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An Efficient Design of Non-Active High Frequency Pass Filter for Applications in Active Power Filters

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Abstract: Recent active power filters can dynamically compensate for high order harmonics (usually the 25th). Despite the fact that the shunt active power filter keeps the source curve nearly sinusoidal, considerable distortion is observed in the source curve due to the presence of high order harmonics (more than 25th). To filter out these harmonics, a passiv high pass filter is used. The design process for these high-pass filters entails more than second-order equations, therefore the parameters are chosen by trial and error. In this paper, a simple design procedure for designing a high pass filter for shunt active power filter applications is proposed. Equations are derived from the fundamentals, and the design process is demonstrated with a case study of a single phase shunt active power filter.

Keywords-shunt active power filter; high pass filter; filter design; total harmonic distortion

INTRODUCTTON

The power quality of the source voltage and current is deteriorated due to an increase in power electronic equipment at the load end of the modern day power system. The Active Power Filter (APF) improves power quality by maintaining sinusoidal voltage and current at the source with a unity power factor [1-4]. The compensating current, which consists of the reactive component of the fundamental current and the harmonic current demanded by the load, is supplied by Shunt APF.Modem shunt APFs are found to compensate current harmonics dynamically (typically till 25 th order). Because of the following reasons, current distortion still exists due to high frequency current harmonics: I uncompensated harmonics of the load current (ii) switching harmonics introduced due to high switching rate of APF [8]. These higher order current harmonics introduce higher order voltage harmonics of high magnitude in the source voltage due to the presence of source inductance. The limits for individual voltage harmonics and Total Harmonic Distortion (THD) of the voltage are 3 percent and 5 percent, respectively, as per I Std. 519 [9]. Reduced hence in higher order current harmonics is also vital for maintaining acceptable voltage quality. A properly designed High Pass Filter (HPF) connected in parallel to the APF, as shown in Fig.l, bypasses the high frequency curves [6-7], [10-12].

Despite the fact that literature demonstrates the use of HPF for reducing higher order current harmonics, a proper design procedure is not shown [10-12]. The majority of the design process is trial and error. This paper gives a systematic procedure for deriving HPF from derived equations. A case study on a single phase shunt APF is used to demonstrate the design process.

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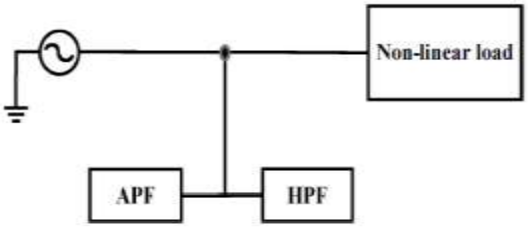


Figure 1. Parallel connection of HPF with APF in a power circuit

PASSIVE HIGH PASS FILTERS

Traditionally three types of passive high pass filters are used as shown in Fig. 2 [6-7], [10]. Fig. 2(a) shows the first order high pass filter whose design is quite simple. When it is used to filter out the high frequency currents, it increases the power losses due to the presence of series resistance. If the source impedance is inductive, the filter capacitance (Ch) resonates with source inductance. This resonance peak is high for small values of filter resistance (Rh)' Thus harmonics of source current that fall near resonant frequency are amplified causing an increase in THD. For large values of Rh, the attenuation decreases, thus affecting the filter performance. Hence the use of first order filter is limited [6-7].

The second order filter as shown in Fig. 2(b) is widely used as an inductor bypasses the resistance at low frequencies. High frequency currents pass through the resistance of the high pass filter. If the value of resistance is low, power dissipation will be low; otherwise a capacitor in series with the resistance is connected as shown in Fig. 2(c) to reduce the power loss. The HPF shown in Fig. 2(c) is a third order filter is used to increase the filter energy efficiency and does not provide any significant increase in filter performance [6-7].

From the above discussion, it is seen that first order filter is not reliable and third order filter is used only when power loss is more. Thus second order filter is most important as it is widely used for reducing the higher order harmonics in current and hence higher order harmonics in source voltage.

In this paper, the design procedure is limited to second order filter shown in Fig 2(b).

