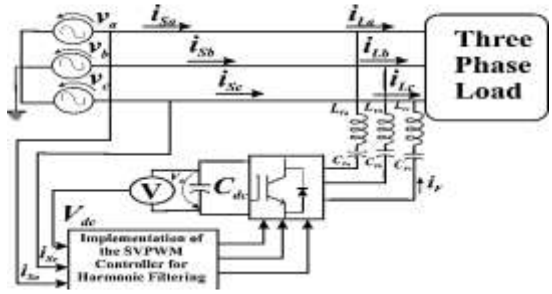

Fig. 12. Configuration of a Hybrid APF using SVPWM

As shown in Fig.12, the shunt APF has a three-phase voltage source inverter as the main circuit and deploys capacitor as the energy storage element on the dc side to maintain the dc bus voltage V_{dc} constant.

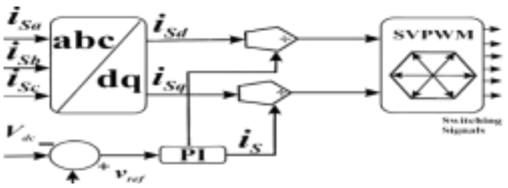

Fig.13. Control block diagram of proposed algorithm

The Fig.13, shows the block diagram of active filter controller used for reducing the harmonics together with hybrid active filter system. In each switching cycle, the controller samples the supply currentsi_{sa},i_{sc}, and the supply current $i_{sc}$is computed with the equation of - (i_{sa}+i_{sc}), as the summation of three supply current is equal to zero. These three-phase supply currents are again measured and transformed into synchronous reference frame (d-q axis) [9].

X. MODELLING OF SHUNT ACTIVE POWER FILTER 4 BASED ON SVPWM TECHNIQUE WITH THREE LEVEL (NPC) INVERTER

The diagram in Fig.15 shows NTV modulation technique, in which the dq-gh transformation directly translates the control variables given in dq coordinates into a non- stationary coordinate system, providing useful variables for the modulation [4].

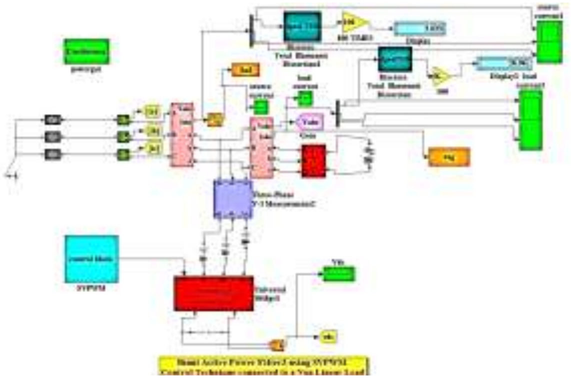

Fig. 14. Simulink Model of Shunt Active Power Filter 3 based on SVPWM technique connected to a non -linear load

All of the calculations are made in the first sextant, therefore the total number of regions involved is divided by six[6].Fig.15 shows the model of the control block based on the SVM algorithm which has an advantage of short processing time. The NTV technique uses only three of the closest vectors per modulation cycle.

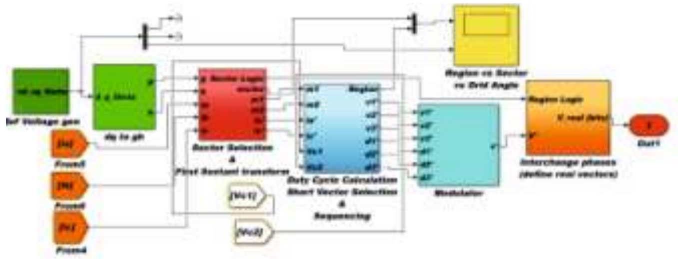

Fig.15. Control block diagram based on the SVM Algorithm.

