Power Enhancement in Distribution Systems Using Space Vector Modulator Controlled Hybrid Filter

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Abstract:- This paper presents a control method for hybrid filter using Space Vector Pulse Width Modulation. In the proposed control method, the Active Power Filter reference voltage vector is generated instead of the reference current, and the desired Active Power Filter output voltage is generated by Space Vector Pulse Width Modulation. The entire power system block set model of the proposed scheme has been developed in MATLAB environment. The APF based on the proposed method can eliminate harmonics, compensate reactive power and balance load asymmetry. Simulation results show the feasibility of the APF with the proposed control method.

Key Words:- Active Power Filter (APF) reference voltage vector, Two Level Inverter, Vector Pulse Width Modulation, Voltage Source Inverter.

1 Introduction
The distortion of voltage and current waveforms and increased reactive power demand in ac mains are due to growing use of non-linear and time-varying loads. Harmonic distortion is known to be source of several problems, such as increased power losses, excessive heating in rotating machinery, and harmonic resonances in the utility, significant interference with communication circuits, flicker and audible noise, incorrect operation of sensitive loads [1, 2].

Generally, LC tuned passive filters have been used to absorb harmonic currents generated by nonlinear loads. Their main advantage is high reliability and low cost. However, passive filters have several drawbacks, which may cause harmonic interaction with the utility problems with the utility system, in the presence of stiff utility sharp tuning of the LC filter is required and may not meet the specified harmonic current limits [3, 4]. This provides the motivation for investigation of an active filter topology, which is practically viable, cost effective and can meet the recommended standard for high power nonlinear loads. For high-power applications, the active filters are not cost effective due to their large rating and high switching –frequency requirement of the Pulse Width Modulation (PWM) inverter.

2 Configuration of Proposed System
This paper studies a transformer less active filter for power conversion systems. Among the various topologies the shunt active filter based on Voltage Source Inverter (VSI) is the most common one because of its efficiency [5]. The performance of active filter depends on the adoptive control approaches. There are two major parts of an active power filter controller. The first is that determines the reference current of APF and maintains a stable DC bus voltage. Various current detection methods, such as instantaneous reactive power theory, synchronous reference frame method, supplying current regulation and etc., are presented. The commonness of these methods is the request for generating reference current of Active Power Filter (APF), either with the load current or the mains current. The second is that controls the VSI to inject the compensating current into ac mains. The commonness of these methods is to control VSI with the difference between real current and reference current.

An alternative control method for shunt APF’s is proposed in this project [6]. The proposed method differs from previously discussed approaches in the following ways: a) To generate APF reference voltage vector instead of reference current; b) to generate desired APF output voltage by Space Vector Pulse Width Modulation (SVPWM) [7, 8] based on generated reference voltage. Therefore, the proposed method is simple and easy to carryout. This paper discussed the basic principle of this method in detail and proved its validity by simulation results.

2.1 Proposed Control Method Using SVPWM
The main section of the APF shown in Fig.2.1 is a forced-commutated VSI connected to dc capacitor.
Considering that the distortion of the voltage in public power network is usually very low, it can be assumed that the supply voltage is ideal sinusoidal and three-phase balanced as shown below:

\[ V_{sa} = V_s \sin(\omega t) \]
\[ V_{sb} = V_s \sin(\omega t - 2\pi/3) \]
\[ V_{sc} = V_s \sin(\omega t + 2\pi/3) \]

Where \( V_s \) is the supply voltage amplitude.

Fig.2.1 Configuration of an APF using SVPWM

It is known that the three-phase voltages \([v_{sa}, v_{sb}, v_{sc}]\) in a-b-c can be expressed as two-phase representation in d-q frame by Clark’s transformation and it is given by

\[ V_s = \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} 2/3 & -1/2 \\ 0 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} \]

(1.2)

It is possible to write equation (3.2) more compactly as

\[ \begin{bmatrix} V_s \\ JV_{sl} \end{bmatrix} = V_s (a^0 + V_{sb} a^1 + V_{sc} a^2) = V_{sd} + jV_{sl} = V_s e^{\theta^s} \]

(1.3)

Where \( a = e^{j\pi/3} \), so balanced three-phase set of voltages is represented in the stationary reference frame by a space vector of constant magnitude, equal to the amplitude of the voltages, and rotating with angular speed \( \omega = 2\pi f \).

