CHAPTER 4

MINIMIZATION OF HARMONICS USING FACTS CONTROLLERS

4.1 SYSTEM HARMONICS

The rapid development of power generated by increased demand for electric energy initially in industries proposed to suppress the harmonics generated by large rated thyristor converters used in HVDC transmission systems. In most of the power electronic system, the line-frequency utility voltage is rectified into a D.C. Voltage, which is then converted into A.C voltage and current of appropriate magnitude, frequency and phase angle in order to meet the load requirements. The purpose of this arrangement is to obtain sinusoidal line current at a high power factor to match the specified limit and subsequently in developing countries led to different technical problems in the systems such as stability limitation and voltage problems. However breaking, advances in semiconductor technology, then enabled the manufacture of powerful thyristor and later other elements such as the gate turn off thyristor and insulated gate bipolar transistors etc. High voltage DC transmission (HVDC) technology is being considered as an alternative to long distance AC transmission based on this development.

Harmonics problem generated by nonlinear loads and thyristor converters become increasingly serious as they are widely used in industrial applications and transmission and distribution systems. Since the HVDC converters are large power converters, they have become important harmonics sources in power systems and without proper compensation the quality of power in system is deteriorates. So far, the shunt passive filters are used, due to their low cost and high efficiency, to reduce harmonics in power systems. However shunt passive filters have many problems to discourage their applications. The filtering performance of passive filters is influenced by the ratio of equivalent impedance of AC source link side and passive power filter
impedance. Since the source impedance is not accurately known and varies with the system configuration, strongly influences characteristic of shunt passive filter. Furthermore the passive filter may fall in series resonance or in parallel resonance with source impedance. Shunt active filters using PWM inverters have been developed as the solution of preceding problems in passive shunt filters. In the beginning, shunt active filter limit is also proposed.

In the view of above requirements, the thesis suggests the various harmonic reduction techniques on the basis of their components rating and their ability to operate with low total harmonics reduction or distortion (THD) in the line current. The limit on the (THD) is specified about 5% for a load connected to a weak utility system, the various techniques are considered here to satisfy these requirements. Fig 4.1 is used to reduce the current ratings of the filters by shaping the link current to be a direct current. The techniques for harmonics reduction can be adopted by using FACTS controllers. [34]

4.2 HARMONICS REDUCTION TECHNIQUES

Harmonic production is an inherent property of any power electronic converter. In HVDC links it is necessary to reduce harmonic penetration into AC system. Increasing the pulse number is one of the solutions to eliminate some harmonics. But in HVDC links the use of increased pulse number has disadvantages such as increasing complexity of transformer connections and problems of insulation. Therefore only simple connections of transformers to achieve 12 pulse numbers are used.

Filters are used to compensate harmonics. The load included is a diode bridge rectifier as shown in Fig 4.1, is used to reduce the current ratings. The simulation is done at 10 kW load on 400V (L-L rms), 50Hz source. This can also be used for higher loads.
**4.3 EVALUATION OF COMPONENTS RATINGS**

1. Switching VA rating = \( V_{\text{max}} I_{\text{Max}} \) \hspace{1cm} (4.1)
2. Capacitor VA rating = \( \frac{I_n^2}{\omega n C} \) \hspace{1cm} (4.2)

Where \( V_{max} \) = Max. Voltage, \( I_{max} \) = Max Current.

\( I_n \) = Rms value of nth harmonics current,

\( \omega_n \) = Angular frequency,

\( C \) = capacitor in farad

3. Inductor VA rating = \( 2.22fL I_{rms} I_{max} \) \hspace{1cm} (4.3)

The rating of transformer is calculated by using the following relation:

4. \( S = 3.V_{max} I_{rms} \frac{1}{\sqrt{2}} \) \hspace{1cm} (4.4)

Where \( V_{max} \) = Max. Phase voltage, \( I_{rms} \) = effective phase current.[43]

5. The switching frequency is constant with \( f = 20 \text{ kHz} \).

6. The Max.peak-to-peak ripple, \( I_{ppmax} \), is 20% of the peak line current supplied by the converter.

7. The inductance required in the current mode control of the converters is calculated on the basis of the peak-to-peak ripple current and not on the basis of the slow rate.