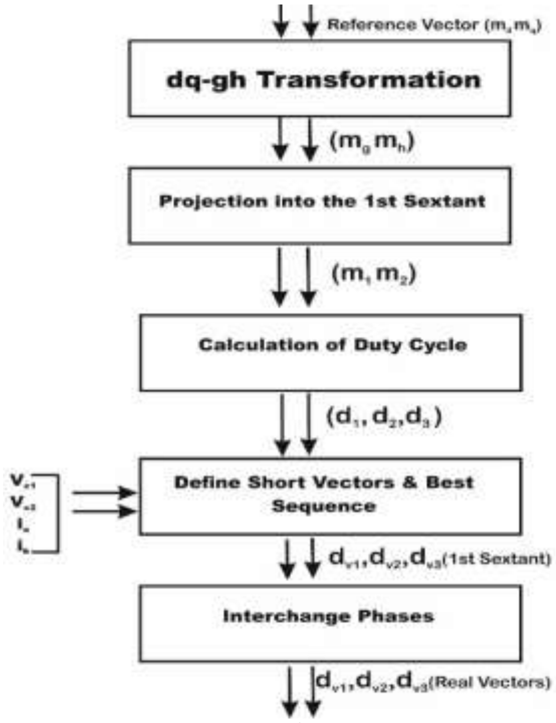

Fig.16. General Diagram of SVM Algorithm

Thus, if the sequences of these vectors are properly applied, this technique produces the minimum switching frequency to the devices[4]. Fig.17 shows the block diagrams for duty cycle calculation and selecting and sequencing the short vector. Fig. 18 shows the model of the filter based on SVM technique with NPC inverter connected to non-linear load[8].

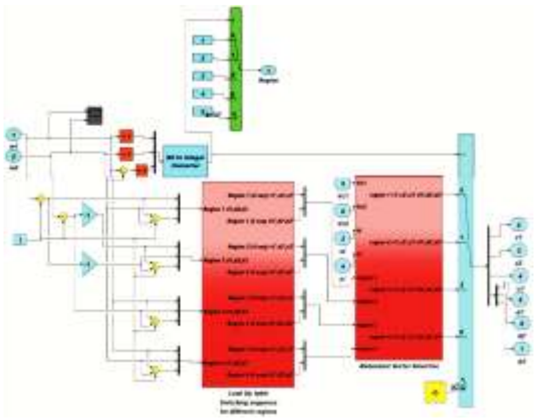

Fig.17.Block diagram showing Duty cycle calculation, short vector selection & Sequencing

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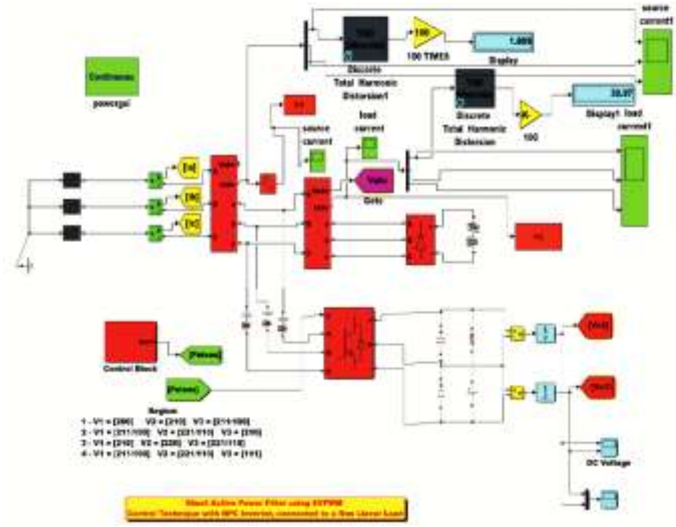

Fig. 18. Simulink Model ofShunt Active Power Filter 4 based on SVM technique with three level (NPC) Inverter connected to a non -linear load.

XI. Simulation Results and Analysis

The performance of the 3 proposed filters are evaluated using MATLAB/SIMULINK power tools. For an input supply voltage of 230V (rms) and switching frequency of 5 kHz, the simulation results before and after power balancing are shown.

