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Control of CHB 11-level SHAPF for Harmonics Minimisation in Power Systems

P.Jyothi, V.Joshi Manohar and M.Trinadh

Abstract— With the rapid use of power electronic devices induces harmonic disturbances in the power distribution systems. They typically draw non sinusoidal currents and voltages from the utility and adverse effects on power system. Recently, power electronics have stirred the interest in active power filter (APF) being extensively used as shunt or series compensator for harmonic mitigation and reactive power compensation in power distribution systems. The objective of APF is to compensate the harmonic currents produced by the non-linear loads to ensure the sinusoidal currents and voltages to improve power quality. Particularly, in control of SAPF two extraction techniques being used to extract the harmonic currents by using frequency domain and time domain approach. Now a days, multilevel inverters have been developed for high power applications because of it's own advantages. Hence, in this paper, the time domain based approach is proposed for multilevel level inverter based shunt APF (SAPF) for reactive power compensation and to minimize %THD to comply with IEEE 519-1992 harmonic guidelines.MATLAB Simulink environment has been used to validate the proposed technique. Finally an effective time domain approach technique is used to control three phase cascaded eleven-level inverter shunt active power filter (SAPF) with less %THD to comply with IEEE harmonic guidelines have been proposed.

Index Terms— cascaded multilevel Level inverter; Instantaneous active and Reactive Power (p-q) Theory, Shunt active power filters (SAPF); % THD.

1. INTRODUCTION

The concept of flexible AC transmission system (FACTS) uses solid state controller to achieve flexibility of power system operation by fast and reliable to increase power transmission and power quality. In a modern power system, increasing of non-linear loads such as rectifiers, cycloconverters, variable speed drives and arc furnaces, large decaying DC components, asymmetrical loads and other electrical equipment can cause high disturbances of harmonics in the power supply system (Bollen,1999) [1]. With the rapid usage of fast switching of switching devices and nonlinear characteristics of the load are the major sources of harmonics and the harmonics generated by non-linear loads have lower order harmonics tend to dominate in amplitude and the waveform has half-wave symmetry there are no even harmonics and harmonic emissions from a large number of non-linear loads of the same type will be added. If the harmonic currents are not mitigated, it can severely effects power system equipments, de-rating, malfunctioning of processing units, harmonic sensible loads, protection devices, and adverse effects on capacitors, motors, transformers causing additional losses, overheating, and causing interference with the sensitive loads etc [2]. In addition to harmonics, industrial and domestic loads consume reactive power which is an importance issue in discussion of power quality

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To minimize these distorted effects in power distribution system different types of compensators have been proposed for harmonic mitigation and reactive power compensation to increase power quality [3]-[4]. Researches proposed three basic harmonic mitigation approaches in power distribution system can be broadly classified as passive filters, active filters and hybrid filters are proposed by Bhattacharya S.et.al (1995) [5]. Among all, active power filters (Akagi et al., 1984) are an up-to-date solution for harmonic mitigation and power quality problems in high power applications. They can suppress not only the harmonic currents but also reactive currents in power distribution system.

