Estimation of Size of Filter Inductor and Capacitor in 6-Pulse and 12-Pulse Diode Bridge Rectifier

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Abstract— For high-power switch mode converters operating on three-phase ac mains, a rectifier with LC low pass filter is an important component that provides intermediate dc link voltage. Since filter inductor and capacitor constitute bulkier components of the overall converter, it is pertinent to estimate their sizes and possibly minimize the overall size. The paper provides closed form expressions to estimate the size of the filter as a function of output power based on the previously available guidelines and datasheet values. It is also seen that it is possible to minimize overall size of filter. While the analytical results are presented for the 6-pulse and 12-pulse rectifier, the validity has been confirmed by comparing the dimensions of prototype filter inductor for a 1 kW, 6-pulse rectifier.

Keywords— Rectifier, Filter, Size, Optimization

I. INTRODUCTION

High power switch-mode power supplies (SMPS) operate on three-phase ac mains. A three-phase rectifier with LC filter is therefore invariably the front-end stage in any off-line SMPS architecture. Most commonly, a 6-pulse diode bridge rectifier [1]-[3] is used as the front-end rectifier. For high power applications, higher-pulse rectifiers, such as 12-pulse rectifier [1]-[3] are used to reduce harmonics on the source and load side. To reduce residual harmonics on the dc side, the rectifiers are invariably associated with LC filter.[8]-[12]

The choice of filter inductance is done to maintain continuous inductor current with ripple as low as reasonably achievable to improve the load regulation of the output voltage, reduce harmonics in the input current and to improve the power factor [1]. The filter capacitor is chosen to reduce the ripple in the output voltage. Often, passive damping is incorporated in the filter stage to damp the harmful resonance in the filter circuit [4]. However, the study presented in this paper is limited to undamped LC filter. The same, however, can be extended to damped filter configurations.

The inductor and capacitor in the filter circuit are the bulkier components and therefore play a major part in deciding the overall size of the converter. A designer is normally provided with the specifications of a power converter and is required to provide an estimate floor space area or size of the

power supply cabinet. In this situation it would be useful if the designer could estimate the size of the inductor and capacitor. Besides, within the given constraints, it is also possible for the designer to vary the values of the inductor and capacitor to optimize the filter for size, cost, weight etc.

A guideline to estimate the size of the filter inductor has been described in [5] in detail. In the first part of this paper, an expression to estimate the size of the inductor is derived using the guidelines and various values given in [5]. In the second part of the paper, attempt has been made to model the size of the capacitor in the form of curve-fit equation using the datasheet values of commercially available capacitors [6]. A way to minimize the overall size of the filter is subsequently discussed. While the analytical results are presented for the 6-pulse and 12-pulse rectifier, the validity has been confirmed by comparing the dimensions of prototype filter inductor for a 1 kW 6-pulse rectifier.

II. DESIGN OF LC FILTER FOR 6 PULSE AND 12 PULSE RECTIFIER

A. LC Filter for 6 Pulse Rectifier

A 6-pulse rectifier with LC filter is shown in Fig. 1. The value of filter inductance is chosen to maintain continuous conduction mode till some value of the load current, called the critical current, I_{cri}. It can be obtained as:

\[ L_{ind} = \frac{0.013V_{L,\text{max}}}{2nfI_{cri}} \]  

Fig. 1: Circuit diagram of 6-pulse diode rectifier.
where, $V_{LL_{\text{max}}}$ is maximum line to line voltage, $f$ is line frequency in Hz.

The estimation of value of filter capacitance is dependent on the cut off frequency $f_{c,6p}$ which is dependent upon the ripple attenuation as:

$$\frac{\Delta V_0}{\Delta V_{r,6p}} = \left(\frac{f_{c,6p}}{f_{r,6p}}\right)^2$$

(2)

where, $\Delta V_0$ is the ripple in the output voltage, $\Delta V_{r,6p}$ is the ripple in the unfiltered rectified voltage and $f_{c,6p}$ is the ripple frequency. For 6 pulse rectifier $f_{c,6p}=6f$. Having chosen $f_c$, the value of filter capacitance can be determined as:

$$C_{6p} = \frac{1}{4\pi^2 f_{c,6p}^2 L_{6p}}$$

(3)

