Effect of K-Factor on Capability in Power Transformers

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Abstract. Harmonic currents generated by nonlinear loads can cause overheating and premature failure of power transformers. According to IEEE Std C57.110TM - 2008, Eddy Current losses are considered proportional to the harmonic current squared multiplied by the harmonic number. This paper will discuss 2 case studies, namely: a transformer without using a harmonic filter and a transformer using a harmonic filter. This research was conducted by measuring the amount of harmonics in arc furnace customers using power quality analysis equipment for 7 days. From the research results obtained indicate that the value of the k-factor is inversely proportional to the maximum transformer capability and is directly proportional to the decrease in transformer capability. So that the transformer that is installed using a harmonic filter has a k-factor value and derating capability is smaller than the transformer without using a harmonic filter, in order not to derating capability of the transformer without using a harmonic filter or a transformer that uses a harmonic filter, it is necessary to use the K-Factor Transformer K-4.

1. Introduction
In recent years in Indonesia, there has been a significant increase in nonlinear loads. Which is caused by electrical / electronic equipment that uses power electronics in households, business and industries. Which cause harmonics in the electric power distribution system[1].

Transformers are considered as an essential component in the electric power system. The nonlinear load on the single-phase transformer causes iron losses and copper losses to increase. This non-linear load causes harmonic distortion which results in increased power losses in the transformer[2]. In the electric power system, the use of equipment with non-linear loads can cause a decrease in the power of the transformer due to the increase in power losses, especially in single-phase transformers. The use of non-linear loads in the electricity system must be controlled. because the main purpose of the electric power system is to deliver electricity with good quality and reliability. However, this ideal condition cannot be fulfilled, because there are various kinds of disturbances, including harmonics caused by non-linear loads which will affect the performance of the electric power system as a whole.

The main purpose of an electric power system is to deliver electric power with a constant voltage and a constant frequency. However, it is not possible to meet these ideal requirements, because there are various kinds of disturbances, including harmonics caused by non-linear loads which will affect the performance of the electric power system as a whole.

Non-linear loads are loads that draw a current that is not sinusoidal. Electrical equipment which includes non-linear loads such as arc furnaces, gas discharged lighting, solid state motor drives,
battery chargers, UPS systems, and electronic power supplies as well as power electronic controlled equipment [3].

Harmonic currents are currents whose frequency is an integer multiple of the fundamental (power supply) frequency. Harmonic currents superimposed on the fundamental currents produce a non-sinusoidal current waveform associated with nonlinear loads. Harmonics are one of the characteristics of electrical quality at steady state conditions in an electrical system that can affect power quality. Harmonics consist of; total harmonic distortion current (THDi) and total harmonic distortion voltage (THDv). Harmonics cause bad impacts on power system equipment, including; reduce the capable power of the transformer.

In this paper, I study the effect of harmonics distortion and k-factor on capability in power transformer. This research is focused on analyzing the effect of arc furnace customers as a non-linear appliance to the harmonic distortion and k-factor in power transformers. The results of this research is expected can provide a reference in finding a solutions to minimized the undesired impacts of arc furnace customers and other non-linear equipment in the electric power system.

2. K-factor Transformer
The K factor is defined as the ratio between the additional loss due to harmonics and the eddy current loss. K-Factor ratings can be a good solution to apply to transformers and are suitable for use for non-linear loads[4]. The K-Factor is given by the following equation:

\[ K - Factor = \sum_{h=1}^{h_{\text{max}}} I_h^2 h^2 \]  \hspace{1cm} (1)

Where :
- \( h \) = harmonic order
- \( I_h \) = total rms current at harmonic number \( h \)

2.1. Relationship between K-Factor and Harmonic Loss Factor
The K-Factor can be formulated as follows:

\[ K - Factor = \sum_{h=1}^{h_{\text{max}}} h^2 \left( \frac{I_h}{I_R} \right)^2 = \frac{I}{I_R^2} \sum_{h=1}^{h_{\text{max}}} I_h^2 h^2 \]  \hspace{1cm} (2)

