CHAPTER 2

STUDY OF SHUNT ACTIVE POWER FILTER

2.1 INTRODUCTION

The Active Power Filter (APF) has been developed in last two decades for mitigating harmonics, reactive power, and voltage balance in the low and medium voltage distribution systems. The APF is connected in series between the supply and load for harmonic voltage compensation and it is connected in parallel for the compensation of supply harmonic current. APFs are constructed with either Voltage Source Inverters (VSI) or Current Source Inverters (CSI). It can be classified based on the type of converter, topology, control scheme, and compensation characteristics.

The major categories of active power filter topologies are

- Series Active Power Filter
- Shunt Active Power Filter
- Hybrid Active Power Filter

Series Active Power Filters were introduced by the end of the 1980s and they can operate mainly as a regulating the output voltage and provide isolation between the non-linear load and the utility system. Series Active Power Filters are connected in series with AC mains through a coupling transformer to mitigate the voltage harmonics and regulate the line or load terminal voltage as shown in Figure 2.1. This type of approach is particularly suggested for compensation of voltage unbalances and voltage
sag from the AC supply. They are suitable for low-power applications and provide an alternative to UPS, since no energy storage (battery) is necessary. The Series Active Filter injects a voltage component in series with the supply voltage, and therefore can be regarded as a controlled voltage source, compensating for voltage sags and swells on the load side.

Shunt Active Power Filter (SAPF) is mainly used to resolve the supply current harmonics compensating for the reactive power in the distribution system caused by the non-linear loads as shown in Figure 2.2. SAPFs are connected in parallel with the power distribution system and provide low impedance paths to ground. The SAPF operates as a current source and injecting the current harmonic components generated by the load but phase shifted by 180°. The components of load harmonic currents are cancelled by the usage of the active filter, and the source current remains sinusoidal and in phase with the respective phase to neutral voltage. Shunt Active Filters are commonly used and they are more economical than Series Active Filters.

Series components must be rated for the full current, including the power frequency component. Such a requirement leads to larger component sizes and therefore costs. Shunt filter components generally must be rated for only part of the system voltage (usually with respect to ground). Such requirements lead to smaller component sizes and therefore costs. Table 2.1 shows comparison between Shunt and Series Active Filters.

The hybrid configuration is a combination of Shunt Active Power Filter and Series Active Power Filter is shown in Figure 2.3. These filers are mainly preferred for high power applications which combine the advantages of both active and passive filters as mentioned in Kocabaş et al (2006) and Chen & Jouanne(2001). With this topology, the passive filters have low impedance for current harmonics at the load side, increasing their bandwidth
operation and improving their performance. This performance is reached with only a low power rating PWM inverter, which acts as an active filter in series with the passive filter referred by Akagi et al (2003). Table 2.2 shows comparison among the hybrid filters.

Figure 2.1 Series Active Power Filter

Figure 2.2 Shunt Active Power Filter
Table 2.1 Comparison between Shunt and Series Active Filters.

<table>
<thead>
<tr>
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<th>Shunt Active Filter</th>
<th>Series Active Filter</th>
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<td>Power Circuit</td>
<td>Voltage fed PWM inverter with current loop</td>
<td>Voltage fed PWM inverter without current loop</td>
</tr>
<tr>
<td>Active filter act as</td>
<td>Current source</td>
<td>Voltage source</td>
</tr>
<tr>
<td>Harmonic producing</td>
<td>Thyristor rectifiers with inductive loads, cycloconverters</td>
<td>Large capacity diode rectifiers with capacity loads</td>
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<td>load suitable</td>
<td></td>
<td></td>
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<tr>
<td>Additional function</td>
<td>Reactive power compensation</td>
<td>AC voltage regulation</td>
</tr>
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Figure 2.3 Hybrid Active Power Filter

Table 2.2 Comparison Hybrid Active/Passive Filters.

<table>
<thead>
<tr>
<th>Hybrid Active/Passive filter</th>
<th>Shunt Active Filter + Shunt Passive Filter</th>
<th>Series Active Filter + Shunt Passive Filter</th>
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<tbody>
<tr>
<td>Power Circuit</td>
<td>Voltage fed PWM inverter with current loop</td>
<td>Voltage fed PWM inverter without current loop</td>
</tr>
<tr>
<td>Active filter function</td>
<td>Harmonic compensation or harmonic damping</td>
<td>Harmonic isolation and harmonic damping</td>
</tr>
<tr>
<td>Advantages</td>
<td>Reactive power controllable</td>
<td>No harmonic current flowing through active filter</td>
</tr>
<tr>
<td>Issues</td>
<td>Share compensation in frequency domain between active filter and passive filter</td>
<td>Difficult to protect active filter against over current. No reactive power control</td>
</tr>
</tbody>
</table>
2.2 CONFIGURATIONS OF SHUNT ACTIVE POWER FILTER

SAPF is mainly configured into single-phase system and three-phase system to meet out the requirements for the different types of non-linear loads connected in supply systems.