### B. LC Filter for 12 Pulse Rectifier

A 12-pulse series-connected diode rectifier with LC filter is shown in Fig. 2. An expression to find the value of filter inductance in a 12-pulse rectifier can be derived as:

$$L_{12p} = \frac{0.00155V_{LL_{\text{max}}}}{2\pi f l_{cri}}$$

(4)

The estimation of value of filter capacitance is dependent on the cut off frequency $f_{c,12p}$ which is dependent upon the ripple attenuation as:

$$\frac{\Delta V_0}{\Delta V_{r,12p}} = \left(\frac{f_{c,12p}}{f_{r,12p}}\right)^2$$

(5)

where, $\Delta V_0$ is the ripple in the output voltage, $\Delta V_{r,12p}$ is the ripple in the unfiltered rectified voltage and $f_{r,12p}$ is the ripple frequency. For 12-pulse rectifier $f_{r,12p}=12f$. Having chosen $f_{c,12p}$, the value of filter capacitance can be determined as:

$$C_{12p} = \frac{1}{4\pi^2 f_{c,12p}^2 L_{12p}}$$

(6)

### III. VOLUME OF INDUCTOR

#### A. Size of Filter Inductance for 6 Pulse Rectifier

It has been established in [5] that the volume of an inductor is a function of many parameters such as inductance value, current, operating flux density, current density, temperature rise, core configuration etc. In this section, the derivation of the size of an inductor as a function of rectifier design parameters such as output power of the rectifier and the ratio of the critical current for continuous operation to the maximum load current is obtained.

$$Vol. = K_{vol} A_p^{0.75} cm^3$$

(7)

where, $K_{vol}$ is the constant related to the core configuration (values available in [5]) and $A_p$ is the area product which is the product of the window area and core area.

Further, the area product can be expressed as a function of energy stored in the inductor as [5],

$$A_p^{(1+x)} = 2 \left(\frac{\text{Energy}}{B_m K_j K_u} \right) cm^4$$

(8)

where, $B_m$ is maximum magnetic flux density, $K_j$ is constant related to chosen current density and temperature rise, $K_u$ is utilization factor and $x$ is constant related to core configuration. Values of these constants are available in [5]. If $I_{dc}$ is the maximum dc current flowing through the inductor, then the energy stored is $0.5\times L_{6p}\Delta I_{dc}^2$. The expression for volume of filter inductor in 6-pulse rectifier can therefore be derived from (1), (7) and (8) as:

$$Vol(I_{6p}) = K_{vol} \left[\frac{96.2 P_d}{2\pi f l_{cri} l_{dc} B_m K_j K_u} \right]^{0.75} cm^3$$

(9)

where, $P_d$ in Watts is the output power. Similarly, the expression for volume of filter inductor in 12-pulse rectifier can therefore be derived from (4), (7) and (8) as:

$$Vol(I_{12p}) = K_{vol} \left[\frac{11.65 \times P_d}{2\pi f l_{cri} l_{dc} B_m K_j K_u} \right]^{0.75} cm^3$$

(10)
Therefore, size of inductor is dependent upon the rated power which provides the direct estimation of volumetric size of the inductor. The factors which decide the size of the filter in case of 12 pulse rectifier is same as in case of 6 pulse diode bridge rectifier.

IV. VOLUME OF CAPACITOR

Electrolytic capacitors are commonly used as the filter capacitor in the front-end mains rectifier circuits. While [5] provides a guideline to estimate the size of filter inductor, the authors are unaware of the procedure or an empirical relationship that models the size of filter capacitor. Described in this section, therefore, is an attempt to model the size of filter capacitor is presented based on the size of commercially available sizes of the capacitor. Two approaches have been proposed in [7] to do that – the one that used a relationship between the size of capacitor as a function of its value and the other one that models the size of the capacitor as a function of energy stored. In this paper, the latter approach is described.