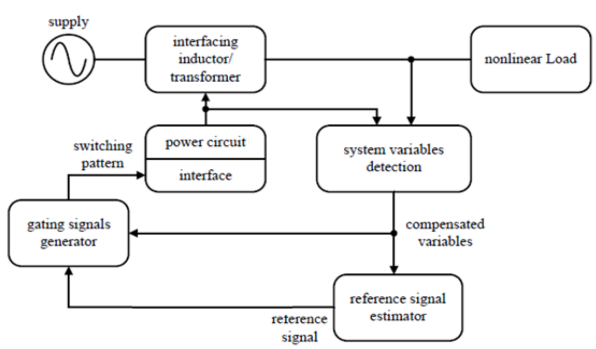

Fig.1.Generalized block diagram for Active power filter

The basic block diagram of APF shown in Fig 1, and the basic principle of APF is to produce compensated harmonic currents that cancel the harmonics caused by the nonlinear load. The information about the harmonic currents which are generated by non linear loads are passed to the compensation current/voltage reference signal estimator which in turn provides the control for the gating signal generator for harmonic current cancellation. **Gonzalez, D. A.,** et.al [3][4] proposed shunt passive filters for harmonic mitigation in power system. The advantages of active power filters over passive filters are: they can suppress not only the current harmonics but also the reactive currents; they do not cause harmful resonances with the power distribution systems and small in size and also less in cost. Another important feature of APF is unlike passive filters, they are independent of the power distribution system properties. In addition to the advantages mentioned above, APF produces electromagnetic interference particularly at high switching frequency operation to mitigate harmonic currents.

Akagi, H [6] proposed the classification of active filters such as series, shunt and hybrid active power filters based on their objectives, system configuration, power circuits and control strategy. Among all, the simplest method of eliminating harmonics by using shunt active power filter (SAPF) connected in parallel, to compensate unbalanced and non-linear loads to be linear and sinusoidal. The SAPF also used for reactive power compensation and harmonic mitigation to improve power quality (PQ) in distribution systems and also efficient solution for the compensation of high current harmonics and unbalance, together with power factor correction and do not produce harmonic resonances in high power application.

Researchers proposed different control techniques to estimate reference voltages and currents of compensating variables for harmonic mitigation in power distribution systems such as notch filter, scalar control, instantaneous reactive power (p-q) theory, synchronous detection method, synchronous d–q frame method, flux-based control method to improve active filter performance. Also, the direct power control method has found application in active filters. Specific harmonics can be cancelled out in the grid using the selective harmonic elimination method [7-9].

Recently, researchers were proposed a novel cascaded two level inverter based SAPF to compensate reactive power in distribution system by using instantaneous reactive (p-q) theory, synchronous reference frame (d-q) theory. In this method two level inverter connected in cascade to achieve four level operation to reduce THD[14]. But, now a days multilevel inverter based SAPF have become an effective solution for reducing harmonics because of low switching losses in multi level inverter compared to two level inverter.

The control strategy of shunt active power filter (SAPF) is a complex process implemented in three separate steps: (i) Signal monitoring (ii) Estimation of compensating signals and (iii) Generation of gating signals for switching devices of voltage source inverter. The reference compensating signals are estimate in terms of voltages or currents are used to generate reference compensating commands based on two approaches one is frequency domain approach and time domain approach. Among these two approaches, time domain approach is widely used because of features such as less computational effort, less calculations, faster response. They are many control methods such as instantaneous reactive (p-q) theory, synchronous reference frame (d-q) theory and Frize-Bucholz-Depen (FBD) theory are used in time domain approach to estimate reference voltages and currents based on instantaneous derivation of compensating signals. This method uses simple algebraic calculations and transformations. Hence, these techniques have been considered for the estimation of reference compensating current. Another approach of compensation in terms of frequency domain is based on Fourier analysis.

Hence, in this paper a novel topology of eleven level cascaded H-bridge multi-level inverter based of SAPF is used by using p-q theory to minimize lower order harmonics. The novel topology uses five cascaded H-bridge inverters connected in cascaded to achieve multilevel operation. To verify the effectiveness of the proposed control techniques, the simulation study is carried out for %THD at distorted non-linear load conditions. International electrical committees like IEEE and ANSI have proposed certain recommendations like IEC-61000 & IEEE Std. 519-1992, recommended practices and requirements for harmonic control in electric power system to regulate harmonics.

This paper is divided as follows: Section II discusses about control strategies of cascaded eleven-level inverter based SAPF, in Section III Time domain extraction techniques such as instantaneous reactive power p-q theory, in section IV Simulation results of instantaneous reactive power p-q theory, and conclusions are presented in Section IV.