8. The ripple component is considered in the calculation of peak values of current but is neglected in the calculation of rms values.

9. In the converters considered, the dc voltage is regulated to be 10% above the peak input voltage.

10. The ripple in the output voltage is neglected in comparison to its average value.
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11. The diode and the output D.C capacitor are not included in the evaluation of component ratings, since the diodes are in expensive and the output D.C capacitors are needed in all schemes for energy storage. [36]

4.4 HARMONIC ANALYSIS

The traditional approach of harmonic reduction is by means of passive filters. The design data and the ratings of passive filters are dependent on the harmonic frequency and impedances of a particular utility system. As a consequence, the passive filters do not prepare themselves to an evaluation and therefore are not used. The booster D.C-D.C converter is included in evaluating the filter schemes to provide a uniform solution. The rating of the switch and inductor ‘L_b’ in the booster converter is calculated as follows: the direct current (D.C) through ‘L_b’ is given as.

\[
I_{dc} = \frac{\text{load power}}{1.359\% V_{LL}} = \frac{10kW}{1.35 \times 415} = \frac{10,000}{1.35 \times 415} = 17.85 \text{ A}
\]

And therefore the peak current through the switch is \(I_{\text{max}}(I_{pk}) = 19.63\text{A}\). The peak Voltage across the switch is the D.C output voltage \(V_d\). The peak Voltage at the input of the booster converter is the peak line-to-line voltage. The D.C Voltage is given as

\[
V_d = 1.1 \times \sqrt{2} V_{LL} = 1.1 \times \sqrt{2} \times 415 = 645.6 \text{V}
\]

In a booster converter, operating at a constant switching frequency, the max. Ripple current occurs at a switch duty ratio of (1/2). Therefore, the inductance ‘L_b’ can be calculated as.

\[
L_b = \frac{V_d}{4f_s I_{ppmax}} = \frac{645.6}{4 \times 20 \times 103 \times 0.2 \times 17.85} = 2.265 \text{ mH}
\]

Where \(I_{ppmax} = 0.2 I_{dc}\), the booster switch and inductor ratings are the same in the two filter schemes considered below.[37]
4.5 FILTERING

4.5.1 Active Filtering

An active filter reduces the distortion in the line current by supplying the harmonic components in the load current as in Fig 4.2. The active filter consists of a six-switch converter. The peak value of the filter current occurs at $\theta = \omega t = 60^\circ$. The peak voltage rating of the switches should be at least equal to the D.C bus voltage $V_{dc}$ within the converter of the active filter. The voltage $V_f$ developed by the active filter is different from the source voltage by the voltage drop across inductance $L_f$. If this inductance is small due to the choice of a high switching frequency, then the voltage $V_f$ is approximately equal to the source voltage.

If a sinusoidal PWM is used, the Minimum required value of

$$V_{dc} = 2\sqrt{2}V_s = \sqrt{2 \times 239.6} = 677.7V$$

(4.8)

![Diagram of an active filter](image)

Fig 4.2 Single line diagram of an active filter
Table 4.1 D.C Voltage Rating of Components

<table>
<thead>
<tr>
<th>Technique</th>
<th>No. of Switches</th>
<th>Switch kVA Rating</th>
<th>Eq. Transformer kVA Rating</th>
<th>Capacity or kVA</th>
<th>V_d Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Filter Boost</td>
<td>Total</td>
<td>L_f L_b Trans. Total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active Filter</td>
<td>6</td>
<td>7</td>
<td>55</td>
<td>0.07 0.1</td>
<td>0.19</td>
</tr>
<tr>
<td>Hybrid filter</td>
<td>12</td>
<td>13</td>
<td>30.5</td>
<td>1.17 0.1 1.95</td>
<td>3.24</td>
</tr>
<tr>
<td>Single phase</td>
<td>3</td>
<td>24.3</td>
<td>10.2</td>
<td>-</td>
<td>648</td>
</tr>
<tr>
<td>Six Switch</td>
<td>6</td>
<td>85</td>
<td>0.18</td>
<td>-</td>
<td>648</td>
</tr>
<tr>
<td>Min. Rect.</td>
<td>2</td>
<td>24.5</td>
<td>2.45</td>
<td>-</td>
<td>786</td>
</tr>
</tbody>
</table>