The size of commercially available electrolytic capacitors depends on many factors: value, voltage rating, maximum datasheet temperature, type of construction, ripple current rating, manufacturer etc. Therefore, perhaps it is difficult to obtain a unique relationship that would describe the volume of the capacitor as a function of energy stored. As an illustrative example, the datasheet values of [6] are used to model the volume – energy dependence:

\[ V_\text{ol}(C_\text{ap})[\text{cm}^3] = a(\text{Energy}[\text{J}])^b \]  

\[ \text{(11)} \]

where, \( a \) and \( b \) are curve-fit constants. For various capacitors of [6], the volume – energy dependence is shown in Fig. 3 and the corresponding curve-fit values obtained are listed in Table 1. Table 1: Curve-fit constants \( a \) and \( b \)

<table>
<thead>
<tr>
<th>Life of capacitor (hours)</th>
<th>( a )</th>
<th>( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;6000</td>
<td>3.2433</td>
<td>0.8269</td>
</tr>
<tr>
<td>&gt;3000,8000,10000,20000</td>
<td>30.912</td>
<td>0.5782</td>
</tr>
</tbody>
</table>

Similarly, the expression for the volume of the filter capacitor for a 12-pulse rectifier as a function of the output dc power can be derived using (4), (6) and (11) as:

\[ V_\text{ol}(C_{12p}) = \frac{125.7K_v^{1.72} f^{0.86}}{I_{c,12p}^2 I_{dc}^2} \left( \frac{I_{c,12p}}{I_{dc}} \right) P_d^{0.8629} \text{ cm}^3 \]  

\[ \text{(13)} \]

Therefore, the size of capacitance can be easily seen as a quantity dependent upon the rated power output.

V. SIZE OPTIMIZATION OF LC FILTER

A. 6-Pulse rectifier

The total size of filter for a 6-pulse rectifier can be found using (9) and (12) as:

\[ V_\text{ol}(L_{C6p}) = \frac{K_v}{\alpha^{0.057}} + \frac{96.2 I_{c,6p}^{1.72} f^{0.86}}{2\pi f R_m K_y K_u} \left( \frac{I_{c,6p}}{I_{dc}} \right) P_d^{0.8629} \text{ cm}^3 \]  

\[ \text{(14)} \]

which can be rewritten as for \( x = -0.125 \) [5]:

\[ V_\text{ol}(L_{C6p}) = K_{1.6p} \frac{I_{c,6p}^{1.72} f^{0.86}}{\alpha^{0.057}} P_d^{0.8629} + K_{2.6p} \frac{I_{c,6p}^{1.72}}{\alpha^{0.857}} P_d^{0.8629} \]  

\[ \text{(15)} \]

wherein,

\[ K_{1.6p} = K_v \alpha^{0.857} \]  

\[ \text{(16)} \]

\[ K_{2.6p} = \frac{96.2 I_{c,6p}^{1.72} f^{0.86}}{2\pi f R_m K_y K_u} \]  

\[ \text{(17)} \]

Fig. 3: Variation of capacitor volume as a function of energy for the capacitors of [6].
A proper choice of $\alpha$ is thus important since the volume of inductor increases and volume of capacitor decreases with decrease in $\alpha$, and vice versa. It is, therefore, expected that there exists a particular value of $\alpha$ for which the overall size of the filter is minimum. This value is termed as the optimum value of $\alpha$, the $\alpha_{opt_{6p}}$. It can be derived from (15) as:

$$\alpha_{opt_{6p}} = \left( \frac{K_{1,6p}}{K_{2,6p}} \right)^{0.5814}$$

(19)

The variation of the inductor, capacitor and total volume with respect to ratio of critical current to the rated current is plotted illustratively as shown in Fig. 3 with the following parameters for EI lamination core type:

- $x = -0.125, K_{vol} = 19.7$
- $K_u = 0.26$
- $K_j = 366$ (corresponding to $\Delta T = 25^\circ C$)
- $B_m = 1.2 T, f = 50 Hz, \frac{l_{cri}}{I_{dc}} = 0.1, f_{csp} = 30 Hz$
- $P_d = 1000 W, K_v = 1.5$

![Fig. 3: Variation of filter inductor, filter capacitor and total volume as a function of $\alpha$ for a 6-pulse rectifier, showing the existence of $\alpha_{opt_{6p}}$.](image)