Where :
- \( h \) = harmonic order
- \( I_h \) = the rms current at harmonic number \( h \) (ampere)
- \( I_R \) = rms rating of load current at fundamental frequency

The relationship between the K-factor and harmonic loss factor (\( F_{\text{HL}} \)) is the formula as follows:

\[ K - Factor = \left[ \frac{\sum_{h=1}^{h_{\text{max}}} I_h^2}{I_R^2} \right] F_{\text{HL}} \]  \hspace{1cm} (3)

The numerical value of the K-Factor is the same as the numerical value of the Harmonic Loss Factor when the rms value of its harmonic load current at the square root is equal to the rated load current of the transformer [1, 7].
2.2. Relationship between K-Factor and Capable Power

The ideal transformer is a transformer that has 100% efficiency, that is, a transformer that does not lose power at all. However, this ideal or perfect transformer is almost impossible to achieve, this is due to several factors that cause loss or loss of power [6]. These factors include factors caused by the iron core which is usually called Core Loss or Iron Loss and the factor caused by the coil or coil on the transformer itself which is usually called Copper loss.

Capable power is the installed capacity minus the losses (Loss Without Load + Loss on Load). As a result of the impact of current harmonics on the transformer can cause an increase in transformer losses so that it can cause a derating capability of the transformer [4]. A reduction in the capable power of a transformer can be formulated, as follows:

a. Harmonic loss factor \( F_{HL} \)

Harmonic loss factor \( F_{HL} \) is an indicator of the effect of increasing losses due to current harmonics on losses in the current transformer rating conditions. Harmonic loss factor \( F_{HL} \) can be formulated, as follows:

\[
F_{HL} = \frac{\sum_{h=1}^{h_{\text{max}}} h^2 I_h^2}{\sum_{h=1}^{h_{\text{max}}} I_h^2} \frac{\sum_{h=1}^{25} I_h^2}{\sum_{h=1}^{25} I_h^2} \left( \frac{I_h}{I_R} \right)^2
\]

(4)

Where :
\( I_h \) = Harmonics currents order of h
\( I_R \) = rms rating of load current at fundamental frequency
\( H \) = Order of 1,2,3,4,…

b. Harmonic loss factor for other stray losses \( F_{HL-OSL} \)

Harmonic loss factor for other stray losses \( F_{HL-OSL} \) is an indicator of the effect of increasing losses due to current harmonics on other stray losses in transformer rating current conditions. Harmonic loss factor for other stray losses \( F_{HL-OSL} \) can be formulated, as follows:

\[
F_{HL-OSL} = \frac{\sum_{h=1}^{h_{\text{max}}} h^{0.8} I_h^2}{\sum_{h=1}^{h_{\text{max}}} I_h^2} \frac{\sum_{h=1}^{25} I_h^2}{\sum_{h=1}^{25} I_h^2} \left( \frac{I_h}{I_R} \right)^2
\]

(5)

c. Eddy current losses \( P_{EC} \)

Eddy current losses in the windings occur due to the alternating flux produced by the load current flow in the transformer windings. Eddy current losses in windings are affected by the skin effect. Eddy Current Loss can be formulated, as follows:

\[
P_{EC} = P_{EC-R} \sum_{h=1}^{h_{\text{max}}} h^2 \left( \frac{I_h}{I_R} \right)^2
\]

(6)

Where :
\( P_{EC} \) = Eddy Current Loss conditions influence current harmonics (kW)
P_{EC-R} = Eddy Current Loss condition load current rating and fundamental frequency (kW)
I_h = Harmonics order currents of n (A)
I_R = rms rating of load current at fundamental frequency (A)
H = Order of 1,2,3,4,…

d. Other stray losses (P_{OSL})
Other target losses can be formulated, as follows:

\[ P_{OSL} = P_{OSL-R} \sum_{h=1}^{h_{\text{max}}} h^{0.8} \left( \frac{I_h}{I_R} \right)^2 \]  