Fig.2.2 Equivalent circuit of a simple power system together with the APF

As shown in Fig.2.1, the shunt APF takes a three-phase voltage source inverter as the main circuit and uses capacitor as the energy storage element on the dc side to maintain the dc bus voltage \( V_{dc} \) constant.

Fig.2.2 shows the per-phase (Phase A) equivalent circuit of the system described in Fig.2.1.

2.2 Compensation Principle

In the Fig. 2.2, \( v_{in1} \) and \( v_{in2} \) denote the output fundamental and harmonic voltages of the inverter, respectively. These voltage sources are connected to a supply source (\( v_{sa} \)) in parallel via a link inductor \( L_f \) and capacitor \( C_f \). The supply current \( i_{sa} \) is forced to be free of harmonics by appropriate voltages from the APF and the harmonic current emitted from the load is then automatically compensated.

It is known from Fig.2.2, that only fundamental component is taken into account, the voltages of the ac supply and the APF exist the following relationship in the steady state

\[ \bar{V}_s = L_f \frac{di_{f1}}{dt} + \frac{1}{C_f} \int i_{f1} dt + \bar{V}_{f1} \]

(1.4)

Where \( \bar{V}_s \) is the supply voltage, \( \bar{I}_{f1} \) is the fundamental current of APF, \( \bar{V}_{f1} \) is the fundamental voltage of APF, and above variables are expressed in form of space vector. The APF is joined into the network through the inductor \( L_f \) and \( C_f \). The function of these is to filter higher harmonics nearly switching frequency in the current and to link two ac voltage sources of the inverter and the network. So the required inductance and capacitance can just adopt a small value. Then the total reactance caused by inductor and capacitor for the frequency of 50Hz, and the fundamental voltages across the link inductors and capacitors are also very small, especially compared with the mains voltages. Thus the effect of the voltage of the link inductor and capacitor is neglected. So the following simplified voltage balanced equation can be obtained from equation (1.4).

\[ \bar{V}_s = \bar{V}_{f1} \]

(1.5)

The control object of APF is to make the supply current sinusoidal and in phase with the supply voltage. Thus the nonlinear load and the active power filter equals to a pure resistance load \( R_o \) and the supply voltage and the supply current satisfy the following equation:

\[ \bar{V}_s = R_s \cdot \bar{I}_s \]

(1.6)

Where

\[ \bar{I}_s = \frac{2}{3} (i_{sa} a^0 + i_{sb} a^1 + i_{sc} a^2) = I_{sd} + jI_{sq} = I_s e^{\theta_i} \]

Then the relationship between \( I_s \) and the supply voltage amplitude \( V_s \) is

\[ \bar{V}_{f1} = \frac{V_s}{\bar{I}_s} \]

(1.7)

Substituting (1.6), (1.7) into (1.5) results in

\[ \bar{V}_{f1} = \frac{V_s}{\bar{I}_s} \]

(1.8)
Equation (1.8) describes the relationship between the output fundamental voltage of APF, the supply voltage and the supply current, which ensure that the APF operate normally. However, for making the APF normally achieving the required effect, the dc bus voltage $V_{dc}$ has to be high enough and stable. In the steady state, the power supplied from the supply must be equal to the real power demanded by the load, and no real power passes through the power converter for a lossless APF system. Hence, the average voltage of dc capacitor can be maintained at a constant value. If a power imbalance, such as the transient caused by load change, occurs, the dc capacitor must supply the power difference between the supply and the load, the average voltage of the dc capacitor is reduced. At this moment, the magnitude of the supply current must be enlarged to increase the real power delivered by the supply. On the contrary, the average voltage of the dc capacitor rises, and the supply current must be decreased. Therefore, the average voltage of the dc capacitor can reflect the real power flow information. In order to maintain the dc bus voltage as constant, the detected dc bus voltage is compared with a setting voltage. The compared results is fed to a PI controller, and amplitude control of the supply current $I_s$ can be obtained by output of PI controller. The Fig. 2.3 shows the block diagram of active filter controller implemented for reducing the harmonics with hybrid active filter system. In each switching cycle, the controller samples the supply currents $i_{sa}$, $i_{sc}$ and the supply current $i_{sc}$ is calculated 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 measured and transformed into synchronous reference frame (d-q) axis. The fundamental component of the supply current is transformed into dc quantities in the (d-q) axis and the supply current amplitude $I_s$ generated by the PI controller. The obtained d-q axis components generate voltage command signal. By using Fourier magnitude block, voltage magnitude and angle is calculated from the obtained signal. These values are fed to the developed code and generated switching actions are applied to the APF. Thus, power balancing of the filter takes place. Further, the performance with different type of loads is presented. The complete simulation model of APF with different type of loads is shown in Fig. 3.1 and Fig. 3.4. For an input supply voltage of 230V (rms) and switching frequency of 5kHz, the simulation results before and after power balancing are shown.

