

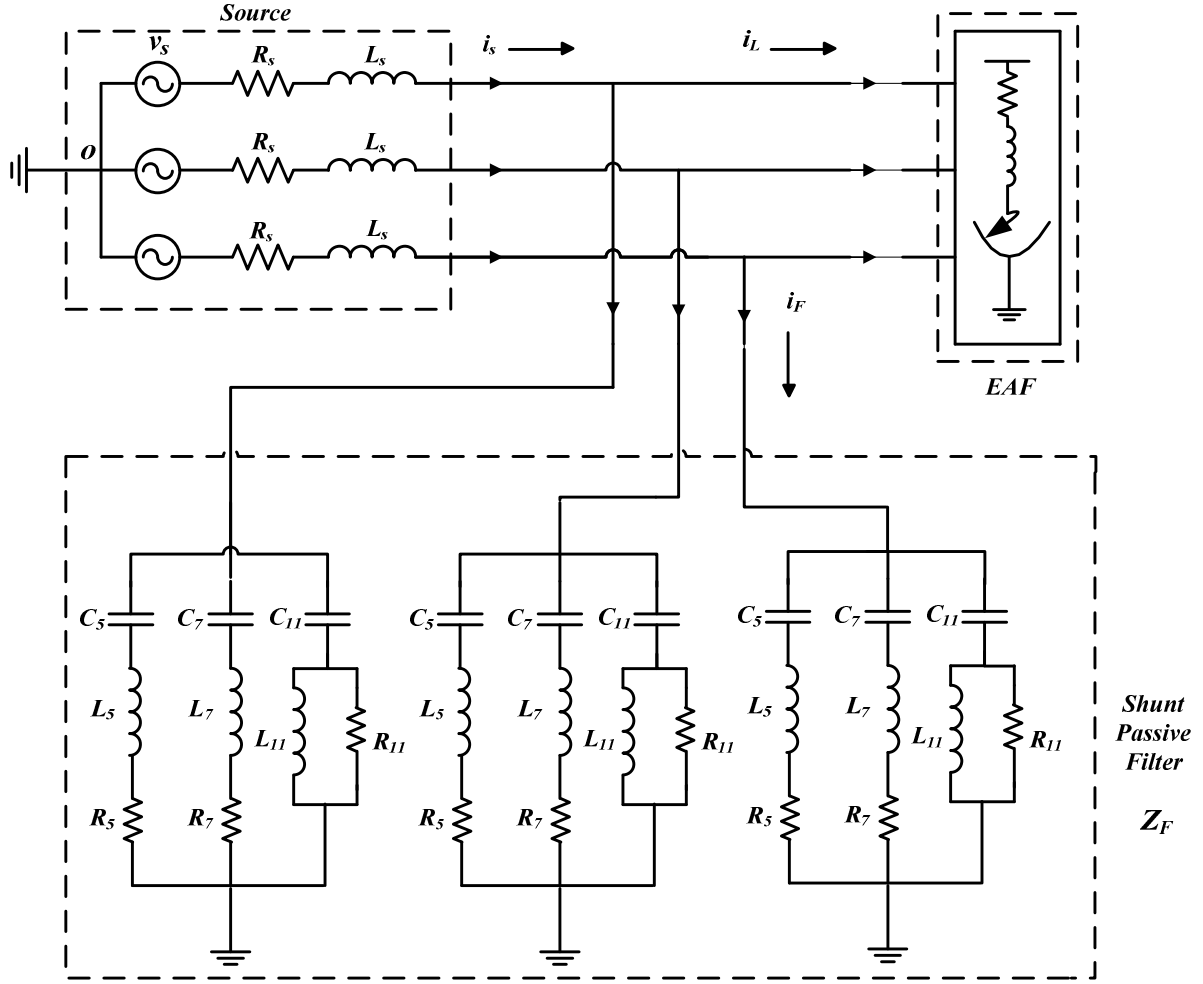
## **3 Passive Filter Design and Simulation**

### **3.1 Introduction**

The passive filters are used to mitigate power quality problems. Generally, passive shunt filters are recommended for current source type of harmonic producing loads [21]. These filter apart from mitigating the current harmonics, also provide limited reactive power compensation and dc bus voltage regulation. However, the performance of these filters depends heavily on the source impedance present in the system, as these filter act as sinks for the harmonic currents. These filters block the flow of harmonic current into ac mains, by providing high impedance path at certain harmonic frequencies for which the filter is tuned. Moreover, the harmonic compensation is practically independent of the source impedance. This chapter presents a detailed investigation into the use of passive filters.