Where:
P_{OSL} = Other stray loss conditions influence current harmonics (kW)
P_{OSL-R} = Other stray losses are the load current rating conditions and the fundamental frequency (kW)
I_h = Harmonics currents order of n (A)
I_R = rms rating of load current at fundamental frequency (A)
H = Order of 1,2,3,4,…

e. Load losses (P_{LL})
Load losses can be formulated, as follows:

\[ P_{LL} = P_{DC} + P_{EC} + P_{OSL} \]

\[ P_{LL}(\text{pu}) = I^2(\text{pu}) \left[ 1 + F_{HL} \cdot P_{EC-R}(\text{pu}) + F_{HL-OSL} \cdot P_{OSL-R}(\text{pu}) \right] \]

f. Maximum Transformer Loading Capability (I_{MAX})
Maximum Transformer Loading Capability can be formulated, as follows:

\[ I_{\text{max}}(\text{pu}) = \frac{P_{LL}-k(\text{pu})}{\sqrt{1 + \left[ F_{HL} \cdot P_{EC-R}(\text{pu}) \right] + \left[ F_{HL-OSL} \cdot P_{OSL-R}(\text{pu}) \right]}} \]

Where:
I_{\text{max}}(pu) = Maximum Transformer Loading Capability
P_{LL-R}(pu) = Load losses (pu)
F_{HL} = Harmonic Loss Factor
P_{EC-R}(pu) = Eddy Current Losses (pu)
F_{HL-OSL} = Harmonic Loss Factor for Other Stray Losses
P_{OSL-R}(pu) = Other stray Losses (pu)

2.3. Standard transformer K-factor rated
The standard K-Factor rating for the transformer and the electrical equipment components contained therein are given in Table 1.
### Table 1. K-Factor Transformer Rating

| Load                                                                 | K-Factor |
|----------------------------------------------------------------------|----------|
| Incandescent lighting (with no solid state dimmers)                  | K-1      |
| Electric resistance heating (with no solid state heat controls)      | K-1      |
| Motors (without solid state drivers)                                 | K-1      |
| Control transformers/electromagnetic control devices                 | K-1      |
| Motor-generators (without solid state drivers)                       | K-1      |
| Electric-discharge lighting                                          | K-4      |
| UPS with optional input filtering                                    | K-4      |
| Induction heating equipment                                           | K-4      |
| Welders                                                              | K-4      |
| PLC’s and solid state controls (other than variable speed drives)    | K-4      |
| Telecommunications equipment                                          | K-13     |
| UPS without input filtering                                           | K-13     |
| Multi-wire receptacle circuits in general care areas of health care, facilities and classroom of schools, etc. | K-13     |
| Multi-wire receptacle circuits supplying inspection or testing equipment on an assembly or production line | K-13     |
| Mainframe computer loads                                              | K-20     |
| Solid state motor drives (variable speed drives)                      | K-20     |
| Multi-wire receptacle circuits in critical care areas and operating/recovery rooms of hospitals | K-20     |
| Multi-wire receptacle circuits in industrial, medical, and educational laboratories | K-30     |
| Multi-wire receptacle circuits in commercial office spaces small mainframes (mini and micro) | K-30     |
| Other loads identified as producing very high amounts of harmonics (especially in higher orders) | K-40     |

With the k-factor transformer rating standard above, we can find out what components of electrical equipment are connected to the transformer. By knowing this, we can provide a solution for the utility to use a k-factor transformer according to the rating conditions. The k-factor transformer is designed to be operated at full load which has a k-factor value equal to or less than its k-factor rating. For example, transformer k-20 can be given full load with a k-factor value of 1 to 20. But if the k-factor is given a load greater than k-20, the transformer cannot work safely at full load and will cause a decrease in its operating value. K-factor transformers require neutral terminals and connections that are larger than standard transformers. [1].

