

An Efficient Design of Passive High Pass Filter for Shunt Active Power Filter Applications

Ravi Shankar Singh¹, Priyanka Maheshwari, Dr. Sanjay Jain³

M.Tech (Electrical Power System) Scholar, RKDF University Bhopal, India¹

Assistant Professor, Department of Electrical Engineering, RKDF University Bhopal, India²

Head of Department, Department of Electrical Engineering, RKDF University Bhopal, India³

ravishankar.rpsit@gmail.com¹, priyankabits4@gmail.com², jain.san12@gmail.com³

Abstract: Modern active power filters are capable to compensate high order harmonics (typically, the 25th) dynamically. Even though, shunt active power filter maintains source current nearly sinusoidal, considerable distortion is observed in source current due the presence of high order harmonics (greater than 25th). A passive high pass filter is used to filter out these harmonics. The design procedure of these high pass filters involves equations of more than second order; hence the parameters are selected by trial and error. In this paper, a simplified design procedure is proposed for designing a high pass filter used for shunt active power filter applications. Equations are derived from the basics and design procedure is demonstrated by considering a case study of a single phase shunt active power filter.

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

INTRODUCTION

Due to increase in power electronic equipment at the load end of the modern day power system, the power quality of the source voltage and current is deteriorated. Active Power Filter (APF) plays an important role in improving power quality by maintaining sinusoidal voltage and current at the source with unity power factor [1-4]. Shunt APF supplies the compensating current which comprises the reactive component of the fundamental current and the harmonic current demanded by the load. Modern shunt APFs are found to compensate current harmonics dynamically (typically till 25 th order). Current distortion still exists due to high frequency current harmonics present because of the following reasons (i) uncompensated harmonics of the load current (ii) switching harmonics introduced due to high switching rate of APF [8]. Due to the presence of source inductance, these higher order current harmonics introduces higher order voltage harmonics of high magnitude in the source voltage. As per IEEE Std. 519, the limits for the individual voltage harmonics and the Total Harmonic Distortion (THD) of the voltage are 3 % and 5 % respectively [9]. Hence reduction in higher order current harmonics is also important in maintaining good quality of voltage. A properly designed High Pass Filter (HPF) connected parallel to APF as shown in Fig.1, bypasses the high frequency currents [6-7], [10-12].

Even though literature shows the use of HPF for reducing the higher order current harmonics, a proper design procedure is not illustrated [10-12]. Most of the design procedure involves trial and error. This paper gives a systematic procedure for the design of HPF from the derived equations. The design procedure is demonstrated by considering a case study on a single phase shunt APF.

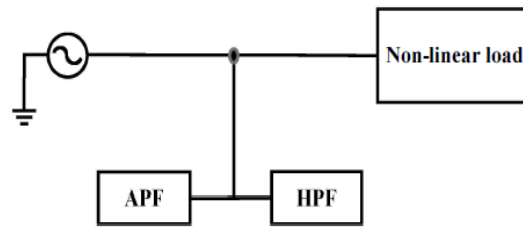


Figure 1. Parallel connection of HPF with APF in a power circuit

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 (C_h) resonates with source inductance. This resonance peak is high for small values of filter resistance (R_h). Thus harmonics of source current that fall near resonant frequency are amplified causing an increase in THD. For large values of R_h , 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).

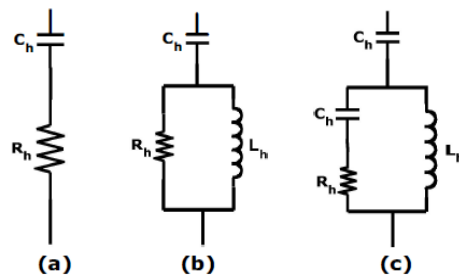


Figure 2. High pass filters (a) First order (b) Second order (c) Third order

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 L_s . 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-I: An equation is derived considering the load impedance and HPF impedance at fundamental (power) frequency. If V_f , I_f and ω_f are the fundamental voltage, fundamental current and angular frequency of the source respectively, the impedance (Z_{Lf}) offered by the load to this fundamental frequency is given by

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

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

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

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

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

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

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

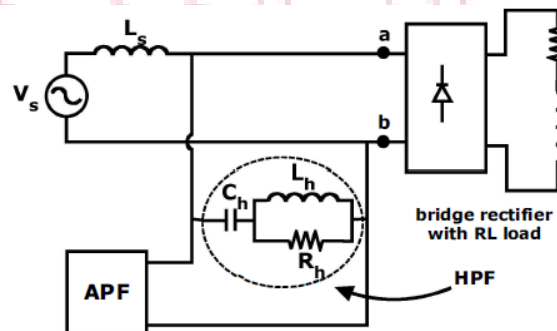


Figure 3. Active power filter model with second order HPF

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 frequeneies. If the resonant frequency falls near one or more critical driving harmonic frequeneies, 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 (R_h) 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. I_h 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 I_h passes through HPF, thus filtering the high frequency harmonics in the source current (passing through L_s) I_{sh} and I_{fh} denote the current passing through source inductance and HPF respectively.