2.2.1 Single-phase SAPF System

Single phase SAPF system takes care of low power range applications such as UPS, Computers and other domestic applications which produce harmonics in the distribution system are discussed by Srinivas & Axel (2001), Mohan et al (1995). To improve the performance of distribution system the Active Filter is implemented at PCC. The two level voltage source inverter with DC link capacitor is used to construct the Active Filter as shown in Figure 2.4. The inverter is connected in parallel with loads to PCC through interface inductor. The single-phase SAPF compensates current harmonics by injecting equal but opposite phase harmonic compensation current. As a result, the compensated current becomes sinusoidal and it is in phase with the voltage.

![Figure 2.4 Single-Phase SAPF](image-url)
2.2.2 Three-Phase SAPF System

In medium and high power applications, three phase Voltage Source Inverters (VSI) are preferred to meet the requirements reported by Drouin et al (1983), Enjeti et al (1992). The some of the non-linear loads are used without neutral such as Adjustable Speed Drives (ASDs) fed from three wire supply systems as shown in Figure 2.5. But other non-linear loads used to connect in three phase four wire system which consists of neutral point where the single phase loads are distributed is given by Wu & Jou (1995). This approach is cost effective and it is simple in design. It utilizes standard three-leg inverter where the dc-link capacitor is split and the midpoint of the two capacitor is used as a neutral conductor for the return path as shown in Figure 2.6. This topology is to provide a three-phase voltage source, where the amplitude, phase, and frequency of the voltages are always controllable are presented by Peng et al (1990), Lin et al (1991). The two level PWM-VSI consists of six power semiconductor switches with dc - link capacitor and it is connected with the PCC through interface inductor as given by Akagi & Fujita (1995). The function of the interface inductor is suppressing the higher order harmonic components caused by the transistor switching operation. Current harmonics reduction is achieved by injecting equal but opposite phase current harmonic components with the PCC thereby minimizing the current distortion and improving the power quality of the system as given by Akagi et al (1986), Wong et al (1989).

2.3 PRINCIPLE OF COMPENSATION

The basic compensation principle of the SAPF is illustrated in Figure 2.7 (a and b). The SAPF is controlled to draw or supply a compensating current $I_c$ from or to the utility respectively so that it cancels current harmonics on the AC side.
Figure 2.5 Three Phase Three Wire SAPF

Figure 2.6 Three Phase Four Wire SAPF

Figure 2.7 (a) Shunt Active Power Filter and (b) Schematic Waveforms

(a)  
(b)
A shunt active power filter can also be used for reactive power compensation in the source side. The instantaneous current and the source voltage are expressed as follows:

\[ i_s(t) = i_L(t) - i_C(t) \]  \hspace{1cm} (2.1)

\[ v_s(t) = V_m \sin \omega t \]  \hspace{1cm} (2.2)

where \( i_s(t) \), \( i_L(t) \), \( i_C(t) \) are instantaneous values of source, load, and filter current respectively; \( v_s(t) \), and \( V_m \) are instantaneous and peak value of source voltage. If a non-linear load is applied, then the load current becomes non-linear and is expressed using Fourier series as follows:

\[ i_L(t) = I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \]  \hspace{1cm} (2.3)

The instantaneous load power is then given by

\[ p_L(t) = v_s(t)i_L(t) \]  \hspace{1cm} (2.4)

which is then rewritten as follows

\[ p_L(t) = V_m \sin \omega t \{ I_1 \sin(\omega t + \phi_1) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \} \]  \hspace{1cm} (2.5)

The equation (2.5) is expressed as follows:

\[ p_L(t) = V_m I_1 \sin^2 \omega t \cos \phi_1 + V_m I_1 \sin \omega t \cos \omega t \sin \phi_1 + V_m \sin \omega t \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \] \hspace{1cm} (2.6)

Now, \( p_L(t) \) can be resolved as

\[ p_L(t) = p_f(t) + p_r(t) + p_h(t), \]  \hspace{1cm} (2.7)
where $p_f(t)$ is real (fundamental) power, $p_r(t)$ is the reactive power and harmonic power is $p_h(t)$. From (2.7), the fundamental (real) power drawn by the load is

$$p_f(t) = V_m I_1 \sin^2 \omega t \cos \phi_1 = v_s(t)i_s(t) \quad (2.8)$$

with

$$i_s(t) = I_1 \sin \omega t \cos \phi_1 = I_{sm} \sin \omega t = I_{max} \sin \omega t \quad (2.9)$$

where

$$I_{max} = I_1 \cos \phi_1. \quad (2.10)$$

If the SAPF provides the total reactive and harmonic power, the source current $i_s(t)$ will be in phase with the utility voltage and would be sinusoidal. The three phase source currents after compensation are

$$i_{ca}^*(t) = \frac{P_f(t)}{V_s(t)} = I_1 \cos \phi_1 \sin \omega t = I_{max} \sin \omega t \quad (2.11)$$