However, the required $V_{dc}$ can be reduced if the sine reference for PWM is modulated with 3rd and 9th harmonics. The Minimum required voltage can then be expressed in terms of the source voltage as

$$V_{dc} = \frac{2\sqrt{2}}{1.155} V_s = \frac{2\sqrt{2}}{1.155} \times 239.6 = 586.74V$$

(4.9)

The actual D.C. bus voltage is $1.1V_{dc}$, based on the operating condition. The inductors required in the active filter for current control are determined from the constants on the Maximum Ripple current, $I_{ppmax}$. In a six switch converter, the Maximum Ripple current occurs at the zero-crossings of the fundamental frequency component of the output voltage. The inductance ‘$L_f$’ can be calculated as.[38]

$$L_f = \frac{V_{dc}}{6fs_{ppmax}}$$

(4.10)

By using eqn-(4.10) $L_f$ is calculated to be 2.75 mH. The total switch and other component ratings are listed in Table 4.1
4.5.2 Hybrid Filtering

Fig 4.3 shows a single-line diagram of a hybrid filter. It consists of an active filter in series and a shunt passive filter network in parallel with the load. The passive filter absorbs all the harmonics in the load current, while the series active filter decouples the utility from the load and the passive filters at the harmonics frequencies. Thus the load and the passive filter draw only fundamental frequency currents from the utility.

Since the load is a six-pulse rectifier, the shunt passive filter network in each phase is assumed to consists of series-tuned filter, tuned to the fifth and seventh harmonics with a high pass filter concept. The total reactive power supplied by the passive filter network at the fundamental frequency is taken to be 20% of the load power. This allows a displacement power factor under light load conditions. The resistors in the series-tuned filter branches are calculated by assuming the quality factor at their respective harmonics frequencies, to be 100. The nth harmonics components in the load current is given as

\[ I_{Ln}(\omega t) = \frac{4}{\pi} I_{dc} \sin(n\pi) \cos(n\omega t) \]  \hspace{1cm} (4.11)

The total harmonics voltage across the passive filter network is calculated by summing the voltages at all harmonics frequencies.

\[ V_f(\omega t) = \sum_{n\neq1} I_{Ln}(\omega t) Z_n \quad \text{------- n\neq1} \]  \hspace{1cm} (4.12)

Where ‘Z_n’ is the impedance of the filter network at the n\(^{th}\) harmonic frequency. The harmonics voltage ‘V_c’ appears across the series active filter. The unknown harmonics, which are the 5\(^{th}\) and 7\(^{th}\) harmonics, will be filtered by capacitors, and the high pass inductor and resistor, are obtained by minimizing the voltage across the passive filter network. The values of components, that minimizing the peak value of the voltage \(V_f\) are listed in Table 4.2.
The value of inductor is such that the high pass filter is tuned to the 17\textsuperscript{th} harmonics. Since the resistor value is infinity, the high pass filter itself will work as a series tuned filter. The tolerance and aging of components can make the shunt passive filter detuning. Assuming the increase of 2\% capacitor value in all the filters. The peak value of voltage $V_f = 58.4V$ as in Fig 4.4. The series active filter has three single phase inverters, each are controlled by four power electronic switches. The peak voltage at each switch is d.c bus voltage. The smallest d.c voltage which allows the complete control of inverter is the peak value of $V_f$. The turns ratio of transformer used for this purpose is 1:1 the current which flows through the switches has fundamental frequency. The ratings of components used are listed in Table- 4.1 and the parameter values of passive filter are given in Table-4.2.

In the MATLAB analysis of hybrid filter, the effects of utility voltage harmonics are neglected. This will result in slightly increase in the ratings of the active filter components. \[39\]

4.6 WAVE SHAPING

4.6.1 Magnetic wave shaping of currents

In this approach the line currents are wave shaped nearly sine wave by the use of magnetic device. Here the three phase inductors, transformer are used as current divider and inter phase
transformer in the line. In this the power electronic devices of three diode bridge rectifiers are
connected to get 18-pulse operation. The overall rating of magnetic group components is 24%
of total load power. The increase of (THD) in line current with the load is 6% of full load. The
regulation of output voltage obtained with this approach is 20%.
A similar magnetic group with different rating is used to get 12-pulse operation with low
harmonics distortion in line current. Another magnetic wave shaping can be used by adopting
differential delta connection transformers for further improvement. The d.c. output voltage can
further be regulated by using booster converter in the output circuit of bridge rectifiers.