2. Cascaded Multi level Inverter Based Sapf And Control Strategies

With the recent advances in power semi conductor technology and availability of switching devices are used in multilevel inverter at higher levels of power rating. Now a day, multilevel inverter based SAPF have become an effective solution for reducing harmonics is increasingly used in various high power applications. Generally, in high power applications, var compensation is achieved using multilevel inverters [10]. Recently, B.G. Fernandes., et.al has proposed a novel cascaded two level inverter based STATCOM for multilevel inverter topology for reactive power compensation using synchronous reference frame (d-q) theory in high power applications [11]. The two level inverter sufferes from high switching losss in high power applications.

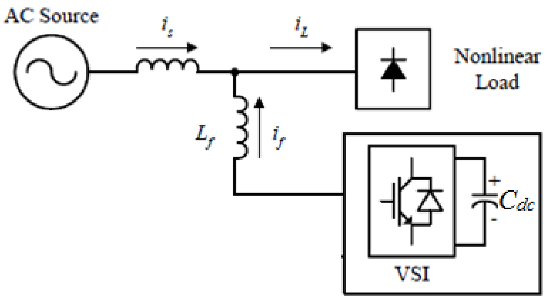

Fig.2. Principle configuration of a VSI based SAPF

The basic SAPF model shown in Fig 2., consists of a voltage source inverter, dc side capacitors (C) with voltage V_{dc} on each capacitor, and a coupling reactor (L_C) or a transformer have been developed for harmonic mitigation and reactive power compensation. The ac voltage difference across the coupling reactor by means of PWM or by control of dc link voltage produces reactive power exchange between the SAPF and the power systems at the point of common coupling (PCC). If the output voltage of the SAPF (V_C) is more than the system voltage (V_L) then reactive power is supplied to the power system and reverse happen if V_C is less than that of V_L. The output voltage of the SAPF can be controlled in two ways either by changing the switching angles while maintaining the dc capacitor voltage at a constant level(direct control) or by changing dc capacitor voltage at fixed switching angles (indirect control) . The charging and discharging of dc capacitor voltage is accomplished by phase shifting of SHAPF voltage with respect to power system voltage.

From topology point of view, the SAPF can be classified into two categories: i) multi-pulse type and ii) multilevel type. In multi-pulse inverter, the units are connected through a specially designed zigzag transformer to achieve high pulse inverter (i.e. 12, 24, 48-pulse) for better waveform and high power applications. The necessity of zigzag transformer which occupies more space and makes the configuration more complex is the major demerit of it. The multilevel inverters are further classified as: diode-clamped or neutral point clamped (NPC) topology, flying capacitors (FC) topology and cascade or isolated series H-bridges (CHB) topology.

Among all the topologies, CHB is the most popular for static var compensation because of the following advantages. (i) Achievements of high power levels by using less rating of semiconductor devices, (ii) no clamping diodes are required in NPC topology (iii) voltage balancing capacitors are not needed in FC topology (iv)Less dv/dt stresses which results in less Electro Magnetic Interference (EMI), (v) lesser common node voltages and producing output voltage with less harmonic distortion.

The cascaded multilevel inverter (CMLI) consists of a number of H-bridge inverters connected in cascade or series with a separate dc source as shown in Fig 3.

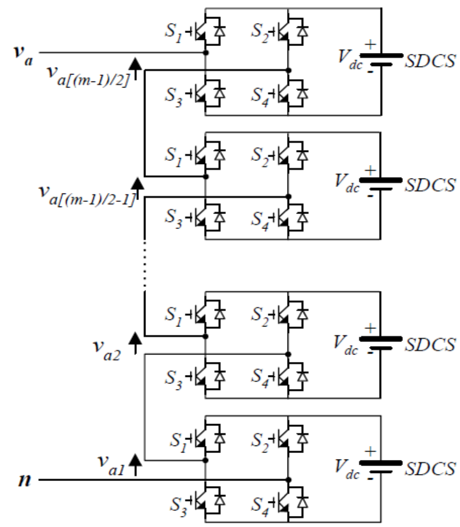

Fig.3. Cascaded Multi Level inverter based SAP

Each H-bridge can produce five different voltage levels:-+2V$_{dc}$, +Vdc, 0, &-2Vdc,–Vdc are connecting different combinations of the four switches. When S_1 and S_4 switches are turned on $+V_{dc}$ is obtained, whereas $-V_{dc}$ can be obtained by turning on switches S_2 and S_3. Zero output voltage is obtained by turning on S_1 and S_2 or S_3 and S_4 .