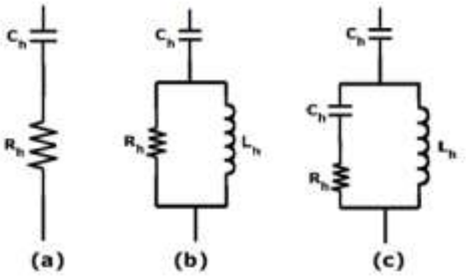


Figure 2. High pass filters (a) First order (b) Second order (c) Third order

Figure 2. High pass filters (a) First order (b) Second order (c) Third order

A PASSIVE HIGH PASS FILTER DESIGN PROCEDURE

The single line diagram shown in Fig.1 is represented as a circuit in Fig.3 which consists of a second order HPF and a voltage source V s with a source inductance Ls• A full wave bridge rectifier with RL load is widely used in practical applications. Hence it is employed here in place of nonlinear load with load terminals 'a' and 'b'. It is assumed that APF shown in Fig. 3 is designed to compensate till 25th harmonic. Hence higher order (> 25) harmonic current is required to be filtered by proper design of HPF. The equations required to design the HPF are derived based on following conditions.

1) Loading effect of the filter on the source

2) Location of resonant frequencies and resonant magnitude of peak of the high frequency model of circuit shown in Fig. 3.

3) Attenuation at switching harmonic frequencies to maintain distortion level as per IEEE Std. 519.

Considering the above conditions, a step by step design procedure is illustrated.

Step-1: An equation is derived considering the load impedance and HPF impedance at fundamental (power) frequency. If Vfi If and wf are the fundamental voltage, fundamental current and angular frequency of the source respectively, the impedance (ZLf) offered by the load to this fundamental frequency is given by

$$Z_{Lf} = \frac{V_f}{I_f} \qquad (1)$$

At fundamental frequency, inductance Lh acts like a short circuit and bypasses Rh and capacitive reactance dominates. Hence the impedance of the HPF at fundamental frequency is given by

$$Z_{HPFf} = \frac{1}{\omega_f C_h} \qquad (2)$$

To avoid loading effect of HPF, ZHPFf is taken 'k' times higher than ZLf given by (3). For example if k > 20, fundamental current of less than 5 % passes through HPF.

$$Z_{HPFf} = kZ_{Lf} \qquad (3)$$

From (1), (2) and (3), the required value of capacitance is approximately given by (4),

$$C_h = \frac{1}{kZ_{Lf}\omega_f} \qquad (4)$$

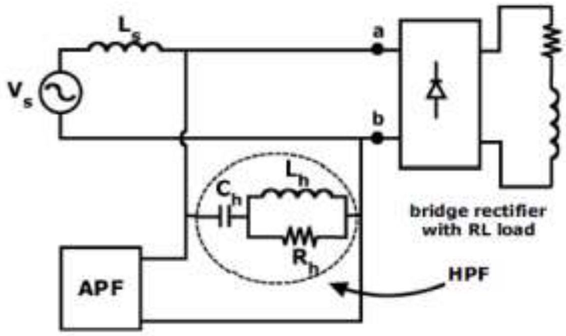


Figure 3. Active power filter model with second order HPF

Figure 3. Active power filter model with second order HPF

Step-2: One of the important factor need to be considered while designing a filter is the system natural resonant frequencies. If the resonant frequency falls near one or more critical driving harmonic frequencies, the latter tend to be amplified. The amount of amplification of these harmonics depends on the magnitude of resonant peak.

Proper location of system resonant frequency is possible by careful selection of inductor and capacitor in HPF.

Similarly the magnitude of resonant peak can be adjusted by proper selection of resistor (Rh) in HPF.

Considering the circuit shown in Fig. 3, the inductance of the load is very high compared to the source inductance. Hence at high frequency, the load across the terminals 'a' and 'b' is assumed to be open circuit. The high frequency model of the circuit shown in Fig. 3 is obtained by representing the load by an open circuit and other part of the circuit by its Norton's equivalent across the terminals 'a' and 'b' is shown in Fig. 4. Ih is the equivalent Norton's current and subscript 'h' denotes that the current contain high frequency harmonics (required to be filtered by HPF). For an ideal HPF, all the current Ih passes through

HPF, thus filtering the high frequency harmonics in the source current (passing through Ls)' Ish and Ifh denote the current passing through source inductance and HPF respectively.

The current divider transfer function (Heds) with respect to source current Ish is [6]

$$H_{cds} = \frac{I_{sh}}{I_h} \tag{5}$$

Fig.5 is the bode plot of the circuit shown in Fig. 4. The resonant frequeneies depend on the values of Lh, Ch, Ls and Rh. Due to series resonance the source current harmonics near series resonant frequency are attenuated but due to parallel resonance the source current harmonics near parallel resonant frequency are amplified. Hence, only parallel resonance is considered here. The value of filter resistance Rh may vary from 0 to 00. Initial analysis is carried out by considering the two limiting values of Rh.