### **3.2 Shunt Passive Filters**

Fig. 3.1 shows the schematic diagram of a shunt passive filter connected at PCC of EAF distribution network. This is the most commonly used configuration of passive filters. In this configuration different branches of passive tuned filters (low pass and high pass) tuned for the more dominant harmonics are connected in parallel with the load. It consists of a set of low pass tuned shunt filters tuned at 5th and 7th harmonic frequencies and high pass tuned for 11th harmonic frequency. This passive filter scheme helps in sinking the more dominant 5th and 7th and other higher order harmonics and thus prevents them from flowing into ac mains.



**Figure 3.1 Schematic diagram of shunt passive filter connected to EAF distribution network**

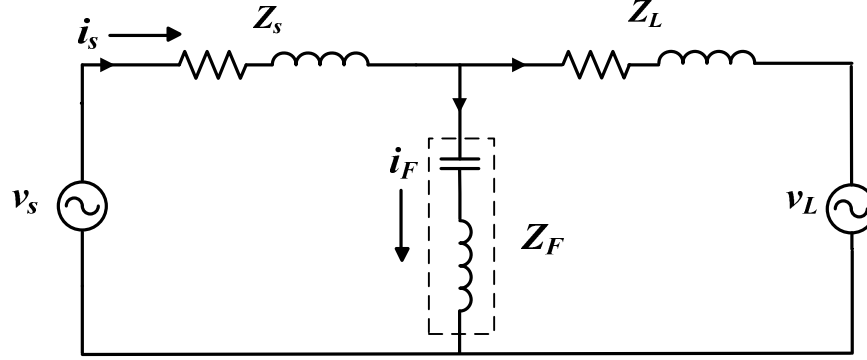
The diversion of harmonic current in the passive filter is primarily governed by the source impedance available in the system. The higher value of source impedance offers better performance of the passive filter.

### 3.2.1 Compensation Principle of shunt passive filters

A passive shunt filter mainly consists of several LCR branches each tuned at a particular frequency. Fig. 3.2 shows the equivalent circuit diagram of a passive tuned shunt filter. The compensation characteristics of a passive shunt filter can be given as [21]:

$$\frac{I_S}{V_L} = \frac{Z_F}{(Z_L \cdot Z_S + Z_L \cdot Z_F + Z_S \cdot Z_F)} \quad (3.1)$$

Eqn. (3.1) implies that the performance of parallel LC filter greatly depends on the source impedance and is determined only by the ratio of the source impedance and the filter impedance.



**Figure 3.2 Equivalent circuit diagram of tuned shunt passive filter**

If  $Z_L=0$ , then eqn. (3.1) results into,

$$\frac{I_s}{V_L} = \frac{Z_F}{(0 + 0 + Z_s \cdot Z_F)}$$

$$\therefore \frac{I_s}{V_L} = \frac{1}{Z_s}$$

$$\therefore I_s = \frac{V_L}{Z_s} = I_L \quad (3.2)$$

This means that passive filter is non-effective.

If  $Z_s=0$ , then eqn. (3.1) results into,

$$\frac{I_s}{V_L} = \frac{Z_F}{(0 + Z_L \cdot Z_F + 0)}$$

$$\therefore I_s = \frac{V_L}{Z_L} = I_L \quad (3.3)$$

This means that the passive filter does not provide harmonic compensation.

It is seen that the filter interaction with the source impedance results in a parallel resonance. For inductive source impedance, this occurs at a frequency below the frequency at which the filter is tuned. It is as follows:

$$f_r = \frac{1}{2 \cdot \pi \cdot \sqrt{(L_s + L) \cdot C}} \quad (3.4)$$

If the filter is tuned exactly at a concern frequency then an upward shift in the tuned frequency results in a sharp increase in impedance as seen by the harmonic. There are some common mechanisms which may cause filter detuning. They are as follows:

- Capacitor fuse-blowing, which lowers the total capacitance, thereby raising the frequency at the filter has been tuned.
- Temperature variation
- System parameter variation
- Manufacturing tolerances in both inductor as well as capacitor.