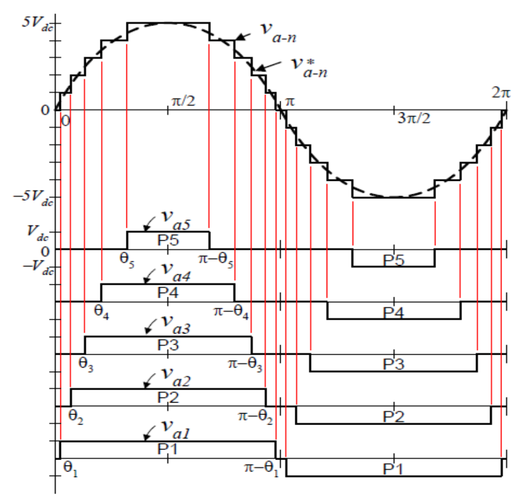

Fig.4. Cascaded Multi Level inverter based SAPF

For an eleven-level inverter which contains five separate sources, the per phase voltage is given by eq (1)

$$V_{an} = V_{a1} + V_{a2} + V_{a3} + V_{a4} + V_{a5} \quad (1)$$

Eleven level inverter of cascaded inverter ac output voltage is shown in Fig 4. The ac output of each H-bridge is connected in series such that the synthesized output voltage waveform is the sum of all of the individual H-bridge outputs.

3. Time Domain Harmonic Extraction Technique:

Harmonic extraction is the process in which, reference current is generated by using the distorted waveform shown in fig 5. The main objective of active power filter is to inject the harmonic current extraction into the converter under non linear condition. Many theories such as p-q theory (Instantaneous reactive power theory), d-q theory, frieze controller, PLL with fuzzy logic controller have been developed based on compensation reference signal in terms of voltage/current is estimated in frequency or time domain approach. Recently, neural networks and the adaptive linear neural networks have been used [7]-[9].

Most APFs have been designed on the basis of instantaneous reactive power theory (p-q), first proposed by Akagi et al in 1983[6].

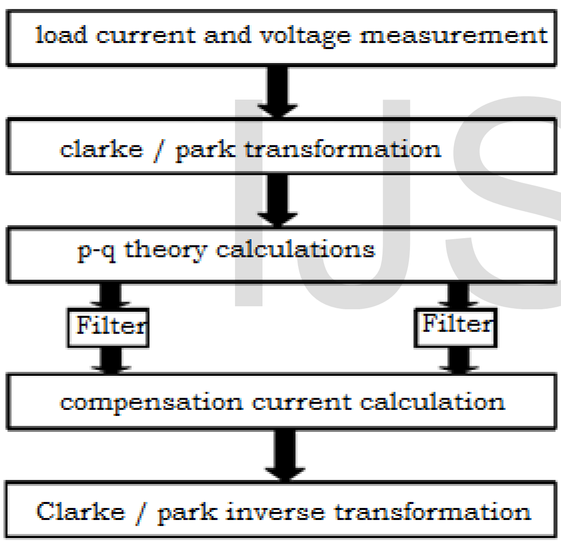

Fig.5. Control algorithm of harmonic extraction technique

This method uses the transformation of distorted currents from three phase frame abc into bi-phase stationary frame based on a set of instantaneous powers defined in the time domain. The three phase supply voltages (va, vb, vc) and currents (ia, ib, ic) are transformed using the Clarke transformation. Initially, it was developed only for three-phase systems without neutral wire, being later worked by Watanabe and Aredes for three-phase four wires power systems [12].

