Comparative study of the derating of distribution transformers

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***Abstract*— Advances in technology in the field of small appliances and the *internet of things* has changed the way we live in society. Most of these devices that have invertors or rectifiers are designated as non-linear loads. Although they require a quality power grid, they generate disturbances and unbalance the same grid in a way that may compromise the lifecycle of several devices as well as distribution transformers.**

When a non-linear load (a load with harmonic contends with frequencies different than the fundamental) is applied to a transformer, might trigger a reaction on the transformer characterized by an increase of the vibration and an increase of the temperature. This increase of temperature is due to the increase of losses due to the skin effect. This chain reaction may lead to a reduction of the power of the transformer (derating of the transformer). This increase in losses is defined and calculated both in the European (CENELEC) and in the Americans (ANSI/IEEE) standards.

The main goal of this work is to create a comparative study of the international standards regarding the derating of distribution transformers.

To achieve this goal, two distribution transformers and several current wave forms will be used to compare the methodologies presented by the international standards.

***Index Terms*—International standards, non-linear load, skin effect, transformer derating**

1 INTRODUCTION

Simplifyng the design of a transformer, we may consider that it is constituted by a magnetic circuit composed by a iron magnetic core, that usually has two copper windings. One of the windings is designated by primary and the other by secondary. By applying of a sinusoidal current waveform to the primary, the variation of magnetic flux create by this winding will be the same that the one on the secondary winding (considering null the magnetic dispersion). The number of coils present on the secondary winding is directly related with the induced electromotive force in the circuit of the secondary. Thus, this way is performed a transformation of current and consequently of tension.

There are several types of transformers, depending on their application. Beginning in Low Voltage (LV) all the way to High Voltage (HV) and single-phase or three-phase. In LV and for the application in electronic devices, exist dry-cast, laminated, toroidal and other types of transformers. These are massively produced and usually used for transformations between 230V/420V to 110V or lower voltage levels.

In the Medium Voltage (MV) level exist the distribution transformers. Usually three-phased, they are used for the transformation of 30-15kV to 0,420kV. It is in this type of transformers that is work focused in. Constructively these transformers may have their windings immersed in isolating dielectric oil and hermetically sealed, as well as being made of cast resin designated by dry cast transformers. Both types may have the capability of no load tap change.

From MV to HV, they are designated Power Transformers (PT). These types of transformers have their windings and the tap changer immersed in isolating dielectric oil. The tap changer is capable of on load tap changes. With this capability the PT are able to actively react to disturbances in the grid that deregulate the output current and tension. These transformers are custom made and designed according to customer specifications. These PT are found in a high level of the chain of power supply (Production -> Transport -> Distribution > Consumer), usually between the production and the distribution, they aren't affected by non-linear loads as the distribution transformers.

The impact over distribution transformers due to currents with harmonic content created by non-linear loads must be analyzed. A transformer subjected to these phenomenon suffers a reduction of it rated power leading to a reduction of it lifetime. The current of a non-linear load is reflected in a distribution transformer through an increase of vibration and temperature (increase of losses and reduction of the lifetime). In order to do not affect the lifetime of the transformer the load must be reduced, in other words, make a derating of the distribution transformer.

It is in this topic that the present work will be developed over. Initially will be tackled the theoretical bases of losses in a transformer, describing how an increase in frequency may cause an increase of the losses in the transformer. In this work will be analyzed the international standards that identify which factor has to be considered to compensate the additional losses caused by the harmonic content of the current waveform. This factor may be considered to ascertain the losses that the transformer is subjected to or for the design sizing of a new transformer for this purpose.

For the execution of the calculations and simulations for each analyzed standard, it will be presented some study-cases, two distribution transformers and several current waveforms of non-linear loads. These study-cases will allow the execution of a comparative study between the methodologies and main variables that influence the factors of each international standard.

2 LOSSES IN TRANSFORMERS

All the losses that are verified in a transformer may be translated by the sum of the no load losses, P_{noload}, with the load losses, P_{load}, as per reproduced in (1).

$$P_{total} = P_{noload} + P_{load} \quad (1)$$

It is considered that the no load losses are the sum of the losses by hysteresis, $P_{hysteresis}$, with a component of additional no load losses, P_{AD}.

$$P_{noload} = P_{hysteresis} + P_{AD} \quad (2)$$

It is also considered that the load losses are the sum of the losses in the windings, P_{wind}, with a component of additional losses due to Eddy currents, P_{EC}.

$$P_{load} = P_{wind} + P_{EC} \quad (3)$$

The losses in the windings are in their majority losses by Joule effect, as expressed in (4)

$$P_{wind} = P_{Joule} = RI_{ef}^2 \quad (4)$$

However, when the transformer is subjected to non-linear loads (within the transformer there are currents with a frequency different from the fundamental), it is verified an increase of losses by Skin Effect.

