Chapter 3

Shunt Active Power Filter and Reference Compensating Current Generation Schemes

3.1 Shunt active power filter

Figure 3.1 demonstrates the working of shunt active power filter. Shunt active power filter is used to eliminate current harmonics injected to the mains by the non-linear load. It comprises of power electronic converter with dc-link capacitor as a voltage source which is maintained at a set constant voltage by active power flow from point of common coupling to SAPF. The power electronic converter may be of a conventional two-level type structure or any multi-level structure as shown in figure 3.1. Embedded systems like digital signal processors used for the control of SAPF are also inherent part of shunt active power filter. Inductor $L_{\text{filter}}$ shown in figure 3.1 is a part of SAPF, which helps in restricting the rate of rise of APF current. Shunt active power filter injects compensating currents at the point of common coupling which are equal in magnitude but out of phase with the load harmonics. Shunt active power filter senses the load current. It extracts the harmonics present in the load current by generating reference compensating current with the help of reference compensating current generation schemes. The reference compensating currents so obtained, are supplied to the current controller which generates gate signals for switching the SAPF, by ensuring that APF compensating (actual) current follows the reference compensating current[19], [20].
3.2 Methods of reference compensating current generation

Basic approach of reference compensating current methods used for the control of shunt active power [28]-[39] as mentioned in Chapter-1 of the thesis, is to generate reference compensating currents which contain harmonics injected by the non-linear load current. Reference compensating currents are generated by various mathematical computations using embedded systems like DSPs. The behavior of the reference compensating current generation method affects significantly the compensation provided by the SAPF.

3.3 Reference compensating current generation methods used in the proposed work

In the proposed work following reference compensating current generation methods are used:
• Instantaneous reactive power theory
• Synchronous reference frame method
• Dc-link voltage regulation method
• Fryze current computation technique

3.3.1 Instantaneous reactive power theory

Instantaneous reactive power theory is proposed by Akagi, Nabae and Kanazawa [16],[35]. It is based on a set of instantaneous powers defined in time domain. This theory is also popularly known as p-q theory. The theory is applicable to three-phase system, with or without neutral. This theory is applicable for steady state as well as transient operation of the system. Here, voltages and currents are first transformed from abc to $\alpha - \beta$ coordinates and then the instantaneous power is defined on these co-ordinates. Due to this, entire three-phase system becomes a single unit for this theory.

Figure 3.2 explains the block diagram of p-q theory. Wherein based on instantaneous reactive power theory calculations, the reference compensating currents are derived, by measuring three-phase source voltages $E_a$, $E_b$, $E_c$ and three-phase load currents $i_{la}$, $i_{lb}$, $i_{lc}$. These sensed parameters are transformed into two orthogonal components $E_\alpha$, $E_\beta$ and $i_{l\alpha}$, $i_{l\beta}$ by Clark’s transformation.

$$\begin{bmatrix} E_\alpha \\ E_\beta \end{bmatrix} = \sqrt{2 \over 3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad (3.1)$$

$$E_\alpha = \sqrt{2 \over 3} \left( E_a - \frac{1}{2} E_b - \frac{1}{2} E_c \right) \quad (3.2)$$

$$E_\beta = \sqrt{2 \over 3} \left( \frac{\sqrt{3}}{2} E_b - \frac{\sqrt{3}}{2} E_c \right) \quad (3.3)$$

Similarly, clark’s transformation is applied to load currents.

$$\begin{bmatrix} i_{l\alpha} \\ i_{l\beta} \end{bmatrix} = \sqrt{2 \over 3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{la} \\ i_{lb} \\ i_{lc} \end{bmatrix} \quad (3.4)$$

$$i_{l\alpha} = \sqrt{2 \over 3} \left( i_{la} - \frac{1}{2} i_{lb} - \frac{1}{2} i_{lc} \right) \quad (3.5)$$
In p-q theory, instantaneous voltages and currents are used for calculations. Conventionally the complex power \( S \) is defined using voltage phasor and conjugate of current phasor. But this concept is valid only for steady state condition with fixed line frequency. Hence in this theory, instantaneous complex power is calculated using instantaneous vectors of voltage and current. The instantaneous complex power \( S \) is the product of voltage vector \( E \) and conjugate of current vector \( i^* \).

\[
S = E \cdot i^* = (E_\alpha + jE_\beta) \cdot (i_\alpha^* - j i_\beta^*)
\]  

(3.7)

As the active filter injects the reactive power \( q \) in the system at point of common coupling the sign convention for \( q \) is negative while active power \( p \) is positive. Thus complex power in terms of active and reactive power is given below.