The current divider transfer function (H_{cds}) with respect to source current I_{sh} is [6]

$$H_{cds} = \frac{I_{fh}}{I_h} \quad (5)$$

Fig.5 is the bode plot of the circuit shown in Fig. 4. The resonant frequeneies depend on the values of L_h , C_h , L_s and R_h . Due to series resonance the source current harmonics near series resonant frequency are attenuated but due to

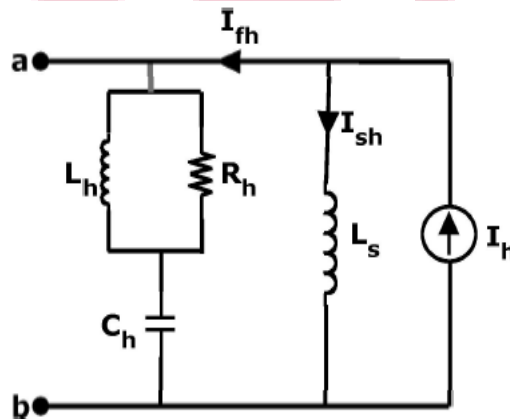


Figure 4. High pass filter with source impedance

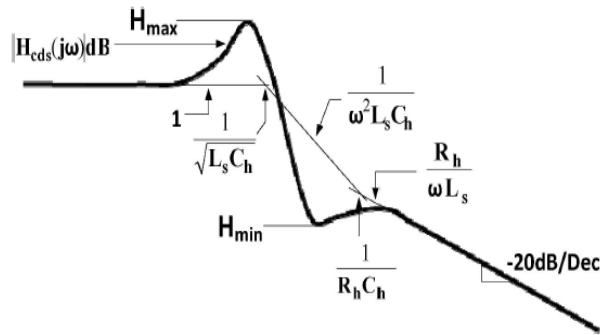


Figure 5. Frequency response of current divider transfer function for HPF shown in Fig. 4

parallel resonance the source current harmonics near parallel resonant frequency are amplified. Hence, only parallel resonance is considered here. The value of filter resistance R_h may vary from 0 to ∞ . Initial analysis is carried out by considering the two limiting values of R_h .

Case I: If $R_h \rightarrow \infty$, the transfer function is The parallel resonant frequency is given by ω_{p1} where

$$H_{cds} = \frac{\frac{1}{C_h s} + L_h s}{\frac{1}{C_h s} + (L_h + L_s)s} \quad (6)$$

The parallel resonant frequency is given by ω_{p1} where

$$\omega_{p1} = \frac{1}{\sqrt{(L_h + L_s)s}} \quad (7)$$

Case II: If $R_h \rightarrow 0$, the transfer function is

$$H_{cds} = \frac{\frac{1}{C_h s}}{\frac{1}{C_h s} + L_s s} \quad (8)$$

In this case the parallel resonant is given by ω_{p2} where

$$\omega_{p2} = \frac{1}{\sqrt{L_s C_h}} \quad (9)$$

$$C_h = \frac{1}{\omega_{p2}^2 L_s} \quad (10)$$

From (7) and (9)

So,
$$\frac{\omega_{p2}^2}{\omega_{p1}^2} = 1 + \frac{L_h}{L_s} \quad (11)$$

$$L_h = L_s \left(\frac{\omega_{p2}^2}{\omega_{p1}^2} - 1 \right) \quad (12)$$

From (4) and (9)

$$\frac{1}{k Z_{Lf} \omega_f} = \frac{1}{\omega_{p2}^2 L_s}$$

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

Case III: If $\infty > R_h \geq 0$.

