Study of Different Control Methods of Active Power Filter for Harmonic Reduction

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Abstract—A theoretical study of various control strategies to extract reference current for Active Power Filter (APF) is given in this paper. This paper presents various type of approaches, methods and techniques in detail. The study also helps the to choose the correct control solutions and power circuit design for APF applications.

Keywords — Harmonic Reduction, Shunt Active Power Filter, Reference current, Fundamental current, Fourier Transform, PQ Theory, Wavelet Transform.

I. INTRODUCTION

Almost nineteen years ago, loads used by industry and customers were linear and passive. Therefore the impact of nonlinear loads on the power system has been less significant. Recently, the development of semiconductor devices has become more advantageous. In addition, various power electronic devices and electronic control tools are used to increase the efficiency of the non-conventional energy sources [1]. Even though, the benefits of using the aforementioned devices are certainly good but there are some demerits of excessive usage of electronic power devices. Because of the power electronic devices, harmonics is a big problem in control systems. Harmonics get entered into power system via a point of common coupling. These harmonics result in further losses, overheating, and overloading [2]. As a result, problems of power quality are increasing more and more. It also causes transient disturbances and reduces efficiency. The use of the above mentioned electronic devices is responsible for harmonic disturbances as well as reactive power disturbances. Harmonics and reactive power is the main reason various problems including transformer overheating, feeder voltage distortion, excess amount of neutral current, malfunction of sensitive equipment, poor power factor and damage to electronic devices[2]. A lot of conventional solutions to these problems have been introduced. A passive power filters and capacitors are the simplest traditional methods to lower the harmonics and increase the power factor. But the system becomes bulky because of condensers and inductors and it also causes resonance which makes the system more unstable. Later, Static var compensators with several power factor correction configurations are added. But some SVC configurations have very long response time so they are not suitable for fast fluctuating loads as well as harmonics of lower order. Several methods of harmonic reduction are developed using the power electronics technique to solve harmonic problems.

II. DIFFERENT CONTROL STRATEGIES

A. Multiplication with Sine Function

![Diagram of power stages of active filter](image)

Above figure shows block diagram of power stage of shunt active power filter. Under normal conditions, the source voltage is represented by equation (1) [4]-[6]

\[ V_s(t) = V_m \sin(\omega t) \]  \hspace{1cm} (1)

and load current produced by nonlinear load is represented by equation,

\[ i_L(t) = i_o(t) + i_p(t) + i_q(t) + i_h(t) \]  \hspace{1cm} (2)

This current equation is composition of four current components which are dc component, active component, reactive component and harmonic component respectively. In general we write above equation (2) as follows,

\[ i_L(t) = \sum_{n=1}^{n} I_n \sin(n \omega t + \theta_n) \]  \hspace{1cm} (3)
Above figure represents basic diagram of proposed technique. As shown in the figure load current is multiplied by unity sine function. Sine function is in the phase with source voltage. This product output given to low pass filter and it is denoted by \( P(t) \) and it is represented by,

\[
P_L(t) = V_m(t)i_L(t)
\]

\[
P_L(t) = V_m\sin(\omega t)\sum_{n=1}^{\infty} I_n\sin(n\omega t + \theta_n)
\]

\[
+ \sum_{n=2} I_m\sin(\omega t)\sin(n\omega t + \theta_n)
\]

\[
P_L(t) = p_r(t) + p_c(t)
\]

Where,

\[
p_r(t) = I_V\sin(\omega t)\cos\theta
\]

\[
p_c(t) = I_V\sin(\omega t)\sin\theta
\]

\[
+ \sum_{n=2} I_m\sin(\omega t)\sin(n\omega t + \theta_n)
\]

\[
p_r(t) \text{ represents real power and } p_c(t) \text{ represents supplied by source combination of reactive and harmonic power. As filter provides reactive and harmonic power, the current supplied from source side is given by }
\]

\[
i_L(t) = \frac{p_r(t)}{V_L(t)} = I_L\cos\theta\sin\omega t = I_L\sin\omega t
\]

Where,

\[
I_L = I_L\cos\theta
\]

The current \( i_L(t) \) is in phase with the source voltage and it is sinusoidal. At the same time, the Active Power Filter (APF) should inject compensation current which is given by following equation:

\[
i_c(t) = i_L(t) - i_L(t)
\]

From figure, output of low pass filter is multiplied by unity sine function. The low pass filter output will have value half of the load current peak value of given by the following equation,

\[
\int_{0}^{T/2} i_L(t)\sin(\omega t)dt = I_L/2
\]

The load current equation in (12) should be periodic with period \( T/2 \). So, source current will set a new value according to load current over a half period of cycle. If even harmonics are present the load current, full cycle integration is required. Source current is estimated with the help of product of low pass filter output and a sine function. Under distorted voltage, along with fundamental component load current harmonic component also supplies to average load power. Hence during distorted supply, alternative methods should be used to produce the reference source current.