\[
S = p - jq
\]

(3.8)

The instantaneous active and reactive powers are derived from the transformed voltages and currents. For considering the switching and conduction loss of the three-
phase converter used as active power filter, due to non-ideal solid state devices, $p_{\text{loss}}$ is added to the active power. Thus equating real and imaginary parts of (3.7) and (3.8), active power ($p$) and reactive power ($q$) are derived as given in (3.9) and (3.10)

\[
p = p_{dc} + p_{ac} = E_{\alpha}i_{\alpha} + E_{\beta}i_{\beta} \]  
\[
q = q_{dc} + q_{ac} = E_{\alpha}i_{\beta} - E_{\beta}i_{\alpha} \]  
\]

Therefore,

\[
\begin{bmatrix}
p \\
q
\end{bmatrix} = \begin{bmatrix}
E_{\alpha} & E_{\beta} \\
-E_{\beta} & E_{\alpha}
\end{bmatrix} \begin{bmatrix}
i_{\alpha} \\
i_{\beta}
\end{bmatrix} \]  
\[
\begin{bmatrix}
i_{\alpha} \\
i_{\beta}
\end{bmatrix} = \frac{1}{E_{\alpha}^2 + E_{\beta}^2} \begin{bmatrix}
E_{\alpha} & -E_{\beta} \\
E_{\beta} & E_{\alpha}
\end{bmatrix} \begin{bmatrix}
p \\
q
\end{bmatrix} \]  
\]

From (3.12)

\[
i_{\alpha}^* = \frac{E_{\alpha}p - E_{\beta}q}{E_{\alpha}^2 + E_{\beta}^2} \]  
\[
i_{\beta}^* = \frac{E_{\alpha}q + E_{\beta}p}{E_{\alpha}^2 + E_{\beta}^2} \]  
\]

Now,

\[
p = p_{dc} + p_{ac} + p_{\text{loss}} \]  
\]

Thus for harmonic compensation

\[
p = p_{ac} + p_{\text{loss}} \]  
\]

The compensating currents are as follows:

\[
i_{\alpha}^* = \frac{E_{\alpha}(p_{ac} + p_{\text{loss}}) - E_{\beta}q}{E_{\alpha}^2 + E_{\beta}^2} \]  
\[
i_{\beta}^* = \frac{E_{\alpha}q + E_{\beta}(p_{ac} + p_{\text{loss}})}{E_{\alpha}^2 + E_{\beta}^2} \]  
\]

Therefore the compensating currents in three-phase form are

\[
i_{\alpha}^* = \sqrt{\frac{2}{3}}i_{\alpha}^* \]  
\[
i_{\beta}^* = -\sqrt{\frac{1}{6}}i_{\alpha}^* + \sqrt{\frac{1}{2}}i_{\beta}^* \]  
\[
i_{\gamma}^* = -\sqrt{\frac{1}{6}}i_{\alpha}^* - \sqrt{\frac{1}{2}}i_{\beta}^* \]  
\]
3.3.2 Synchronous reference frame method

Here, A-B-C phase load currents \( (i_{la}, i_{lb} \) and \( i_{lc} \) ) are transformed into rotating d-q axis \( (i_{ld} \) and \( i_{lq} \) \) [30], [35], [101]. The d-q transformation, which changes quantities of conventional three phase system into components along direct (d) and quadrature (q) axis, is proposed in [14]. In rotating d-q axis frame, all the components associate with angular frequency \( \omega \) become dc quantities and rest all non-dc (ac). Thus non-linear load current along direct and quadrature axis consists of dc and ac quantities \( (i_{ld,dc}, i_{lq,dc}, i_{ld,ac}, i_{lq,ac}) \) as shown in (3.22) and (3.24).

\[
\begin{align*}
i_{ld} &= i_{ld,ac} + i_{ld,dc} \\
&= \frac{\sqrt{2}}{3} (i_{la} \cos[\omega t] + i_{lb} \cos[\omega t - \frac{2\pi}{3}] + i_{lc} \cos[\omega t + \frac{2\pi}{3}]) \quad (3.23) \\
i_{lq} &= i_{lq,ac} + i_{lq,dc} \\
&= \frac{\sqrt{2}}{3} (-i_{la} \sin[\omega t] - i_{lb} \sin[\omega t - \frac{2\pi}{3}] - i_{lc} \sin[\omega t + \frac{2\pi}{3}]) \quad (3.25)
\end{align*}
\]