Let ω_p be the parallel resonant frequency for a given value of R_h 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 ω_p and other is to limit the magnitude of resonant peak. This is achieved by

1. analyzing the source current harmonics and selecting ω_{P_1} and ω_{P_2} in a frequency band where no critical source current is present.
2. tuning damping resistance (R_h) 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 ω_{P_2} . This defines the lower limit of ω_{P_2}

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

Modern 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

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

From (14) and (15),

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

From (16)

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

This shows the constraint on 'k'. To avoid loading effect as discussed in Step-1, the value of 'k' is selected as high as possible.

b) From (12), it is observed that L_h 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 L_h 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 R_h . 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),

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

From (18), it can be observed that high value of R_h 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 R_h can be obtained by taking the typical values of quality factor used

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

Selection of R_h

The value of R_h is obtained by selecting the quality factor Q_h . The quality factor is represented as

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

Typical values of quality factor are $0.5 \leq Q_h \leq 2$. The limits of R_h are defined based on the limits of Q_h . 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 ($R = 10 \Omega$, $L = 50 \text{ mH}$)

Table 1. Major parameters of the prototype

<i>Parameters</i>	<i>Symbol</i>	<i>Value</i>
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 fp1 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, fp1

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

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

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

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

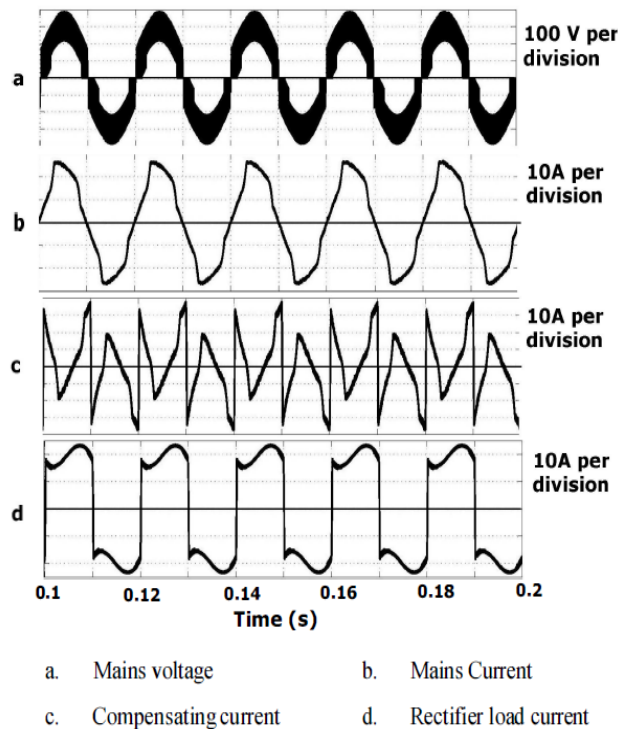


Figure 6. Simulation results of the APF model without connecting HPF

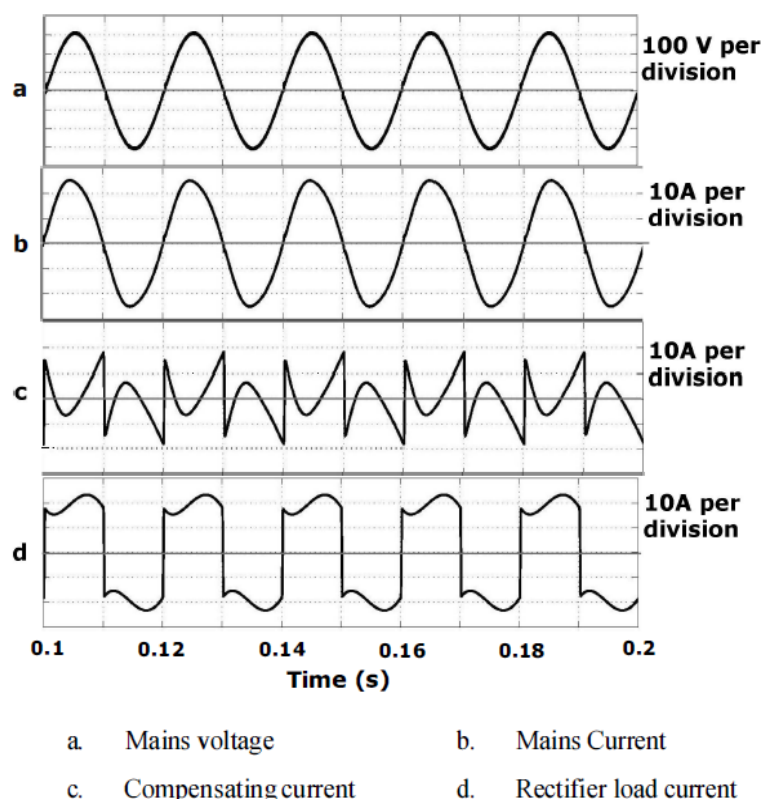


Figure 7. Simulation results of the APF model without connecting HPF

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.