A. Performance of Shunt Active Power Filter 1 connected to a Non Linear Load.

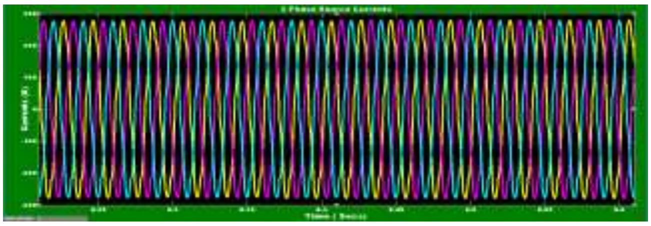

Fig. 19. Input source Current Waveform

Fig.19 shows the source current waveform after compensation.

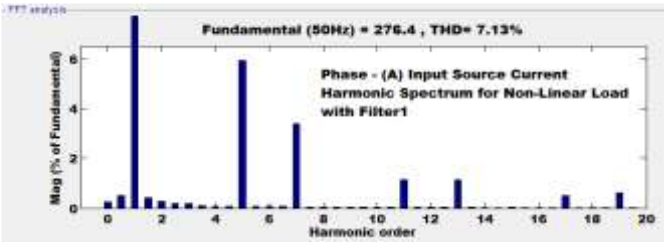

Fig.20. Harmonic spectrums for nonlinear load condition with Filter1

The Fig.20, shows the current harmonic spectrum of three-phase nonlinear load with Filter1 after compensation.

B. Performance of Shunt Active Power Filter 2 connected to a Non Linear Load.

Fig.21 is the source current waveform after compensation. The Fig.22, shows the current harmonic spectrum of three-phase nonlinear load with Filter 2 after compensation.

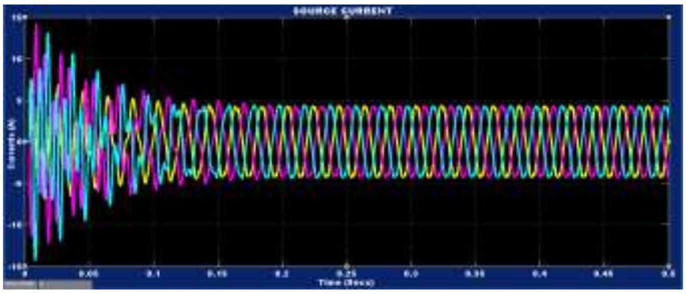

Fig.21. Input Source Current Waveform

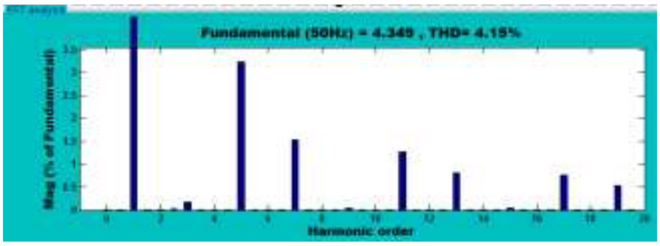

Fig.22. Harmonic spectrums for nonlinear load condition with Filter2

C. Performance of Shunt Active Power Filter 3 connected to a Non Linear Load.

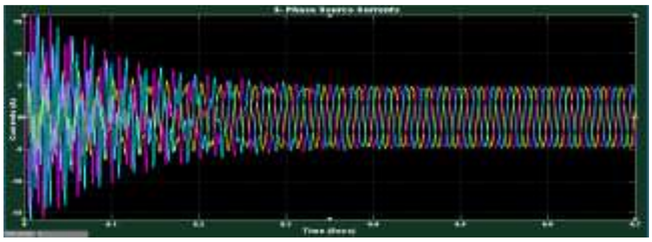

Fig.23. Input Source Current waveforms for Non Linear load condition with Filter 3.

Fig.23 is the source current waveform after compensation.The Fig.24, shows the current harmonic spectrum of three-phase nonlinear load with Filter 3 after compensation.