Where, \( \omega \) = angular frequency. For reactive power compensation and current harmonic elimination, the dc offset is removed by using a high pass filter. Hence, fundamental is removed and the rest will be harmonic current. Then again d-q to A-B-C transformation is carried out to get three phase reference compensating currents as shown in figure 3.3. The compensating currents \( i_{ca}^*, i_{cb}^*, i_{cc}^* \) can be obtained as follows:

\[
\begin{align*}
i_{ca}^* &= \frac{\sqrt{2}}{3} (i_{ld,ac} \cos[\omega t] - i_{lq} \sin[\omega t]) \\
i_{cb}^* &= \frac{\sqrt{2}}{3} (i_{ld,ac} \cos[\omega t - \frac{2\pi}{3}] - i_{lq} \sin[\omega t - \frac{2\pi}{3}]) \\
i_{cc}^* &= \frac{\sqrt{2}}{3} (i_{ld,ac} \cos[\omega t + \frac{2\pi}{3}] - i_{lq} \sin[\omega t + \frac{2\pi}{3}])
\end{align*}
\]

Figure 3.3: Synchronous reference frame method
3.3.3 DC-Link voltage regulation method

The basic operation of this method is shown in figure 3.4. The supply currents along with providing active power to the load, also maintain the SAPF dc-link voltage. The estimation of the reference currents from the measured dc-link voltage is the basic idea behind the PI controller based operation of the APF [37]-[38]. The dc-link capacitor voltage $V_{dc}$ is compared with its reference value $V_{dc}^*$ in order to maintain the stored energy in the capacitor constant. The PI controller is applied to regulate the error between the dc-link capacitor voltage and its reference. The output of PI controller ($I_{smax}^*$) gives the magnitude for peak of the component of supply current which compensates for dc-link capacitor voltage imbalance and switching losses of SAPF. $I_{smax}^*$ is multiplied by sinusoidal signals of magnitude equal to unity in order to obtain the instantaneous supply reference currents $i_{sa}^*$, $i_{sb}^*$, $i_{sc}^*$. These supply reference currents are compared respectively with the nonlinear load currents $i_{la}$, $i_{lb}$ and $i_{lc}$ and the result of comparison of each phase gives reference compensating currents $i_{ca}^*$, $i_{cb}^*$ and $i_{cc}^*$ respectively. The result of comparison between this reference compensating current and the actual compensating current is sent to hysteresis controller (of each phase, conventionally) in order to generate the switching pulses.

![Figure 3.4: Control scheme for reference current generation by regulating the dc-link voltage](image-url)
3.3.4 Fryze current computation technique

If linearity between voltage and current is desired while performing power compensation, even under distorted and/or unbalanced source voltages, the method of compensation used is known as the generalized Fryze current computation method [39]. The approach for implementation of Fryze current computation technique is explained in figure 3.5. Here the basic approach is to determine the minimized currents (generalized fryze currents) from average value of three-phase instantaneous active power. In order to ensure linearity between current and voltage, admittance $G_e$ is represented by an average value. Average value of $G_e$ is obtained by passing it through a low-pass filter. The generalized Fryze currents are represented by $i_{wa}$, $i_{wb}$ and $i_{wc}$ and are defined as $i_{wk} = G_e E_k$, where $k = a, b$ and $c$.

![Figure 3.5: Fryze current computation technique](image)

The desired reference compensating currents calculated from the active current, after compensation, can be written as,

$$i_{ca}^* = i_{la} - i_{wa} \quad (3.29)$$
$$i_{cb}^* = i_{lb} - i_{wb} \quad (3.30)$$
$$i_{cc}^* = i_{lc} - i_{wc} \quad (3.31)$$
3.4 Design considerations for shunt active power filter

3.4.1 Active power filter inductor and dc-link design (design for simulation studies)

Essential parameters for design are PCC voltage (phase to neutral) $E_a = 230$ V, PCC line voltage $V_{line} = \sqrt{3} * E_a = 398$ V, load current $I = 5.67$ A

- DC-link capacitor voltage ($V_{dc}$)

For a two-level converter structure connected to PCC, dc-link voltage ($V_{dc}$) for single-phase and three-phase system is given by (3.32) and (3.33) respectively.

$$V_{dc} = \sqrt{2} * E_a$$  \hspace{1cm} (3.32)

$$V_{dc} = \sqrt{2} * V_{line}$$  \hspace{1cm} (3.33)

Hence, $V_{dc} = 563$ V. Thus, $V_{dc}$ is considered as 600 V.

- DC-link capacitance $C_{dc}$ [63]

In shunt active power filter the filter has to supply in general only the reactive power component, however in order to take account of switching power loss taking place in the devices (IGBTs) of the active filter, the capacitor needs to supply small amount of active power also. DC-link capacitance $C_{dc}$ is calculated by using the relationship between rating of the system and energy stored in the capacitor.