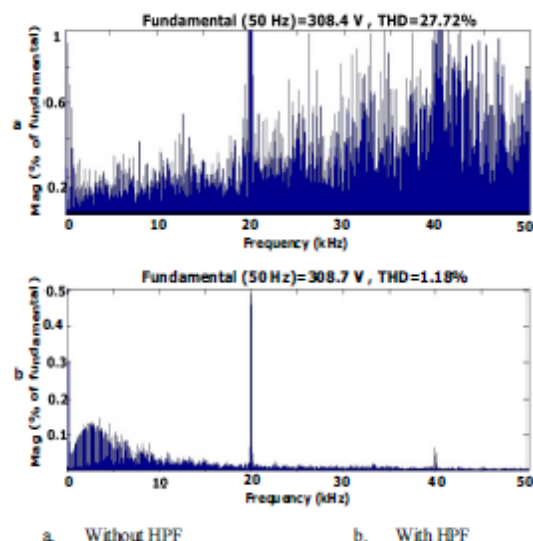


Figure 8. Harmonic spectrum of voltage

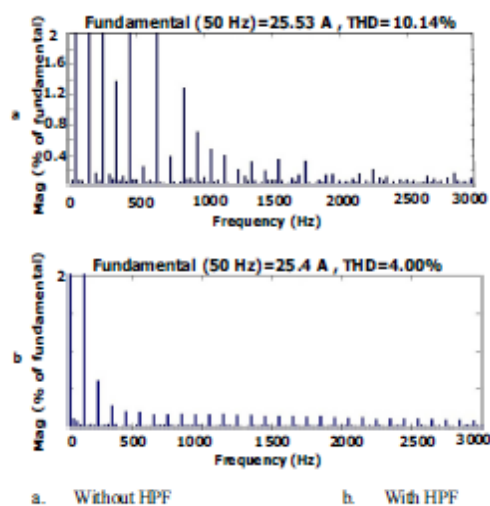


Figure 9. Harmonic spectrum of current

CONCLUSION

In power quality improvement, APF in coordination with a HPF is needed to have better results. The proper design of the HPF is necessary to eliminate higher order harmonics, as APF is capable of eliminating harmonics typically till 25th order. From the above design procedure and test result, it is seen that the designed HPF is capable of improving the power quality effectively reducing THD. With the use of HPF, the THD and the magnitude of harmonics of source voltage and current are found to be well below the limits specified by IEEE Std. 519.

REFERENCES

- [1] A. Ghosh and G. Ledwich, "Power Quality Enhancement Using Custom Power Devices," New York, USA: Springer Publisher, e2000
- [2] R. C. Dugan, M. F. McGranaghan, S. Santoso and H. W. Beaty, "Electrical Power Systems Quality," 2nd ed. USA: McGraw-Hill, 2002

- [3] H. Akagi, "New trends in active filters for power conditioning," IEEE Trans. on Industry Applications. 1996. 32(6): 1312-1322.
- [4] H. L. Jou, 1. C. Wu and H. Y. Chu, "A new single phase active power filter," IEE Proc., Electr. Power Appl., Vol. 141, No. 3, May 1994, pp. 129-134
- [5] B. Singh, K. Al-Haddad and A. Chandra, "A review of active filters for power quality improvement," IEEE Trans. On Industrial Electronics, Vol. 46, No. 5, Oct 1999, pp. 960-971
- [6] J. K. Phipps, "Transfer function approach to harmonic filter design," IEEE Industry Application Magazine, March/April 1997, pp.68-82
- [7] D. Sutanto, M. Bou-rabee, K. S. Tam and C. S. Chang, "Harmonic filters for industrial power systems," IEE Proc., International Conf. on Advances in Power Sys. Con!., Operation and Management, Vol. 2, Nov 1981, pp. 594-598
- [8] N. Mohan, T. Undeland and W. Robbins, "Power Electronics: Converters, Applications and Design," Singapore: John Wiley, 1994
- [9] "IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems," IEEE Std. 519-1992
- [10] D. A. Gonzalez and J. C. Meeall, "Design of filters to reduce harmonic distortion in industrial power systems," IEEE Trans. On Industry Applications, Vol. 1A-23, No. 3, May/June 1987, pp. 504-511
- [11] Z. Salam and P. C. Tan, "A new single-phase two-wire hybrid active power filter using extension p-q theorem for photovoltaic application," IEEE Proc., PECon 2004, pp. 126-131
- [12] S. Fukuda and M. Yamaji, "Design and characteristics of active power filter using current source converter," IEEE IAS Annu. Meeting, Vol. 2, 1990, pp. 965-970
- [13] J. C. Das, "Passive filters-Potentials and limitations," IEEE Trans. On Industry Applications, Vol. 40, No. 1, Jan./Feb. 2004, pp. 232-241