#### 3. Case Study

The objects studied were: customers of 20 kV arc furnaces with an installed power of 3,115 kVA, supplied from the Sei Rotan 150/20 kV substation with a power transformer capacity of 31.5 MVA.

In IEEE Standard 519-1992, Point Common Coupling (PCC) has determined the limit for the TDD (Total Demand Distortion) content of current harmonics in electric power systems. To be able to apply these limits, it is necessary to determine the amount of 3-phase short circuit current in the 20 kV bus and 0.4 kV Dyn transformer, as in Figure 1. below.
3.1. Description

Figure 1. Single Line Short Circuit Diagram 3 phase on the 20 kV / 0.4 kV Bus and Filter Mounting

The results Harmonisa distortion measurements on March 9, 2009 with the following results:

Figure 2. THDi Loading Conditions 9 March 2009

Figure 3. THDv Loading Conditions 9 March 2009

The results of measuring the individual spectrum of current harmonic distortion (IHDi) dated March 9, 2009, are as follows:
o Current harmonic spectrum of order 5

![Figure 4. IHDi 5th Order Conditions of Loading 9 March 2009](image)

o Current harmonic spectrum of order 11

![Figure 5. IHDi 11th Order Conditions of Loading 9 March 2009](image)

Table 2. Comparison of IHDi Measurement Results March 9, 2009 with IEEE Standard 519-1992

| IEEE Standard 519-1992 for Vn ≤ 69 kV | Value | 5th order | 11th order | 23rd order |
|-------------------------------------|-------|-----------|------------|-----------|
| Isc / IL                           | 50 - 100 | 10.0       | 14.02      |           |
| h < 11                              |       |           |            |           |
| 11 ≤ h < 17                         | 4.5   | 5.48      |            |           |
| 17 ≤ h < 23                         | 4.0   |           |            |           |
| 23 ≤ h < 35                         | 1.5   | 1.56      |            |           |
| 35 ≤ h                              | 0.7   |           |            |           |
| TDD                                 | 12.0  |           |            |           |

From Figure 1, the Harmonic filter can be determined with specifications: L (inductor) of 96 mH (milli Hendry); C (capacitor) of 4.80 µF (micro Farad) with a capacity of 1.809 kVAR; 30.15 Ampere.

3.2. Measurement Techniques

The location of the Harmonic measurement is shown in Figure 1. Harmonic measurement locations in this case study are the primary side (20 kV) of the 20 / 0.4 kV customer transformer 3,115 kVA.
Measurement of harmonic currents from arc furnaces customers is carried out directly by using a Power Quality Analyzer (PQA) measuring device for 7 days and then the data will be entered into a software called powerlog so that we get the harmonic data, as shown in Figure 2 – Figure 5. For the calculation of the k-factor uses equation 1.

3.3. Simulation Results
From the simulation results of this arc furnaces customer with a connected power of 3,115 kVA using a 20,000/400 Volt Distribution Transformer, resulting in 2 cases, that is:

Case 1. Without Using Harmonic Filters
The k-factor value on March 9, 2009 from a system that does not use a harmonic filter is 3.38, as shown in Table 3.

Table 3. Harmonic Current and K-Factor Calculation of Transformer Without Using Harmonic Filters