Similarly,

$$i_{cb}^*(t) = I_{max} (\sin \omega t - 120) \quad (2.12)$$

$$i_{cc}^*(t) = I_{max} (\sin \omega + 120) \quad (2.13)$$

The control scheme of SAPF system is shown in Figure 2.8. In this thesis, control algorithms such as PI/FLC/PI-FLC/SRF/PSO/GA/QBGA are implemented to find the optimum gain values for the PI controller and to estimate the maximum value of supply current $i_{sm}^*$. The instantaneous reference supply currents ($i_{sa}^*, i_{sb}^* and i_{sc}^*$) are computed using $I_{sm}$ and unit voltage vectors($U_{sa}, U_{sb}$ and $U_{sc}$). The instantaneous compensation currents
are derived using the reference currents \((i_{ca}^*, i_{cb}^* \text{ and } i_{cc}^*)\) and by sensing the actual supply currents \((i_{sa}, i_{sb} \text{ and } i_{sc})\). The minimum and maximum value of the compensation current is to be measured using min-max controller.

### 2.4 DESIGN OF SHUNT ACTIVE POWER FILTER

Harmonic current generated by the non-linear loads is fed into the power supply through the PCC. These harmonics corrupt the quality of power supply and subsequently affect the other electrical equipment’s connected to it. Shunt Active Power Filter (SAPF) is designed and realized for enhancement of power quality in terms of current harmonics and reactive-power compensation. Practically, the SAPF is a three phase AC/DC boost converter, where the DC capacitor is used as energy storage element and the inductors \(L\) are used to control the filter currents.

The preliminary design considerations and assumptions are as follows:

1. The AC source voltage is sinusoidal.
2. To design the interface inductor, AC side line current distortion is assumed to be 5%.
3. The power semiconductor switches-bridge is supposed ideal.
4. In Figure 2.8, \(U_{sa}, U_{sb}, U_{sc}\) are the supply voltages, \(I_{sa}, I_{sb}, I_{sc}\) are the supply currents, \(I_{La}, I_{Lb}, I_{Lc}\) are the load currents, \(I_{ca}, I_{cb}, I_{cc}\) are the filter currents and \(V_{dc}\) is the DC capacitor voltage and all currents and voltages are balanced i.e.

\[
U_{sa} + U_{sb} + U_{sc} = 0, \ I_{sa} + I_{sb} + I_{sc} = 0, \ I_{ca} + I_{cb} + I_{cc} = 0
\]

5. The sampling frequency \(f_s\) and the switching frequency are chosen appropriately.
6. The load currents $I_{La}, I_{Lb}, I_{Lc}$ are balanced and periodic of frequency is $f_m$.

7. The maximum current of the devices implementing the bridge switches is $I_{f_{max}}$.

![Diagram of Control Scheme for SAPF](image)

Figure 2.8 Control Scheme for SAPF
8. The steady-state capacitor voltage must be kept inside the range $V_{dc\ min}, V_{dc\ max}$. The upper bound $V_{dc\ max}$ depends on the capacitor chosen and on the number of capacitors connected in series. The lower bound $V_{dc\ min}$ depends on the controllability constraints.

9. The capability of reactive power compensation is fixed.

10. The PWM-VSI is assumed to operate in the linear modulation mode ($0 \leq m_a \leq 1$).

11. The switching frequency selected is a function of the highest order of harmonics to be compensated.

2.4.1 Selection of Devices

The power switches used in the converter must be able to work efficiently at a higher switching frequency and with higher current density. The voltage and current rating of the device selection depends on the maximum current flow through the device and maximum voltage stress on the device during the OFF period. The maximum line current is same as the per phase current in a three-phase system. Maximum voltage stress in the switch is to avoid by selecting the blocking voltage is slightly higher than the $V_{dc}$ to prevent failure of device as discussed by Mahapatra (1999), Stark et al (2006). The switching frequency of the inverter should be as large as possible. From the literature, it is learnt that switching frequency used should be atleast ten times the harmonic frequency to be compensated were presented by Guoqiao et al (2008), Serpa et al (2007). However, the switching losses increase if the device is operated at higher switching frequency.
2.4.2 Selection of Reference Capacitor Voltage $V_{dc \, ref}$:

As per the compensation principle, the active power filter adjusts the current $I_{c1}$ to compensate the reactive power of the load. If the SAPF compensates the entire fundamental reactive power of the load, $I_{s1}$ will be in phase and $I_{c1}$ should be orthogonal to $V_s$ as shown in Figure 2.9. The three phase reactive power delivered from the SAPF can be calculated from the vector diagram. The active filter can compensate the reactive power from utility only when $Vc1 > Vs$.