### Table 1: Parameter Values

<table>
<thead>
<tr>
<th>System parameters</th>
<th>Values of parameters</th>
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</thead>
<tbody>
<tr>
<td>Supply system</td>
<td>230 V (rms), 50 Hz, three-phase supply</td>
</tr>
<tr>
<td>Balanced linear load</td>
<td>$Z_L = 75 + j 62.83 , \Omega$</td>
</tr>
<tr>
<td>Unbalanced linear load</td>
<td>$Z_L = 75 + j 31.42 , \Omega$, $Z_L = 100 + j 23.56 , \Omega$, $Z_L = 85 + j 31.42 , \Omega$</td>
</tr>
<tr>
<td>Non-linear load with resistance</td>
<td>$R=1000 , \Omega$</td>
</tr>
<tr>
<td>APF</td>
<td>$C_{dc}=1000 \mu F$, $V_{ref} = 750 V$, $C_t = 24 \mu F$, $L_t = 30 , mH$</td>
</tr>
</tbody>
</table>
3.2 Simulation Results

3.2.1 For Balanced Linear Load
Source current and load current are scaled by factor 25 for comparison purpose.

The Fig.3.2 shows the simulation results of the APF when load is three-phase balanced RL load. Fig.3.2 (a) is the waveforms of the phase-A supply voltage and load current before compensation. Fig.3.2 (b) is the waveforms of the phase-A supply voltage and supply current waveforms.

3.2.2 For Unbalanced Linear Load
The Fig.3.3 shows the simulation results of APF when three-phase unbalanced RL load is considered. Fig.3.3 (a) is the waveforms of the three-phase load current before compensation. Fig.3.3 (b) is the waveforms of the three-phase mains current after compensation. From the figures, it can be seen that APF controller can remedy the system unbalance.

3.2.3 For non-linear load with resistance
The Fig.3.5 shows the behavior of the APF when the non-linear load is a three-phase diode bridge rectifier with resistance load. Fig.3.5 (a) is the waveforms of the source phase voltage. Fig.3.5 (b) is the waveforms of the load current before compensation. Fig.3.5 (c) is the waveforms of the supply current after compensation.
The Fig.3.6 shows the simulation of harmonic spectrum of APF when the non-linear is a three-phase diode bridge rectifier with resistance load. Fig.3.6 (a) is the harmonic spectrum of the current before compensation on the load side. Fig.3.6 (b) is the harmonic spectrum of the current after compensation on the source side. The harmonic spectrum of the load current shows that magnitude of the 5\textsuperscript{th}, 7\textsuperscript{th}, 11\textsuperscript{th} and 13\textsuperscript{th} harmonics is very large. The harmonic spectrum of the source current shows that magnitude of the 5\textsuperscript{th}, 7\textsuperscript{th}, 11\textsuperscript{th} and 13\textsuperscript{th} harmonics are evidently reduced after compensation. The load current Total Harmonic Distortion (THD) is 27.98\%, while the supply current THD is 6.32\%. It should be noted that the higher frequency harmonics caused by APF in mains current can be canceled easily by a small passive filter, and there are pulses in main current at the points, where \( \frac{di}{dt} \) of load current is large, because fixed switching frequency restrict the tracking capability of APF.

4 Conclusion

In this paper, a control methodology for the APF using SVPWM is proposed. This method requires few sensors, simple in algorithm and able to compensate harmonics and unbalanced loads. The performance of APF with this method is done in MATLAB/Simulink. The algorithm will be able to reduce the complexity of the control circuitry. The harmonic spectrum under non-linear load conditions shows that reduction of harmonics is better. Under unbalanced linear load, the magnitude of three-phase source currents are made equal and also with balanced linear load the voltage and current are made in phase with each other. The simulation study of two level inverter is carried out using SVPWM because of its better utilization of dc bus voltage more efficiently and generates less harmonic distortion in three-phase voltage source inverter. This SVPWM control methodology can be used with series APF to compensate power quality distortions.

5 References