This transformation may be viewed as a projection of the three-phase quantities onto a stationary two-axis reference frame. The Clarke transformation for the voltage variables is given by [13]:

$$\begin{bmatrix} V_0 \\ V_\alpha \\ V_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

(2) Similarly, this transform can be applied on the distorted load currents

$$\begin{bmatrix} I_0 \\ I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I \end{bmatrix}$$

(3) The instantaneous active power p(t) is defined by:

$$p(t) = v_a i_a + v i_b + v_c i_c \qquad (4)$$

The instantaneous reactive power can be given by:

$$q(t) = -\frac{1}{\sqrt{3}}[(V_a - V_b)i_c + (V_b - V_c)i_a + (V_c - V_a)i_b + V_\alpha i_\beta - V_\beta i_\alpha \qquad (5)$$

It is important to notice that the instantaneous reactive power q(t) signify more than the simple reactive power. The instantaneous reactive power take in consideration all the current and voltage harmonics, where as the habitual reactive power consider just the fundamentals of current and voltage.

From Eq.(4) and Eq.(5) the instantaneous active and reactive power can be given in matrix form by:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ -V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad (6)$$

A Low Pass Filter (LPF) is used to separate the direct component from the alternating component to separate the harmonics from the fundamentals of the load currents shown in fig 6. The direct component represents the fundamentals of current and voltage and the alternating term is the power of the harmonics of currents and voltages.

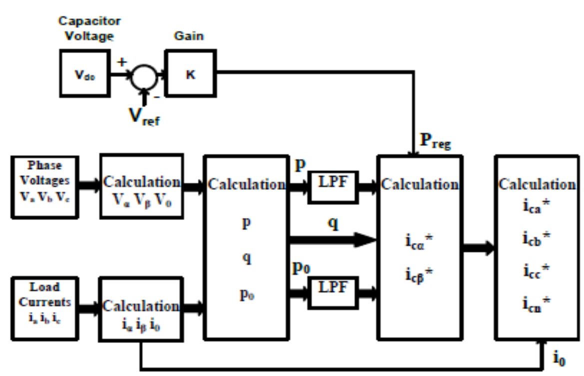

Fig. 6. Instantaneous reactive power (p-q) theory

The harmonic current components of the load currents can be given after the separation of direct and alternating terms of instantaneous power, using the inverse of Eq. (6) which gives:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{V_\alpha^2 + V_\beta^2} \begin{bmatrix} V_\alpha & -V_\beta \\ V_\beta & V_\alpha \end{bmatrix} \begin{bmatrix} \tilde{p} \\ \tilde{q} \end{bmatrix} \qquad (7)$$

Where, the ˜ sign points to the alternating term and the ¯

sign points to the direct component of each active and reactive power. The APF reference current given can be given by equation

$$\begin{bmatrix} i_{fa} \\ i_{fb} \\ i_{fc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (8)$$

Figure 5 represents the principle of active and reactive instantaneous power having the advantage of harmonic compensation or reactive power compensation. The reactive power q(t) is directly send to the reference current calculation block without the use of any extraction filter.

4. Results:

A three-phase 60 kVA four-wire (3 phases and neutral wire), 230V (phase-to-neutral), 50 Hz electrical system, with line impedance of 0.2 pu is considered. This electrical system feeds a non linear load. The proposed SAPF is controlled by p-q theory and the obtained results are shown in Fig. 7-9. From Fig.7, it shows that three-phase load current of non-linear loads and three-phase source currents and voltages compensated by a SAPF. From fig. 7 it is observed that a non linear load is connected to electrical system at 0.1 sec and the proposed SAPF which is controlled by p-q theory is connected during the period of 0.05 sec to 0.09 sec.