4.6.2 Active wave shaping of current
In this method the sine wave shaping of line current is done by adopting active controlling with
power electronic switches, operating at high frequency.

4.6.3 Single switch method
A single-phase a.c. circuit for power factor correction is used as in Fig 4.4 Three such circuits
are used to rectify three phase voltages, by providing at least two isolators in them to obtain
proper control. Both line frequency and high frequency isolators can be used in this approach.
Since high frequency power electronic converter required is an additional expenses, therefore a
line frequency transformer is preferred for this purpose.
With the selected ratings of components, the line input current has its rms value of 8A Max.
Ripple current of 2.27A, d.c.output voltage of 645V & \( L_d = 3.55 \text{mH} \) respectively. The rating of
switches, inductors and transformers for this approach is given in Table 4.1.
4.6.4 Multi-switches method

The load in this method is directly connected through six-switches PWM-rectifier as in Fig 4.5. The switches are operated such that a unity power factor is achieved. The line current obtained in this approach is within the distortion limit of 5%.

The peak value of line current obtained is 20A. Now under the control of PWM-switches, the required output voltage will be minimum when the fundamental sine wave frequency is modulated with third and ninth harmonics as it was obtained in the six-switches active filter. On the basis of operating condition, the required minimum voltage \( V_d \) can be expressed in terms of fundamental component of the rectifier phase voltage \( V_a \) as follows.

\[
V_d = \frac{2.2\sqrt{2} V_{al}}{1.155}
\]  

(4.13)

The relationship between source voltage \( V_{as} \) and the fundamental voltage \( V_{a_1} \) as per Fig 4.6 at UPF is as under

\[
V_{a_1}^2 = V_{as}^2 + (\omega L_s I_{a_1})^2
\]  

(4.14)

![Circuit diagram for power factor correction](image)

Fig 4.4 Circuit diagram for power factor correction

The input inductance of six-switches rectifier \( L_s \) is obtained by using equations (4.10). The inductance \( L_s \) and d.c.output voltage \( V_d \) are obtained as 1.37mH and 646V respectively.
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The total switch rating and the equivalent inductor rating are calculated to be 84 kVA and 165 kVA respectively [40]

4.6.5 The current modulated method

In this method zig-zag transformer rectifier is used with two boosters D.C – D.C converter at the diode bridge converter, as shown in Fig-4.7. To modulate the link current to be \((I_d + i_3)\) and \((I_d - i_3)\). Where \(I_d\) is D.C. component and \(i_3\) the third harmonic component of link current.

The total third harmonic current \(2i_3\) from the output. The midpoint ‘n’ is injected into a.c.side through zig-zag transformer. The zig-zag connection of transformer produces high magnetizing impedance for third harmonic current. The total third harmonic current is divided equally into three limbs of transformer.

Fig 4.5 Circuit diagram of a six-switch rectifier

Fig 4.6 Phasor diagram of source voltage, fundamental voltage and line current
The line current has a distortion less than 5% when third harmonic current $i_3 = 0.51I_d$. The relationship between fundamental current $I_{as1}$ and D.C. Component $I_d$ and $i_3$ is given by:

$$I_{as1} = \frac{\sqrt{6} \ (I_d + i_3)}{\pi} \frac{4\sqrt{2}}{4\sqrt{2}} \quad \text{(4.15)}$$

which gives $I_d = 16.4A$ and $i_3 = 8.3A$ & The $I_{max} = (I_d + i_3 + Ippmax/2)$