### B. PQ Transformation

Akagi have presented the theory of the instantaneous reactive power for three phase system. It is also called as p-q theory [7]-[8]. This theory consists of an algebraic transformation of the three phase quantities (a-b-c coordinates) to the two phase quantities (a-β-0 coordinates). The p-q theory implements the Clarke transformation that projects three phase quantities into the stationary reference frame with the help of real matrix.

1) **The clark transformation:** The Clarke transformation transforms the three phase instantaneous voltages i.e. \( V_a, V_b \) and \( V_c \) into two phase instantaneous voltages i.e. \( V_0, V_a \) and \( V_b \) respectively on \( a\beta0 \)-axes. The Clarke Transformation and its inverse transformation is given as follows,

\[
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
= \begin{bmatrix}
\frac{1}{\sqrt{3}} & 1 & 1 \\
-\frac{1}{\sqrt{3}} & 1 & -1 \\
0 & \sqrt{3} & -\sqrt{3}
\end{bmatrix}
\begin{bmatrix}
V_0 \\
V_a \\
V_b
\end{bmatrix}
\]  

\[
\begin{bmatrix}
V_0 \\
V_a \\
V_b
\end{bmatrix}
= \begin{bmatrix}
\frac{1}{\sqrt{3}} & 1 & 1 \\
-\frac{1}{\sqrt{3}} & 1 & -1 \\
0 & \sqrt{3} & -\sqrt{3}
\end{bmatrix}^{-1}
\begin{bmatrix}
V_a \\
V_b \\
V_c
\end{bmatrix}
\]  

One advantage to use the \( a\beta0 \) transformation is that it helps to segregate zero sequence components from the three phase abc quantities. The \( a \) and \( \beta \) axes contains positive sequence and negative sequence components respectively. For balanced three phase voltage system the Clarke transformation and its inverse is written as follows respectively. The matrices in (15) and (16) are axes-transformation of three phase abc coordinates to \( a\beta0 \) frame as given in Fig. 3. \( a\beta0 \) axis is a static frame. The \( a, b \) and \( c \) axes are spatially separated by 120
degrees from each other and αβ0 axes are shifted by 90 degrees apart from each other.

\[
\begin{bmatrix}
  v_α \\
  v_β \\
  v_{0}
\end{bmatrix} = \begin{bmatrix}
  1 & 1 & 0 \\
  1 & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\
  0 & -\frac{\sqrt{3}}{2} & -\frac{1}{2}
\end{bmatrix} \begin{bmatrix}
  v_0 \\
  v_α \\
  v_β
\end{bmatrix}
\]

(15)

\[
\begin{bmatrix}
  v_α \\
  v_β \\
  v_{0}
\end{bmatrix} = \begin{bmatrix}
  1 & 1 & 0 \\
  1 & -\frac{1}{2} & \frac{\sqrt{3}}{2} \\
  0 & -\frac{\sqrt{3}}{2} & -\frac{1}{2}
\end{bmatrix} \begin{bmatrix}
  v_p \\
  v_q \\
  v_0
\end{bmatrix}
\]

(16)

2) The p-q Theory: The p-q Theory [9],[30] is explained for three phase system. Three instantaneous powers quantities are given as in zero sequence power p0, real power p and the instantaneous imaginary power q.

\[
\begin{bmatrix}
p_0 \\
p \\
q
\end{bmatrix} = \begin{bmatrix}
  0 & 0 & 0 \\
  0 & v_α & v_β \\
  0 & -v_β & v_α
\end{bmatrix} \begin{bmatrix}
i_α \\
i_β \\
i_0
\end{bmatrix}
\]

(17)

If zero sequence components (current and voltages) are absent in three phase three wire system (i.e. i0 = 0) then we get only the instantaneous power on the axes. Hence the energy per unit time is represented by the instantaneous real power p for three phase three wire systems. Now relation between the real and imaginary power component p and q respectively is given as follows,

\[
\begin{bmatrix}
p \\
q
\end{bmatrix} = \begin{bmatrix}
v_α & v_β & i_α \\
-v_β & v_α & i_β
\end{bmatrix}
\]

(18)

Both the powers p and q contains fixed value and a oscillating components and mathematically it can be expressed as follows:

\[
p = \bar{p} + \tilde{p}
\]

\[
q = \bar{q} + \tilde{q}
\]

(19)

Similarly, for three phase four wire system a zero sequence power quantity is written as addition of a constant and oscillating components given by equation (20)

\[
p_0 = \bar{p}_0 + \tilde{p}_0
\]

(20)

3) P-Q theory to Active Power Filters: only p and p0 are useful quantities among all the power quantities obtained by using the p-q theory because they represents transfer of energy from the source side to the load side. Other power quantities are compensated by shunt active power filter as shown fig 4.