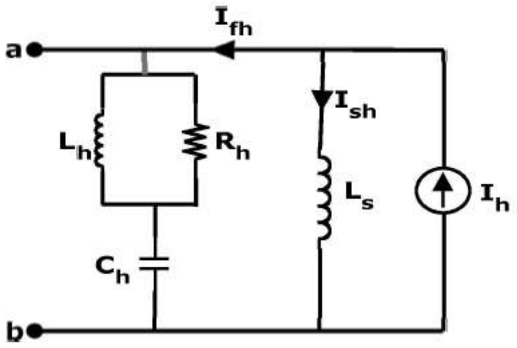


Figure 4. High pass filter with source impedance

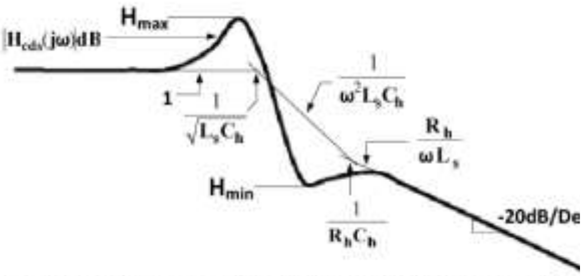


Figure 5. Frequency response of current divider transfer functior for HPF shown in Fig. 4

Case I: If Rh ---+ ∞, the transfer function is The parallel resonant frequency is given by ffiPI' where

$$H_{cds} = \frac{\frac{1}{C_{hs}}+L_hs}{\frac{1}{C_{hs}}+(L_h+L_s)s} \tag{6}$$

The parallel resonant frequency is given by ω_{P_1} where

$$\omega_{P_1} = \frac{1}{\sqrt{(L_h+L_s)s}} \tag{7}$$

Case II: If Rh---+ 0, the transfer function is

$$H_{cds} = \frac{\frac{1}{C_{hs}}}{\frac{1}{C_h s}+L_s s} \tag{8}$$

In this case the parallel resonant is given by ωp2' where

$$\omega_{P_2} = \frac{1}{\sqrt{L_sC_h}} \tag{9}$$

$$C_h = \frac{1}{{\omega_{P_2}}^2L_s} \tag{10}$$

From (7) and (9)

So,

$$\frac{{\omega_{P_2}}^2}{{\omega_{P_1}}^2} = 1 + \frac{L_h}{L_s} \tag{11}$$

$$L_h = L_s\left(\frac{{\omega_{P_2}}^2}{{\omega_{P_1}}^2} - 1\right) \tag{12}$$

From (4) and (9)

$$\frac{1}{kZ_{Lf}\omega_f} = \frac{1}{{\omega_{P_2}}^2L_s}$$

$$k = \frac{Z_{Lf}\omega_f}{{\omega_{P_2}}^2L_s} \tag{13}$$

Case III: If ∞ > Rh ≥0.

Let wp be the parallel resonant frequency for a given value of Rh between 0 and ∞. It is seen from (7) and (9) that

$$\omega_{P_1} \leq \omega_P \leq \omega_{P_2}$$

As already discussed, parallel resonance of HPF with source inductance causes amplification of harmonics in source current that fall near parallel resonant frequency. So, one of the design constraints is the location of ffip and other is to limit the magnitude of resonant peak. This is achieved by

1. analyzing the source current harmonics and selecting ffip, and ffip2 in a frequency band where no critical source current is present.

2. tuning damping resistance (Rh) to reduce the resonant peak It can be observed from (10) and (12) that the values of the capacitor and inductor are obtained by proper selection of ω_{P_1}, and ω_{P_2}

Selection of ω_{P_1} and ω_{P_2}

a) From (13), it is observed that loading effect due to HPF is reduced by increasing the value of k and hence ffip2' This defines the lower limit of ω_{P_2}

$$\omega_{P_2} \geq \sqrt{\frac{kZ_{Lf}\omega_f}{L_s}} \qquad (14)$$

Modem APFs are capable of compensating harmonics typically till 25th order [5]. So HPF is required to filter all the high harmonics that APF is not able to compensate. From Fig. 5, it is observed that attenuation of the HPF starts approximately from parallel resonant frequency. Hence the upper limit upper limit of ω_{P_2} is

$$\omega_{P_2} < 25\omega_f \qquad (15)$$

From (14) and (15),

$$\sqrt{\frac{kZ_{Lf}\omega_f}{L_s}} < \omega_{P_2} < 25\omega_f \qquad (16)$$

From (16)

$$k < \frac{625L_s\omega_f}{Z_{Lf}} \qquad (17)$$

This shows the constraint on 'k'. To avoid loading effect as discussed in Step-l , the value of 'k' is

selected as high as possible.