The PWM-VSI is assumed to operate in the linear modulation mode ($0 \leq m_a \leq 1$), and then the amplitude modulation factor $m_a$ is calculated as stated in Chiang & Chang (1999).

\[
m_a = \frac{V_m}{V_{dc}/2} \quad \text{where} \quad V_m = \sqrt{2}V_{c1} \quad (2.14)
\]

Hence, $V_{dc} = 2\sqrt{2}V_{c1}$ for $m_a = 1 \quad (2.15)$

where $V_{c1}$ - fundamental components in the ac side of PWM inverter.

From the vector diagram

\[
V_{c1} = V_s + j\omega L_c I_{c1} \quad (2.16)
\]
The range of the $V_{c1}$ should be $V_s \leq V_{c1} \leq 2V_s$

The larger $V_{c1}$ means higher $V_{dc}$ and thus higher voltage stress are caused to the switches. Once $V_{c1}$ is determined, the required $V_{dc}$ is calculated with the equation (2.15) by substituting $m_a = 1$.

### 2.4.3 Selection of Inductor

The interface inductors should be at lower flux density with enough ventilation between the conductor and core of the inductor. The following necessities can be enforced on the estimation of interface inductor value is represented by Chaoui et al (2008).

- Provide path for compensation currents (also the rate of change of current) for harmonics and reactive power
- Ensure filtering to a certain quality level of PWM-inverter output current and voltage source ripples

The ripple current of the PWM converter can be given in terms of maximum harmonic voltage that occurs at the frequency $m_f \omega$:

$$I_{ch}(m_f \omega) = \frac{V_{ch}(m_f \omega)}{m_f \omega L_c} \quad (2.17)$$

where $m_f$ is the frequency modulation ratio of the PWM converter.

where, the subscript $h$ is used for representing the harmonics, $m_f$ is the frequency modulation ratio of the PWM-VSI. For the quantitative representation, Ripple Attenuation Factor (RAF) is defined as

$$RAF = \frac{I_{ch}}{I_{c1, rated}} \quad (2.18)$$
The three-phase reactive power $Q_{c1}$ delivered from the SAPF to the system is calculated from the vector diagram,

\[
Q_{c1} = 3V_s I_{c1} = 3V_s \left(\frac{V_{c1}}{\omega L_{c1}}\right) \left(1 - \frac{V_s}{V_{c1}}\right) \quad (2.19)
\]

By solving equations (2.17) and (2.19) simultaneously the value of $L_c$ and $V_{c1}$ can be calculated.

### 2.4.4 Selection of Capacitor

The DC side capacitor serves to maintain a DC voltage with a less ripple in steady state and it serves as an energy storage element to supply the active power difference between load and source during the transient period. In steady state, the real power supplied by the source is equal to the required load power demand. In case any change in load conditions, the real power demand in load side changes. The difference in real power between source and load is regulated by using DC capacitor. If the DC capacitor voltage is attained the reference voltage, the real power supplied by the source is equal to load demand. The real and reactive power injection results in the ripple voltage of the capacitor which introduces finite delay.

The DC capacitor selection is based on the principle of instantaneous power flow on dc and ac side of PWM inverter. The selection of $C_{dc}$ can be governed by reducing the voltage ripple. As per the specification of peak-to-peak voltage ripple $V_{dr,p-p\ (max)}$ and rated filter current $I_{c1,\text{rated}}$ the dc side capacitor $C_{dc}$ can be found from

\[
C_{dc} = \frac{\pi I_{c1}}{\sqrt{3} \omega V_{dr,p-p(\text{max})}} \quad (2.20)
\]
2.5 CONCLUSION

The SAPF system is implemented with either current source inverter or voltage source inverter depending upon the requirements. The PWM-VSI inverter is more popular to construct SAPF to mitigate supply current harmonics as it is more dominant than supply voltage harmonics. Also PWM-VSI has advantages such as less weight and it is possible to increase the multilevel topology in order to improve its performance. Based on the nature of the load, the system may be considered either single phase or three wire and four wire configuration. The basic compensation principle and design criterion for various components in SAPF has been studied in detail in this chapter. In next chapter a detailed study is presented on multilevel inverter.