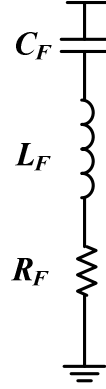
So the filter banks are tuned to around 6% below the desired frequency as per IEEE standard 1531 [101].

### 3.3 Shunt Passive Filter Design

The design of shunt passive filter is carried out as per the reactive power requirements. The filter is designed to compensate the reactive power of the system. Hence the shunt passive filter helps in maintaining the regulation of dc link voltage within limits and power factor improvement as improving the THD of supply current. It also sinks the harmonic currents of the frequencies at which the passive filter has been tuned. The shunt passivefilter consists of first order series tuned low pass filters tuned for 5<sup>th</sup> and 7<sup>th</sup> harmonics and a second order damped high pass filter tuned for 11<sup>th</sup> harmonics.

#### 3.3.1 Low pass filter design

In low pass filter  $R_F$ ,  $L_F$  and  $C_F$  are connected in series as shown in Figure 3.3.



**Figure 3.3 Shunt connected low pass filter**

The impedance of low pass filter is given by:

$$Z_F = \left[ R_F + j \cdot \left( h \cdot X_L - \frac{X_C}{h} \right) \right] \quad (3.5)$$

$$X_C = \frac{V_{ph}^2}{Q_F \cdot h} \quad (3.6)$$

$$X_L = \frac{X_C}{h^2} \quad (3.7)$$

The reactive power requirement may be initially assumed around 25% of the rating of the load [102]. It may be equally divided among different filter branches. The values of series tuned elements may be calculated from eqn. (3.6) and (3.7). The quality factor for low pass filter is:

$$Q_L = \frac{X_L}{R_F} \quad (3.8)$$

Here  $Q_L$  is considered as 40 to calculate the value of the resistive element.

The resonant frequency is given by:

$$f_0 = \frac{1}{2 \cdot \pi \cdot \sqrt{L_F \cdot C_F}} \quad (3.9)$$

### 3.3.2 High pass filter design

The high pass filter Figure 3.4 consists of a capacitor which is connected in series with the parallel combination of the resistor and inductor.

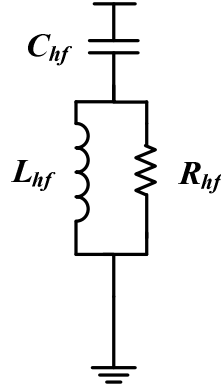


Figure 3.4 Shunt connected high pass filter

For second order damped filter, the impedance at any harmonics  $h$  is given by:

$$Z_{hf} = \left[ \frac{R_{hf} \cdot (h \cdot X_{hf})^2}{R_{hf}^2 + (h \cdot X_L)^2} + j \cdot \left( \frac{R_{hf}^2 \cdot h \cdot X_L}{R_{hf}^2 + (h \cdot X_L)^2} - \frac{X_C}{h} \right) \right] \quad (3.10)$$

$$X_{hf} = \left( \frac{1}{h^2 - 1} \right) \cdot \frac{V_{ph}^2}{Q_L} \quad (3.11)$$

Resonant frequency for  $h^{\text{th}}$  harmonic is:

$$f_0 = \frac{1}{2 \cdot \pi \cdot h \cdot C_{hf} \cdot R_{hf}} \quad (3.12)$$

$$Q_L = \frac{L_{hf}}{R_{hf}^2 \cdot C_{hf}} \quad (3.13)$$

### 3.3.3 Parameter calculations

Harmonic distortion in power distribution network can be suppressed using two approaches namely, passive and active filtering. Passive filtering is the simplest conventional

solution to mitigate the harmonic distortion. PF consists of passive parameters  $C_f$ ,  $L_f$  and  $R_f$ , calculated by:

$$C_f = \left( \frac{Q}{V_{ph}^2 \cdot 2\pi f} \right) \quad (3.14)$$

$$L_f = \left( \frac{1}{C_f \cdot (2\pi \cdot f_h)^2} \right) \quad (3.15)$$

$$R_f = Q_L \cdot 2\pi \cdot f_h \cdot L_f \quad (3.16)$$

$Q$  is reactive power to be generated by the filter at fundamental frequency,  $V$  is voltage at which filter is to be installed,  $Q_L$  is quality factor,  $f$  is fundamental frequency and  $f_h$  is tuning frequency where  $h$  is harmonic order. The filtering performance of the passive filter is determined by this impedance except for resonant frequency. Therefore, the capacitance value should be as high as possible and inductance value should be as low as possible to obtain low characteristic impedance. However large capacitance value makes the passive filter bulky and results in a high reactive current. Selecting a low inductance value also increases the switching ripples. Another parameter included in the filter design is the quality factor ( $Q_L$ ) which defines the sharpness of the filter. The mathematical representation of quality factor given in (3.16) shows that the resistance value of the filter is based on  $Q_L$  value. Generally quality factor term is not adjusted to change the filtering characteristic because of the considerable increase in losses. Typical values of  $Q_L$  ranges 10 to 40. By considering all these criteria and to minimize the initial cost of the system, 2720 kVAr passive filters at 13.8 kV line voltages tuned for 5<sup>th</sup>, 7<sup>th</sup> and 11<sup>th</sup> harmonic order are decided to use in the hybrid power system.  $L_f$  and  $C_f$  parameters are calculated using (3.14), (3.15) and (3.16) as follows:

$$C_{f5} = C_{f7} = C_{f11} = \left( \frac{Q}{V^2 \cdot 2\pi f} \right) = \left( \frac{2720000}{13800^2 \times 2 \times \pi \times 50} \right) = 4.549 \times 10^{-5} = 45.49 \mu F$$

$$L_{f5} = \left( \frac{1}{C_{f5} \cdot (2\pi f_5)^2} \right) = \left( \frac{1}{45.49 \times 10^{-6} \times (2 \times \pi \times 50 \times 5)^2} \right) = 0.008919 = 8.919 \text{ mH}$$

$$L_{f7} = \left( \frac{1}{C_{f7} \cdot (2\pi f_7)^2} \right) = \left( \frac{1}{45.49 \times 10^{-6} \times (2 \times \pi \times 50 \times 7)^2} \right) = 0.004551 = 4.551 \text{ mH}$$

$$L_{f11} = \left( \frac{1}{C_{f11} \cdot (2\pi f_{11})^2} \right) = \left( \frac{1}{45.49 \times 10^{-6} \times (2 \times \pi \times 50 \times 11)^2} \right) = 0.001842 = 1.842 \text{ mH}$$

Taking  $Q_L$  to be 10,  $R_f$  for various tuning frequencies is calculated as:

$$R_{f5} = Q_L \cdot 2\pi f_5 \cdot L_{f5} = 10 \times 2 \times \pi \times 50 \times 5 \times 0.008919 = 140.029 \Omega$$

$$R_{f7} = Q_L \cdot 2\pi f_7 \cdot L_{f7} = 10 \times 2 \times \pi \times 50 \times 7 \times 0.004551 = 100.021 \Omega$$

$$R_{f11} = Q_L \cdot 2\pi f_{11} \cdot L_{f11} = 10 \times 2 \times \pi \times 50 \times 11 \times 0.001843 = 63.650 \Omega$$

The designed passive filter element values are tabulated in Table 3.1

**Table 3.1 PF element values**

| Element/tuning frequency | $L_f$ (mH) | $C_f$ ( $\mu F$ ) | $R_f$ ( $\Omega$ ) | $Q_L$ |
|--------------------------|------------|-------------------|--------------------|-------|
| 5 <sup>th</sup>          | 8.919      | 45.49             | 140.029            | 10    |
| 7 <sup>th</sup>          | 4.551      | 45.49             | 100.021            | 10    |
| 11 <sup>th</sup>         | 1.843      | 45.49             | 63.65              | 10    |

### 3.4 Summary

This chapter described about the shunt passive filter design. It elaborated the design and compensation principle of passive filter for low pass and high pass filter. In this chapter the low pass filter is tuned for 5<sup>th</sup>, 7<sup>th</sup> and 11<sup>th</sup> order harmonic frequencies. The values of the filter component are given in Table 3.1. The design of the passive shunt filter is carried out as per the reactive power requirements. This filter is designed to compensate the requirements of reactive power of the system.