The voltage across each winding of zig-zag transformer is given as $(1/\sqrt{3}) \ V_s$ as in Fig 4.8. Where as the current is $(2/3) \ i_3$. Since there are no secondary windings in the transformer. Therefore the rating of three windings is $(2.3 \ kVA)$. Like in an open delta transformer. Let the leakage impedance to be considered as 3%. Now the leakage impedance $X_L$ of the winding at 50Hz can be obtained as follows.
\[ X_L = 0.015 \times \frac{V_{ph}}{\sqrt{3}} \times \frac{1}{(\frac{2}{3})i_3} = 0.375\Omega \] (4.16)

Where the \((2/3) i_3\) is current at fundamental frequency is assumed. The third harmonic voltage at the mid-point ‘n’ with respect to neutral of the three phase utility voltage is given as.

\[ V_n = 3 \times (2x1) \times (2/3) i_3 = 12.45V \] (4.17)

For proper control of each booster converter, the output voltage must be greater than the peak input voltage. The peak voltage at the input of each booster converter is estimated by taking the algebraic sum of peak phase voltage and the peak voltage at the mid-point ‘n’, the output voltage is given as

\[ V_d = 2x1.1 \times (\sqrt{2}V_{uc} = \tilde{V}n) = 784.2V \] (4.18)

Based on the operating conditions, the maximum peak-to-peak ripple current in the booster converter is 5.63A and inductance 0.87 mH. Since a split capacitor output is present, the peak voltage rating of each switch is equal to one-half the d.c.output voltage. The total ratings for the switches and inductors are given in Table 4.2. [41]

| Technique     | No. of Switches | Switch kVA | Switch Rating | Eq. Transformer kVA | Eq. Transformer Rating | Capacitor kVA | | Total |
|---------------|-----------------|------------|---------------|---------------------|------------------------|---------------|--------|
|               | Filter Boost    |            |               |                     |                        |               |        |
| Active Filter | 6               | 1          | 7             | 4.18                | 1.27                   | 5.45          | 0.015  |
| Hybrid filter | 12              | 1          | 13            | 1.70                | 1.27                   | 2.97          | 0.011  |
| Single phase  | 3               |            |               | 1.01                |                        |               | 1.15   |
| Min. Rect.    | 2               |            |               | 243                 |                        |               | 1.40   |

Table 4.2 D.C Output Voltage Rating of Normal Components

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Table 4.3 Capacity ratings of elements

<table>
<thead>
<tr>
<th>Harmonics Filter</th>
<th>Capacitor µF</th>
<th>Capacitor kVA/Ph</th>
<th>Inductor (mH)</th>
<th>Equivalent Trans. kVA/Ph</th>
<th>Resistance in Ohm</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>277</td>
<td>24.15</td>
<td>10.5</td>
<td>0.259</td>
<td>192</td>
</tr>
<tr>
<td>7</td>
<td>185</td>
<td>1.643</td>
<td>77.7</td>
<td>0.121</td>
<td>205</td>
</tr>
<tr>
<td>HP</td>
<td>26.18</td>
<td>0.648</td>
<td>0.93</td>
<td>0.005</td>
<td>R_{hp} = \infty</td>
</tr>
</tbody>
</table>

4.7 SIMULATION RESULTS

Fig 4.9 Simulated diagram of Diode-bridge rectifier

Fig 4.10 Input voltage Vs Time waveform
(Time on x-axis, Vs on y-axis)
Fig 4.11 Output current Vs Time waveform
(Time on x-axis, I₀ on y-axis)

Fig 4.12 Output voltage Vs Time waveform
(Time on x-axis, Vs on y-axis)
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Fig 4.13 Simulated diagram of active filter

Fig 4.14 Input D.C voltage Vs Time waveform (Time on x-axis, Vs on y-axis)
Fig 4.15 A.C voltage Vs Time waveform (Time on x-axis, V₁ on y-axis)

Fig 4.16 Three-phase voltage Vs Time waveform (Time on x-axis, Vs on y-axis)
Eᵣ-phase, Eᵧ-phase & Eₜ-phase

Fig 4.17 Three-phase Current Vs Time waveform (Time on x-axis, Iₛ on y-axis)
Iᵣ-phase, Iᵧ-phase & Iₜ-phase

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Fig 4.18 Output current Vs Time waveform (Time on x-axis, $I_o$ on y-axis)