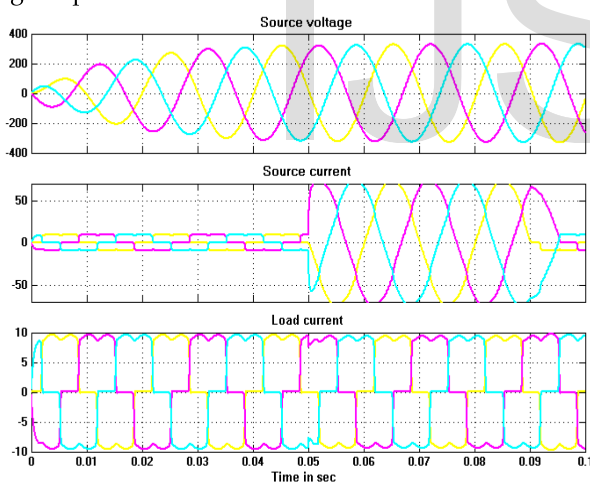

Fig. 7. Instantaneous reactive power (p-q) theory

FFT analysis before connecting the SAPF is shown in Fig. 7. It is seen that %THD present due to the non linear load is 28.29% and lower order harmonics such as 5th, 7th, 11th and 13th are present in higher in magnitude with the values of 22%, 12%, 8% and 7% respectively. The filter design to eliminate all lower order harmonic is expensive and complicated. The developed cascaded H- bridge multilevel inverter based SAPF is connected to the electrical system at 0.05sec and FFT analysis at 0.06 sec is represented in Fig 8-9.

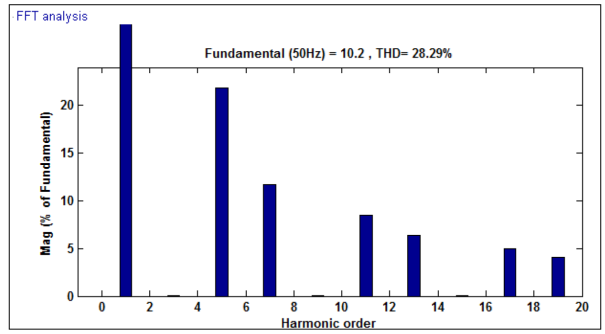

Fig 8.Instantaneous reactive power (p-q) theory under unbalanced condition.

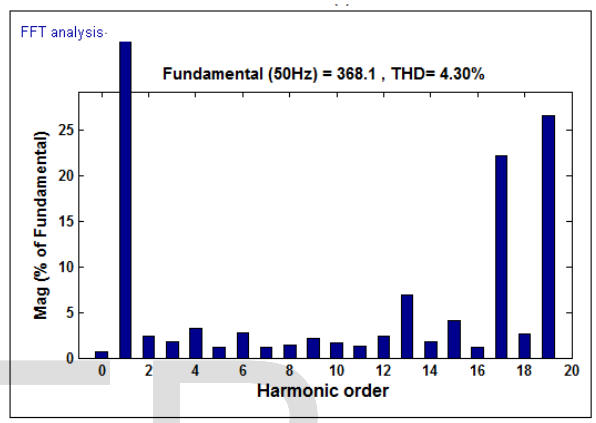

Fig 9. Instantaneous reactive power (p-q) theory under balanced condition

The results proved that developed SHAPF successfully eliminated all the lower order harmonics say 5th, 7th, 11th and 13th to a greater extent and %THD is found to be 4.30%. The magnitudes of 5th, 7th, 11th and 13th are below 5% only. The value of %THD is very near to IEEE 519-1992 harmonic guidelines too.

5. Conclusions:

In this paper, a study of current harmonics, voltages and reactive power compensation and their consequences on the electrical systems have been analysed. The performance of SAPF depends not only on the choice of its power circuit, but also on control strategy. The harmonic extraction operation based on instantaneous reactive power (p-q) theory, theory is considered to control the proposed topology. The Obtained results proved that the techniques have successfully eliminated all the targeted order such as 5th, 7th, 11th and 13th. The %THDs obtained by using p-q 4.30%. Though, the (p-q) technique have successfully minimised all lower order harmonics and value of %THD is 4.30%.

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