From fig. 4 we can see the power p0 is transferred from the source side to the active power filter via α-β coordinates. After that this power is given to load side by active power filter via 0 coordinate. The dc capacitors are used to compensate oscillating power p- and p0-. These power quantities are stored in the capacitor and later on transferred to the load side. Capacitors are not required for the compensation of instantaneous imaginary power (q) which contains the reactive power component. Shunt active power filter eliminates only harmonic components. Instantaneous reactive power theory is not applicable for reactive power compensation. Hence another auxiliary circuit is required for compensation of reactive power component. A hybrid filter can be designed by using passive filter in synchronization with active power filter. These hybrid filters perform both harmonic and reactive power compensation. It also helps to improve power factor. This method have fast response time over the other techniques. One demerit of this method is that its algorithm cannot regenerate sinusoidal source current under deformed source voltage. Hence, practically this algorithm is not applicable to distribution systems where some distorted voltage is available in PCC voltage.

![Fig.4 Implementation of pq theory to shunt active power filter](image)

C. Fourier Transform method

It is easy and basic algorithm which is based on Fourier transform technique. This technique produces the reference current even under the distorted supply [10]-[11]. This method also gives a better transient response to load current. If load current contains odd harmonics then it gives better transient response for half cycle and if load current carries even harmonics then it gives good transient response for one cycle. Let us Assume the supply voltage is rigid because of the source inductance and capacitance. As shown in fig. 5 the

(20)
source side supplies a nonlinear load. Nonlinear load consists of a bridge rectifier with load (R, RL, etc). An active power filter is connected to the PCC via a inductor. The filter is used nothing but a voltage source inverter (VSI) which supplies the harmonics and reactive quantities.

In general, source voltage and load current can be written as follows which is given by equation (21) and (22) respectively.

\[ v_s(t) = V_{dc} + V_{m1} \sin(\phi_1 + \omega t) + V_{m2} \sin(\omega t + \phi_2) + \cdots + V_{mn} \sin(n\omega t + \phi_n) \]

\[ i_l(t) = I_{dc} + I_{m1} \sin(\omega t + \phi_1) + I_{m2} \sin(2\omega t + \phi_2) + \cdots + I_{mn} \sin(n\omega t + \phi_n) \]

Using equation (21) and (22) we get

\[ i_s^* = \frac{i_{m1}}{2} \sin(\omega t - \phi_1) \]

\[ i_c^* = \frac{i_{m1}}{2} \cos(\omega t - \phi_1) \]

From (27), the fundamental peak component of the supply voltage is represented by (28).

\[ |v_{m1}| = \frac{2}{\sqrt{2}} |C_{r1}| \]

Using equation (26), (27) and (28) we can calculate fundamental peak value of source current. In the time domain, equation (25) is written as

\[ i_{m1}^* = I_{m1} \sin(\omega t - r_\phi) \]

From equation (29) the compensating reference current is calculated as follows,

\[ i_{c}^* = i_{m1}^* - i_{c}^* \]

D. Wavelet Transform

A Wavelet Transform (WT) method [13]-[18] is used to extract fundamental component of frequency from three phase unbalanced and non sinusoidal load current. Multi resolution analysis (MRA) [15] method is used to extract fundamental component of frequency is shown in fig. 6. The controller tuning parameters are used as inputs to time frequency signals. The extraction using FFT gives incorrect outputs if the signals are distorted. One of the disadvantage of Fourier transform is that points observed in a observation window should be proportional to the numbers of samples per time. If the points in the observation window are not in proportion with number of sample per period it leads to inaccuracy in the extraction. The Wavelet Transform method helps to minimize the above demerit. Wavelet analysis is a new method to applied mathematics [18]. The voltage and current quantities are transferred to the time and frequency axes using the complex wavelet with the help of scaling and translation factors [19].

\[ P_{avg} = \frac{1}{T} \int_{t}^{t+T} v_s(t) i_l(t) dt \]
III. CONCLUSION

1. This paper gives variety of compensation methods for three phase active power filter. The multiplication of sine function is very simple and easy method among all. Voltage related information is not required in this method for calculation. If load current contains odd harmonics then algorithm provides good response time for half period of cycle and if load current contains even harmonics then it gives good response time for one cycle. But both algorithms give unsatisfactory performance for deformed supply.

2. The pq theory is a fast method. But it also unable to regenerate sinusoidal source current under distorted source voltage.

3. The Fourier transform technique and wavelet transform are good one among all other methods.

REFERENCES


[9] H. Akagi “Instantaneous power theory and applications to power conditioning”,