b) From (12), it is observed that Lh depends on square of the ratio of ω_{P_2} to ω_{P_1}. By choosing the ω_{P_1} nearer to ω_{P_2} the value of Lh reduces. Thus decreases the cost of designed inductor. However if the ω_{P_2} and ω_{P_1} are too near, the frequency response of HPF becomes more sensitive to the changes in Rh. Hence a compromise must be made in choosing the value of ω_P

Thus ω_{P_1} and ω_{P_2} are selected in a frequency band whose upper limit lies below $25\omega_{P_2}$

Step-3: As frequency tends to be very high (near switching frequency),

$$H_{cds} = \frac{R_h}{L_s s} \qquad (18)$$

From (18), it can be observed that high value of Rh results in low attenuation near switching frequency and low magnitude resonant peak at parallel resonance. The HPF will show good performance when peak at resonance is low and attenuation at switching frequency is high. Hence an optimum value is to be selected. The limits of Rh can be obtained by taking the typical values of quality factor used

for HPF in the literature [7], [11].

Selection of Rh

The value of Rh is obtained by selecting the quality factor Qh. The quality factor is represented as

$$Q_h = R_h\sqrt{\frac{C_h}{L_h}} \qquad (19)$$

Typical values of quality factor are $0.5 \leq Qh \leq 2$ The limits of Rh are defmed based on the limits of Qh. By selecting quality factor close to 0.7, the series resonance and high pass performances are satisfactory.

A CASE STUDY

To demonstrate the performance of the proposed high pass filter, a single phase APF circuit is built in MATLAB/Simulink with the parameters as given in Table. 1. A sinusoidal voltage source of 220 V rms (50 Hz) is connected to a full wave bridge rectifier with RL load (R =10 Ω, L = 50 mH)

Table 1. Major parameters of the prototype

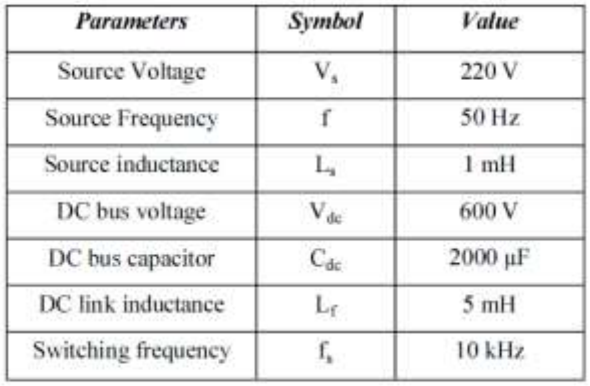


Table 1. Major parameters of the prototype

Parameters	Symbol	Value
Source Voltage	V_s	220 V
Source Frequency	f	50 Hz
Source inductance	L_s	1 mH
DC bus voltage	V_{dc}	600 V
DC bus capacitor	C_{dc}	2000 µF
DC link inductance	L_f	5 mH
Switching frequency	f_s	10 kHz

From simulation of the given model without any compensation, it is seen that load impedance at fundamental frequency

$$Z_{Lf} = \frac{V_f}{I_f}$$

Choice of ω_{P_1} and ω_{P_2}

Corresponding cut-off frequencies in Hz be fp1 and fp2. From (15),

$$f_{P_2} < 1250 \text{ Hz}$$

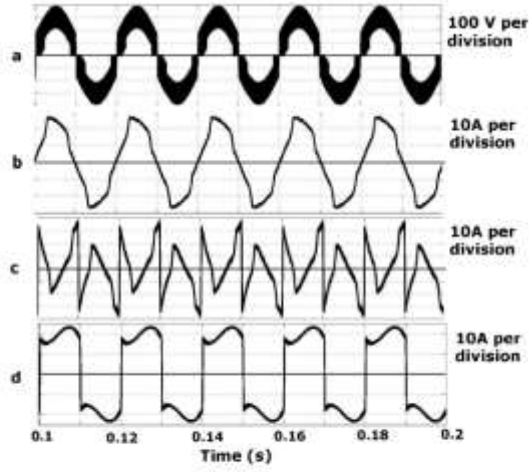
Hence frequencies fpl and fp2 are chosen near to 1250 Hz; such that at those frequencies the magnitude of frequency component of source current is less than 2 % of the fundamental. From the frequency response of the source current, fpl

and fp2 are chosen as 1160 Hz and 1230 Hz respectively. Hence the frequency components in radis are as follows

