Rating of Transformers supplying Harmonic-Rich Loads

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Losses in Transformers

No-load loss (‘iron loss’)
- energy consumed in eddy current and hysteresis loss
- present 100% of the time

Load losses

Resistive loss (‘copper loss’)
- dependent on square of load current
- most important during high load periods

Eddy current loss
## Distribution transformer efficiency standards
### HD 428 & 538

<table>
<thead>
<tr>
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Source: CENELEC

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# Distribution transformer efficiency standards

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Source: CENELEC
Full load losses in a 100kVA C-C’ transformer

Total loss = 1685 W

- Winding: 88%
- Magnetic: 12%
Full load losses in a 100kVA C-C’ transformer

Total loss = 1685 W
Full load losses in a 100kVA C-C’ transformer

- Resistance: 84%
- Magnetic: 12%
- Eddy Current: 4%

Total loss = 1685 W
Current waveform for a typical PC
Harmonic profile of a typical PC

![Harmonic profile graph]

- **Harmonic profile of a typical PC**
- **Current (A)**
- **Harmonic**

0.0000
0.1000
0.2000
0.3000
0.4000
0.5000
0.6000

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
Typical harmonic profile - 6 pulse converter
Effect of harmonics on transformers

There are two issues that affect Transformers supplying harmonic-rich loads:

• Triple-n harmonic currents circulate in delta windings, increasing resistive losses, operating temperature and reducing effective load capacity

• Harmonic currents, being of higher frequency, cause increased magnetic losses in the core and increased eddy current and skin effect losses in the windings
Effect of triple-n harmonics in transformers

Triple-n harmonic currents circulate in delta windings - they do not propagate back onto the supply network.
Harmonic mitigation by transformer

Delta-star transformers
Effect of harmonics on transformers

There are two issues that affect Transformers supplying harmonic-rich loads:

- Triple-n harmonic currents circulate in delta windings, increasing resistive losses, operating temperature and reducing effective load capacity

- Harmonic currents, being of higher frequency, cause increased magnetic losses in the core and increased eddy current and skin effect losses in the windings
Increased eddy current losses in transformers

Increased eddy current loss can be calculated by:

\[ P_{eh} = P_{ef} \sum_{h=1}^{h_{\text{max}}} I_h^2 h^2 \]

where:
- \( P_{eh} \) is the total eddy current loss
- \( P_{ef} \) is the eddy current loss at fundamental frequency
- \( h \) is the harmonic order
- \( I_h \) is the per unit RMS current at harmonic \( h \)
K-Rating of Transformers

There are two approaches to rating transformers supplying harmonic rich load:-

- Designing for the anticipated duty - e.g. the American system, established by UL and manufacturers, which specifies harmonic capability of the transformer - known as *K-factor*.

- De-rating to survive the anticipated duty - e.g. the European system, developed by IEC, which defines de-rating factor for standard transformers - known as *factor K*.
**K-Rating of Transformers - US System**

First, calculate the K factor of the load according to:

\[ K = \sum_{h=1}^{h_{\text{max}}} I_h^2 h^2 \]

where:

- \( h \) is the harmonic order
- \( I_h \) is the RMS current at \( h \) in per unit of total current
K-Rating of Transformers - US System

For this typical PC load, the K factor is 11.6
(For worked examples see LPQI AN 3.5.2 or IEE 1100 1992)
Next, a transformer with a higher K rating is selected from the standard range:

4, 9, 13, 20, 30, 40, 50
**K-Rating of Transformers - European System**

In Europe, the transformer de-rating factor is calculated according to the formulae in BS 7821 Part 4. The factor K is given by:

\[
K = \left[ 1 + \frac{e}{1 + e} \left( \frac{I_1}{I} \right)^2 \sum_{n=2}^{N} \left( n^q \left( \frac{I_n}{I_1} \right)^2 \right) \right]^{0.5}
\]

- **e** is the ratio of eddy current loss (50 Hz) to resistive loss
- **n** is the harmonic order
- **q** is dependent on winding type & frequency, typically 1.5 to 1.7
**K-Rating of Transformers - European System**

For the same PC load, the de-rating factor is 78%
Harmonic Diversity - K Factor

No of Units (pairs)

K Factor

1 2 5 10 20 41
K-Rating - Calculation software

Enter the harmonic number and harmonic current for each harmonic that is present and "Add" to the list. Remember to include the fundamental with a harmonic number of one. Currents may be absolute values or relative to the fundamental current as 1.

Calculation method:
- [ ] K Factor
- [ ] Factor K

Fundamental eddy current loss: 0.10
Eddy current loss exponent: 1.7

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<tr>
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</tr>
<tr>
<td>3</td>
<td>0.820</td>
</tr>
<tr>
<td>5</td>
<td>0.580</td>
</tr>
<tr>
<td>7</td>
<td>0.380</td>
</tr>
<tr>
<td>9</td>
<td>0.180</td>
</tr>
<tr>
<td>11</td>
<td>0.045</td>
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RMS current: 1.479
K - rating: 11.61

Calculate
**K-Rating - Calculation software**

![CDA K Factor Calculator](image)

- **Calculation method**
  - K Factor
  - Factor K

- **Fundamental eddy current loss**: 0.10
- **Eddy current loss exponent**: 1.7

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<tr>
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<tr>
<td>13</td>
<td>0.091</td>
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<tr>
<td>17</td>
<td>0.059</td>
</tr>
<tr>
<td>19</td>
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- **RMS current**: 1.042
- **Factor K de-rate to**: 85.56%

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K-Rating - Calculation software
**K-Rating - Calculation software**

![CDA K Factor Calculator](image)

**Harmonic No.** | **Magnitude**  
--- | ---  
1 | 1  
3 | 0.820  
5 | 0.580  
7 | 0.380  
9 | 0.180  
11 | 0.045  

**Fundamental eddy current loss:** 0.10  
**Eddy current loss exponent:** 1.7  
**RMS current:** 1.479  
**Factor K de-rate to:** 77.53%
Full load losses in a 100kVA C-C’ transformer

Total loss = 3245 W

- Resistance: 53%
- Magnetic: 41%
- Eddy Current: 6%
80% load losses in a 100kVA C-C’ transformer

Total loss = 2156 W

- Resistance: 51%
- Magnetic: 39%
- Eddy Current: 10%
Effect of additional losses on life-time

80 % load

Working temp = \( t \times \frac{P_k}{P_f} = 90 \times 1.28 = 115^\circ C \)

Life – time = \( T \times 2^{\frac{t \times (P_k - P_f)}{10P_f}} \)

Life – time = \( T \times 2^{40 \times 2^{-2.5}} = 7 \text{ years} \)
70% load losses in a 100kVA C-C’ transformer

Total loss = 1699 W
Effect of additional losses on life-time

70 % load

Working temp = \( t \times \frac{P_k}{P_f} = 90 \times 1.0083 = 90.75^\circ C \)

Life – time = \( T \times 2^{\left(-\frac{\partial t}{10}\right)} \)

\[ \text{Life – time} = T \times 2^{\left(-\frac{t \times (P_k - P_f)}{P_f \times 10}\right)} = 40 \times 2^{-0.075} = 38 \text{ years} \]
The real world

Selection and management

- small change in loading - large effect on lifetime.
- derate then add the ‘headroom’
- management practices must maintain derating for the life of the transformer when
  - adding new loads
  - making changes to any harmonic filters within the installation