**B. 12-Pulse Rectifier**

The total size of filter for a 12-pulse rectifier can be found using (10) and (13) as:

$$Vol(LC_{12p}) = \frac{K_{1,12p}}{\alpha^{0.857}} + \frac{K_{2,12p} \alpha^{0.8629}}{P_d^{0.857}}$$

(21)

wherein,

$$K_{1,12p} = K_{vol} \left( \frac{11.65}{B_m K_j K_u} \right)^{0.857}$$

(22)

$$K_{2,12p} = \left( \frac{125.7 K_j^{1.73}}{f^{0.8629} \left( \frac{f}{f_{csp}} \right)^{1.73}} \right) P_d^{0.8629}$$

(23)

$$\alpha = \frac{l_{cri}}{I_{dc}}$$

(24)

The optimum value of $\alpha$, the $\alpha_{opt_{12p}}$. It can be derived from (21) as:

$$\alpha_{opt_{12p}} = \left( \frac{K_{1,12p}}{K_{2,12p}} \right)^{0.5814}$$

(25)

The variation of the inductor, capacitor and total volume with respect to ratio of critical current to the rated current is plotted illustratively as shown in Fig. 3 with the following parameters for EI lamination core type:

- $x = -0.125, K_{vol} = 19.7$
- $K_u = 0.26$
- $K_j = 366$ (corresponding to $\Delta T = 25^\circ C$)
- $B_m = 1.2 T, f = 50 Hz, \frac{l_{cri}}{I_{dc}} = 0.1, f_{csp} = 30 Hz$
- $P_d = 1000 W, K_v = 1.5$

![Fig. 4: Variation of filter inductor, filter capacitor and total volume as a function of $\alpha$ for a 12-pulse rectifier, showing the existence of $\alpha_{opt_{12p}}$.](image)

**VI. Prototype Validation of Filter For 6-Pulse Rectifier**

For a 6-pulse rectifier of output power 1000 W with 40 V, 25 A output, for $f=50$ Hz, $V_{LL_{max}}=38$ V (considering design margins for various drops and line variation), $f_{csp}=30$ Hz, $I_{cri}=2.5 A$, the values of inductance can be found out as $L_{eq}=630\mu H$.

An inductor is fabricated for temperature rise of 25$^\circ$C in EI lamination core. The design and fabrication data of the inductor...
is summarized in Table 2. Photograph of the inductor is shown in Fig. 5.

Table 2: Summary of design and fabrication data for the inductor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
<td>630 ( \mu ) H</td>
</tr>
<tr>
<td>DC current</td>
<td>25 A</td>
</tr>
<tr>
<td>Core cross sectional area</td>
<td>7.44 cm(^2)</td>
</tr>
<tr>
<td>Number of turns</td>
<td>19</td>
</tr>
<tr>
<td>Flux density ((B_m))</td>
<td>1.2 T</td>
</tr>
<tr>
<td>Window utilization factor ((K_u))</td>
<td>0.26</td>
</tr>
<tr>
<td>Dimensions of inductor</td>
<td>9 X 4.7 X 7.5 cm</td>
</tr>
<tr>
<td>Volume of the inductor</td>
<td>317.25 cm(^3)</td>
</tr>
</tbody>
</table>

Fig. 5: Photograph of prototype filter inductor fabricated.

The following parameters can be noted from [2]:

\[ x = -0.125, K_{vol} = 19.7 \text{ and } K_f = 366. \]

The volume of inductor is therefore calculated using (9) as 329.61 cm\(^3\). The resulting error between the estimated and actual inductor size is 3.75%.

Further, for these parameters the \( \epsilon_{opt,6p} \) is found out to be 0.1179.

VII. CONCLUSION

The paper presents closed form expression derived to estimate the size of filter inductor and capacitor in three phase rectifier circuits as a function of output power, earlier published empirical constants and data sheet values. A method to optimize overall size of the LC filter is also proposed. The validity is confirmed with a prototype fabricated filter inductor for a 1 kW rectifier and results are encouraging. The model derived datasheet values of the electrolytic capacitors is approximate due to discrete values and voltage ratings available from the manufacturer. It needs to be refined further with more data from different manufacturers.

REFERENCES