$\omega_{P_1} = 2320\pi$ rad/s and $\omega_{P_2} = 2460\pi$ rad/s

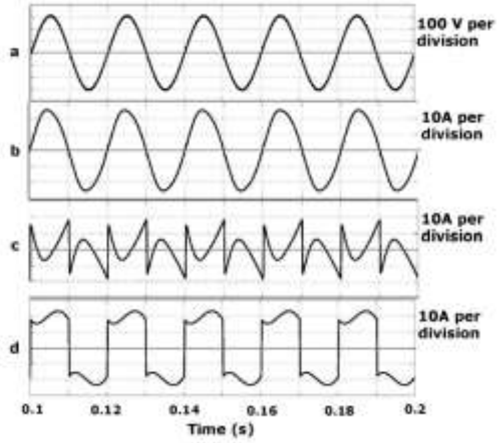
By using equations (10), (12) and (19),

$L_h = 0.124$ mH, $C_h = 16.75\mu$F, $R_h = 1.90\Omega$



a. Mains voltage b. Mains Current
c. Compensating current d. Rectifier load current

Figure 6. Simulation results of the APF model without connecting HPF



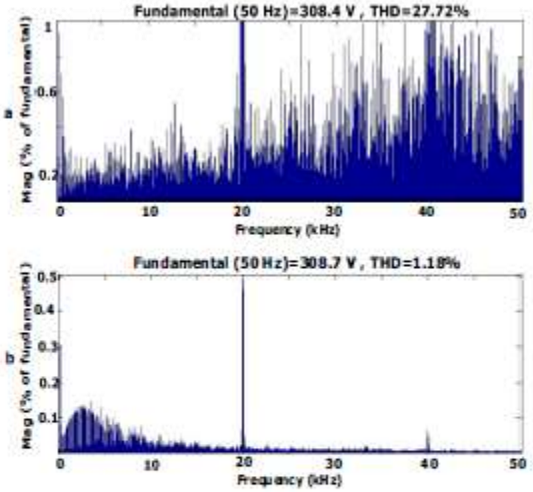
a. Mains voltage b. Mains Current

c. Compensating current d. Rectifier load current

Figure 7. Simulation results of the APF model without connecting HPF

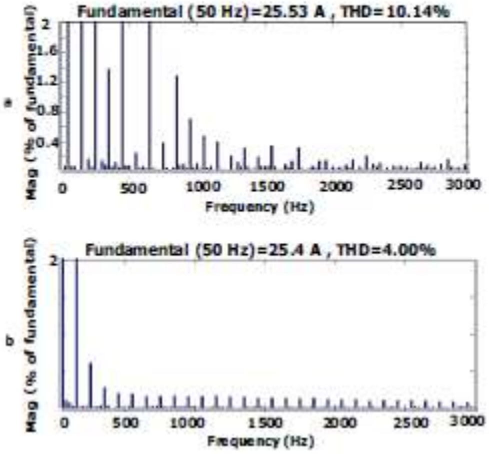
Performance of the active power filter before and after connecting HPF

Fig. 6 shows the simulated results of the active power filter model prior to connecting HPF. From the figures, it can be seen that the source current and voltage are highly distorted. Fig. 8(a) and Fig. 9(a) show the harmonic content in the source voltage and source current without HPF. THD of the voltage and current are 27.7 % and 10.1 % respectively. Simulated results after connecting HPF are shown in Fig. 7. It is observed that the distortion of the mains current and voltage decreased to a level as mentioned in the standards IEEE Std. 519. Fig. 8(b) and Fig. 9(b) show the harmonic content in the source voltage and source current with HPF. THD of the voltage and current are 1.2 % and 4 % respectively.



a. Without HPF b. With HPF

Figure 8. Harmonic spectrum of voltage



a. Without HPF b. With HPF

Figure 9. Harmonic spectrum of current

CONCLUSION

In order to improve power quality, an APF in conjunction with an HPF is required. The proper design of the HPF is required to eliminate higher order harmonics, as APF can only eliminate harmonics up to the 25th order. The above design process and test results show that the designed HPF is capable of enhancing power quality while effectively reducing THD. The THD and the magnitude of harmonics of source voltage and current were found to be well within the limits set by IE Std. 519 when HPF was used.

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