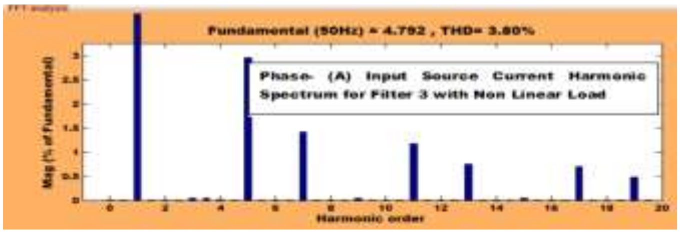

Fig. 24. Input source current harmonic spectrums for nonlinear load condition with Filter 3

D. Performance of Shunt Active Power Filter 4 connected to a Non Linear Load.

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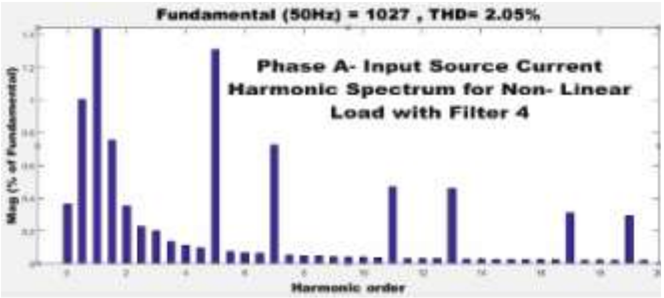

Fig. 25. Input source current harmonic spectrums for nonlinear load condition with Filter 4

The Fig.25, shows the current harmonic spectrum of three-phase nonlinear load with Filter 4 after compensation.

TABLE.1

RESULT ANALYSES FOR NONLINEAR SYSTEM

Non-Linear load							
Filter 1		Filter 2		Filter 3		Filter 4	
THD Load Side	THD Load Side	THD Load Side	THD Load Side	THD Load Side	THD Source side	THD Load Side	THD Source side
30%	7.13%	26%	4.15%	26%	3.8%	26%	2.05%

Table 1 shows the simulation of harmonic spectrum of APF with PWM Technique and SVPWM Technique used for non-linear load used. The harmonic spectrum of the source current shows that magnitude of the 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics are evidently reduced after compensation. The load current Total Harmonic Distortion (THD) is 30%, while the supply current THD is 7.13% when filter1 is used. The load current Total Harmonic Distortion (THD) is 26%, while the supply current THD is 4.15%, when filter 2 is used. The load current Total Harmonic Distortion (THD) is 26%, while the supply current THD is 3.80%. when filter 3 is used. . The load current Total Harmonic Distortion (THD) is 26%, while the supply current THD is 2.05%. when filter 4 is used. The harmonic spectrum shows that there is abetter reduction of higher order harmonics in three-phase source current when non-linear load is simulated using SVM/SVPWM technique.

XII. CONCLUSIONS

SAPF is the most preferred and effective solution to current harmonic problems. Other than providing superior mitigation performance and high flexibility in handling dynamic system conditions, it was popularized by the availability of suitable power semiconductor switching devices and powerful controller at affordable prices. In this paper a three phase three wire shunt active filter with controller based on instantaneous active and reactive power (the p-q) theory, simulated in MATLAB/SIMULINK environment, is compared with PWM and SVPWM techniques with NPC based filters, to compensate the problems of the harmonics and reactive power during non-linear loads. It was experimented that when voltage unbalance or distortion or both are present in the system simultaneously, the simple p-q theory didn't work well. Therefore, PWM and SVPWM control techniques are also observed and their performance are studied. In this research work, four models for three-phase active power filter using four different control techniques, for balanced non-linear load are designed and simulated using MATLAB/Simulink software package for the reduction of harmonics in source current. After careful consideration between different modulation techniques, it is concluded that the space-vector-pulse-width modulation (SVPWM) used with NPC based filters is found to be most popular technique.

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