| h  | \(I_h \text{ (\% Fund)}\) | \(I_h / I_l\) | \(I_h / I_l \text{ }^2\) | \(I_h / I_l \text{ }^2 \times h^2\) |
|----|-----------------|-------------|----------------|----------------|
| 1  | 100             | 1           | 1.1120385      | 1.2366297      |
| 3  | 2.4377083       | 0.0243771  | 0.0271083      | 0.0007349      | 0.0066137 |
| 5  | 14.0166667      | 0.1401667  | 0.1558707      | 0.0242957      | 0.6073921 |
| 7  | 6.0864583       | 0.0608646  | 0.0676838      | 0.0045811      | 0.2244735 |
| 9  | 0.8497926       | 0.0084948  | 0.0094465      | 0.0008092      | 0.0072282 |
| 11 | 5.4832292       | 0.0548323  | 0.0609756      | 0.0037180      | 0.4498812 |
| 13 | 3.2946875       | 0.0329469  | 0.0360818      | 0.0013424      | 0.2268584 |
| 15 | 0.7281250       | 0.0072813  | 0.008097       | 0.0000656      | 0.0147514 |
| 17 | 2.6185417       | 0.0261854  | 0.0291192      | 0.0084791      | 0.2450510 |
| 19 | 1.3095383       | 0.0130953  | 0.0145631      | 0.0002121      | 0.0765620 |
| 21 | 0.6503125       | 0.0065031  | 0.0072317      | 0.0000523      | 0.0236034 |
| 23 | 1.5557292       | 0.0155572  | 0.0173003      | 0.0002903      | 0.1583300 |
| \(\sum\) | 1.1606250       | 0.0116063  | 0.0129066      | 0.0001666      | 0.1041127 |

After the K-Factor is obtained, then calculate the Maximum Capable Power of the Transformer in accordance with equation (8).

\[
\text{Imax (pu)} = \sqrt{P_{LL} - s(\text{pu})} \quad \text{Imax (pu)} = 94.82% \\
\text{Imax (pu)} = \sqrt{1 + \left[ F_{IL} \cdot P_{L0} - s(\text{pu}) \right] \left[ F_{IL} \cdot \text{OSL} \cdot P_{OSL} - s(\text{pu}) \right]}
\]

Obtained a maximum capability power of 94.82% and a decrease in ability of 5.18%, with THDi of 19.08%.

Results of K-Factor and Maximum Capability of Power Transformers for 7 days are shown in Table 4.
Table 4. Results of Maximum Capability Vs K-Factor Transformer Without Using Harmonic Filters

| NO  | DATE       | K-FACTOR | MAXIMUM CAPABLE POWER (%) | DERATING TRAFO (%) |
|-----|------------|----------|----------------------------|--------------------|
| 1   | 08-Mar-09  | 2.79     | 98.13                      | 1.87               |
| 2   | 09-Mar-09  | 3.38     | 94.82                      | 5.18               |
| 3   | 10-Mar-09  | 2.84     | 96.00                      | 4.00               |
| 4   | 11-Mar-09  | 2.41     | 97.00                      | 3.00               |
| 5   | 12-Mar-09  | 2.52     | 96.77                      | 3.23               |
| 6   | 13-Mar-09  | 2.54     | 96.71                      | 3.29               |
| 7   | 14-Mar-09  | 2.58     | 96.62                      | 3.38               |

Case 2. Using Filter Harmonic
The K-factor value on March 9, 2009 from a system that uses a harmonic filter is 2.22, as shown in table 5.
Table 5. Harmonic Current and K-Factor Calculation of Transformer Using Harmonic Filters

| h   | I_b (% Fund) | I_h | I_b /I_h | (I_b /I_h)^2 | (I_b /I_h)^2 h^2 |
|-----|--------------|-----|----------|--------------|-------------------|
| 1   | 100          | 1   | 1.1120385| 1.2366297    | 1.2366297         |
| 3   | 1.6547164    | 0.0165472| 0.0184011| 0.0003386    | 0.0030474         |
| 5   | 5.9145133    | 0.0951451 | 0.1058051 | 0.0111947    | 0.2796777         |
| 7   | 4.1314879    | 0.0413149 | 0.0459437 | 0.0021108    | 0.1043055         |
| 9   | 0.5766265    | 0.0057663 | 0.0064123 | 0.0000414    | 0.0033305         |
| 11  | 3.7220160    | 0.0372202 | 0.0413903 | 0.0017132    | 0.2072915         |
| 13  | 2.2364359    | 0.0223645 | 0.0248700 | 0.0006185    | 0.1045294         |
| 15  | 0.4942513    | 0.0049425 | 0.0054963 | 0.0000302    | 0.0067970         |
| 17  | 1.7774661    | 0.0177747 | 0.0197661 | 0.0003907    | 0.1129120         |
| 19  | 0.8889452    | 0.0088895 | 0.0098854 | 0.0009774    | 0.0352774         |
| 21  | 0.4414321    | 0.0044143 | 0.0049089 | 0.0000241    | 0.0106269         |
| 23  | 1.0560290    | 0.0105603 | 0.0117434 | 0.0001379    | 0.0729356         |
| 25  | 0.7878323    | 0.0078783 | 0.0087610 | 0.0000768    | 0.0479179         |
| ∑   |              |      |          |              | 2.22              |