Rating of the system (P) is given by

$$P = \frac{V_{line}}{\sqrt{2}} * I = \frac{398}{\sqrt{2}} * 5.67$$  \hspace{1cm} (3.34)

$$= 1596 \text{ VA}$$

Energy stored in the capacitor (E) is given by

$$E = \frac{1}{2} C_{dc} V_{dc}^2$$  \hspace{1cm} (3.35)

$$E = P * T$$  \hspace{1cm} (3.36)

Where, T is the discharging time of dc-link capacitor $C_{dc}$. Its value is considered as 40mS (two fundamental cycles) [63].

Thus, from (3.35) and (3.36)

$$P * T = \frac{1}{2} C_{dc} V_{dc}^2$$  \hspace{1cm} (3.37)
\[ C_{dc} = \frac{P \cdot T}{(1/2) V_{dc}^2} \quad (3.38) \]
\[ C_{dc} = \frac{1596 \times 40 \times 10^{-3}}{(1/2)600^2} \quad (3.39) \]
\[ = 355 \, \mu F \]

Thus, in order to have stiff dc-link, \( C_{dc} \) is taken as rounded off value 1000 \( \mu F \).

- SAPF inductor \( L_{filter} \)

The SAPF inductor must be small enough so that the actual compensating current \( \frac{di}{dt} \) is always greater than that of the reference compensating current which in turn helps in tracking the reference compensating current effectively. Now, the standard inductor differential equation for \( \frac{di}{dt} \) is given by (3.40) where \( \Delta V \) is the voltage across the inductor.

\[ \frac{di}{dt} = \frac{\Delta V}{L_{filter}} \quad (3.40) \]

The maximum possible SAPF inductance should be used to achieve the lowest average switching frequency. Thus, maximum value of SAPF inductor is

\[ L_{filter} = \frac{\Delta V}{\max(\frac{di}{dt})} \quad (3.41) \]

The maximum \( \frac{di}{dt} \) of the actual compensating current has to be determined for each harmonic component based on its amplitude and frequency. Thus, the maximum value of SAPF inductor to be considered is given by the equation:

\[ L_{filter} = \frac{(V_{dc}/\sqrt{2}) - (V_{line}/\sqrt{2})}{n \cdot \omega \cdot I_n} \quad (3.42) \]

Where, \( \omega = 2\pi f \) (f being the fundamental frequency of supply) and \( I_n \) is the current of \( n^{th} \) order harmonic.

Inductor should allow the flow of compensating current which includes the harmonic components of load current. Also at the same time it should be ensured that it does not allow the high frequency harmonics generated due to switching of the inverter to flow to the supply [63]. Figure 3.6 shows the simulation result of non-linear load current. Table 3.1 gives the amplitude of each harmonic in the FFT of load current. Triplen and third harmonics are neglected. Contributions of harmonics upto 19th order are considered for inductor design.
Chapter 3 SAPF and Reference Compensating Current Generation Schemes

Figure 3.6: One fundamental cycle of load current $i_{la}$ (simulation result) [X-axis: 0.002 s/div.; Y-axis: 2 A/div.]

Table 3.1: Contribution of individual harmonics in load current (simulated)

<table>
<thead>
<tr>
<th>Order of harmonics</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5^{th}$</td>
<td>0.25</td>
</tr>
<tr>
<td>$7^{th}$</td>
<td>0.17</td>
</tr>
<tr>
<td>$11^{th}$</td>
<td>0.12</td>
</tr>
<tr>
<td>$13^{th}$</td>
<td>0.09</td>
</tr>
<tr>
<td>$17^{th}$</td>
<td>0.07</td>
</tr>
<tr>
<td>$19^{th}$</td>
<td>0.06</td>
</tr>
</tbody>
</table>

$L_{\text{filter}} = \frac{600}{\sqrt{2}} - \frac{308}{\sqrt{2}}$

\[
L_{\text{filter}} = \frac{600}{\sqrt{2}} - \frac{308}{\sqrt{2}}
\]

\[
= \left(\frac{600}{\sqrt{2}} - \frac{308}{\sqrt{2}}\right)
\]

Here for simulation studies $L_{\text{filter}}$ is taken as 1 mH as a result of which it not only blocks high frequency harmonics caused by switching of the shunt APF inverter but at the same time it allows the flow of reference compensating current through it. Also higher $L_{\text{filter}}$ makes the response of active power filter sluggish, hence in order to get fast dynamic compensation, the $L_{\text{filter}}$ must be as small as possible.

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