Fig 4.19 Output voltage Vs Time waveform (Time on x-axis, $V_o$ on y-axis)
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Fig 4.20 Simulated diagram of a hybrid filter

Fig 4.21 Input D.C voltage Vs Time waveform (Time on x-axis, $V_{dci}$ on y-axis)
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Fig 4.22 Three-phase voltage Vs Time waveform (Time on x-axis, V on y-axis) 
$V_R$-phase, $V_Y$-phase & $V_B$-phase

Fig 4.23 Three-phase current Vs Time waveform (Time on x-axis, I on y-axis) 
$I_R$-phase, $I_Y$-phase & $I_B$-phase
Fig 4.24 Output current Vs Time waveform (Time on x-axis, I₀ on y-axis)

Fig 4.25 Output voltage Vs Time waveform (Time on x-axis, V₀ on y-axis)
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Fig 4.26 Simulated diagrams for power factor correction

Fig 4.27 Output current Vs Time wave form (Time on x-axis, I_o on y-axis)
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Fig 4.28 Output voltage Vs Time waveform (Time on x-axis, $V_o$ on y-axis)

Fig 4.29 Waveform of output current of D2 & D4 (Time on x-axis, $I_{dc}$ on y-axis)

Fig 4.30 active & reactive power waveform (Time on x-axis, P-Q on y-axis)
(yellow line for P, purple line for Q)
Fig 4.31 Simulated diagram of six-switch rectifier
Fig 4.32 Waveforms of Rectified DC voltage, current-ph1, current-ph2, diodes output current (Time on x-axis, I on y-axis)

Fig 4.33 Improved Three-phase voltage Vs Time waveform (Time on x-axis, V on y-axis) 
$V_R$-phase, $V_Y$-phase & $V_B$-phase

Fig 4.34 Improved Three-phase current Vs Time waveform (Time on x-axis, I on y-axis) 
$I_R$-phase, $I_Y$-phase & $I_B$-phase
Fig 4.35 Output current Vs Time waveform (Time on x-axis, \( I_o \) on y-axis)

Fig 4.36 Output voltage Vs Time waveform (Time on x-axis, \( V_o \) on y-axis)
Fig 4.37 Simulated diagram of zigzag TR. Rectifier
Fig 4.38 Input voltage Vs Time waveform (Time on x-axis, $V_i$ on y-axis)

Fig 4.39 Output current Vs Time waveform (Time on x-axis, $I_o$ on y-axis)

Figure 4.40 Output voltage Vs Time waveform (Time on x-axis, $V_o$ on y-axis)
4.8 CONCLUSION

The component ratings are taken as, the base VA as the load rating of 10kW. The minimum required rectified D.C. bus voltage is 1.35x415 = 560.3V. This is based on the component ratings. Further the following observations are made:

- This approach has the lowest switch VA ratings, but requires large transformer isolation, resulting in large weight and high cost. The active filter has a fairly high VA rating and the hybrid filter requires a large number of switches. These schemes are more likely to be used in connection with a cluster of harmonics producing loads in distribution system.

- The Zig–Zag transformer rectifier has VA ratings in comparison with the single-phase approach. It requires only two switches, each with a voltage rating of half the d.c. bus voltage. It has simple control and high reliability. The reactively high value of the minimum D.C. bus voltage can be an advantage if the inverter-load supplied from the D.C. bus makes full use of it. For example the higher D.C. bus voltage provides a large hold up time in case of utility power interruption, because of the available energy $E = \frac{1}{2} C \left(V_{d1} - V_{d2}\right)^2$, where $V_{d1}$ is nominal d.c. bus voltage and $V_{d2}$ is the voltage below which the inverter load cannot be operated.

- It is difficult to evaluate these schemes in terms of losses, for example in inductive elements, to reduce losses by increasing their weight and cost. Another way is the conducted and radiated electromagnetic interference. In the single phase approach and the Zig – Zag transformer rectifier approach it is possible to obtain zero current switching of semi conductor switches by using quasi-resonance concepts.
Conclusion is that this chapter evaluates various techniques for current harmonic reduction. In three phase utility interface of power electronic loads, the VA ratings of components are presented along with the characteristics of these techniques which are ideal for all applications.