After the K-Factor is obtained, then calculate the Maximum Capable Power of the Transformer in accordance with equation (8).

\[
\text{Imax (pu)} = \sqrt{\frac{P_{LL - k(\text{pu})}}{1 + [F_{HL - PEC - k(\text{pu})} + F_{HL - OSL - k(\text{pu})}]}}
\]

\[
\text{Imax (pu)} = 97.47\%
\]

Obtained a maximum capacity of 97.47% and a decrease in ability of 2.53%, with THDi of 12.95%. The results of the K-Factor and the Maximum Capacity of the Power Transformer for 7 days are shown in Table 6.

Table 6. Results of Maximum Capability Vs K-Factor Transformer Using Harmonic Filters

| NO | DATE       | K-FACTOR | MAXIMUM CAPABLE POWER (%) | DERATING TRAFO (%) |
|----|------------|----------|---------------------------|-------------------|
| 1  | 08-Mar-09  | 1.95     | 98.13                     | 1.87              |
| 2  | 09-Mar-09  | 2.22     | 97.47                     | 2.53              |
| 3  | 10-Mar-09  | 1.98     | 98.07                     | 1.93              |
| 4  | 11-Mar-09  | 1.78     | 98.57                     | 1.43              |
| 5  | 12-Mar-09  | 1.83     | 98.46                     | 1.54              |
| 6  | 13-Mar-09  | 1.84     | 98.43                     | 1.57              |
| 7  | 14-Mar-09  | 1.86     | 98.38                     | 1.62              |
When compared to the magnitude of the K-factor in a system without a harmonic filter (3.38) and a system that uses a harmonic filter (2.22), then the K-factor in a system that uses a harmonic filter is 34.32% smaller than a system that does not use a harmonic filter, so it has an impact by increasing the Transformer Capability from 94.82% to 97.47%.

To avoid a decrease in the Maximum Capability of the Power Transformer due to Harmonics, a K-Factor Transformer with class K-4 can be used.

4. Conclusion
Harmonics produced by arc furnace consumers greatly affect the size of the k-factor. The greater the resulting harmonics, the greater impact on increasing the value of the k-factor. The greater the k-factor will cause the maximum power of the power transformer to decrease and the derating of the power transformer to increase. Arc furnace consumers who do not use harmonic filters will cause the k-factor value to be greater than arc furnace consumers who use harmonic filters. Arc furnace consumers who do not use harmonic filters cause the k-factor value to be 3.38, which is greater than arc furnace consumers who use harmonic filters whose k-factor value is only 2.22. Likewise, the maximum capacity, without filter is 94.82% and derating is 5.18%. Meanwhile, those using a harmonic filter have a maximum power of 97.47% and a derating of 2.53%. So the use of harmonic filters on arc furnace consumers can reduce the k-factor on the power transformer by 34.32% from systems without using a harmonic filter.

5. Suggestion
Arc furnace consumers who have harmonic emissions that exceed the set standards, are required to reduce their harmonic emission levels, one of which is by using harmonic filters. Whereas in the power transformer, so that there is no decrease in capable power and an increase in derating, you can use the k-factor transformer. However, until now, the use of k-factor transformers has only been limited to Low Voltage - Low Voltage transformers.

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