Finally the additional losses due to the Eddy currents are originated by the variation of the flux of the electromagnetic field which flows through windings, core, core protections and transformer tank. These currents have a single effect of temperature rising in the transformer, due to Joule effect.

2.1 *Skin Effect*

The Skin effect is related to a time variant non-uniform distribution of electrical current. This variation with frequency is translated in a time variable magnetic field as well as a time variable electrical field. A variation of magnetic field induces electromagnetic forces that originate currents. These currents will originate new electromagnetic forces that will counter act upon the initial ones. Thus so reducing the section of the material where the current is distributed in.

This reduction of the total flux might be modulated through the creation of a layer where the current is distributed. This phenomenon is described as Skin Effect.

The relationship between the thickness of the layer δ and the angular frequency ω of the current is expressed by (5).

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \quad (5)$$

The thickness of this layer will be directly related to the section of the conductor cable. If for example it is subjected to high frequencies, the thickness will reduce and so the section of the cable.

In order to clarify this concept it were executed three simulations considering a conductor with a circular section on which were applied a rated current with different frequencies. It will be verified the behavior of the current in the section due to the frequency in which is applied. For this example it was considered a circular section cable with a area of 300 mm^2 and it is charged, for example, with a current of 20A. In each figure it will be represented the distribution of current density per square meter and the relationship between the current density and its distance to the cable center.

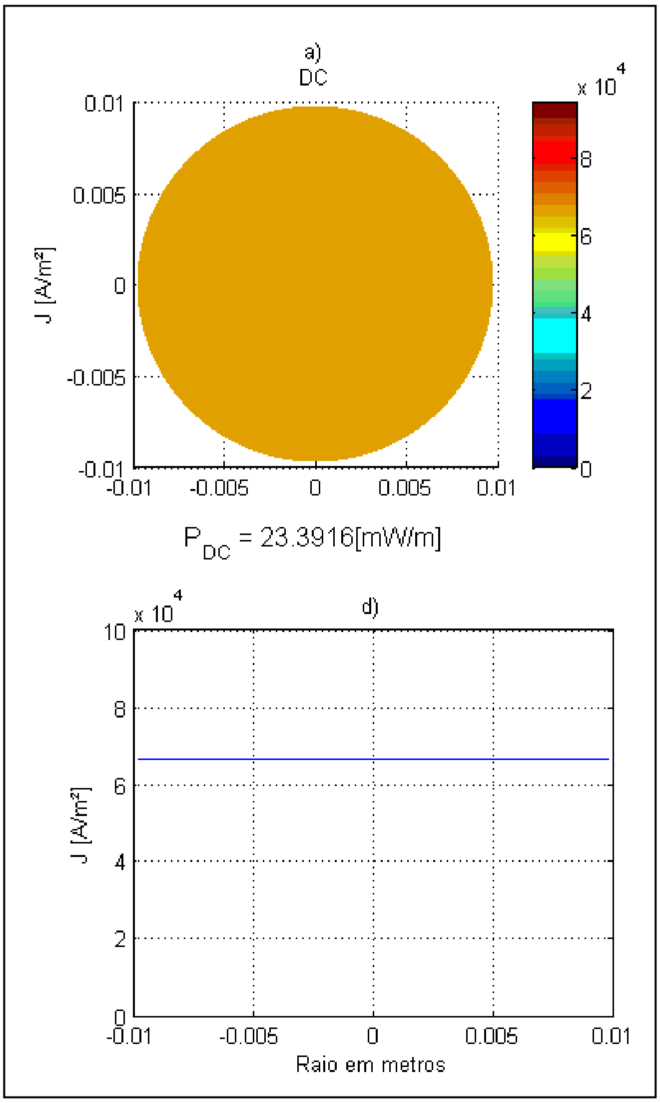

Figure 1 – Skin Effect Simulation on copper conductor with DC current

In Figure 1 a) it is the radial representation of the distribution of the DC current in the cable. As expected it shows a uniform distribution throughout the entire section. In Figure 1 d) is represented the value of the current density and as expected it is translated in a straight line as it is uniformly distributed in the conductor.

In Figure 2 b) one verifies a small increase of current density towards the periphery of the cable section. In this case one notices a variation of 7.4% between the center of the cable and the periphery.

The Figure 2 e) expresses this variation as shown by the small slope in the graphical representation.

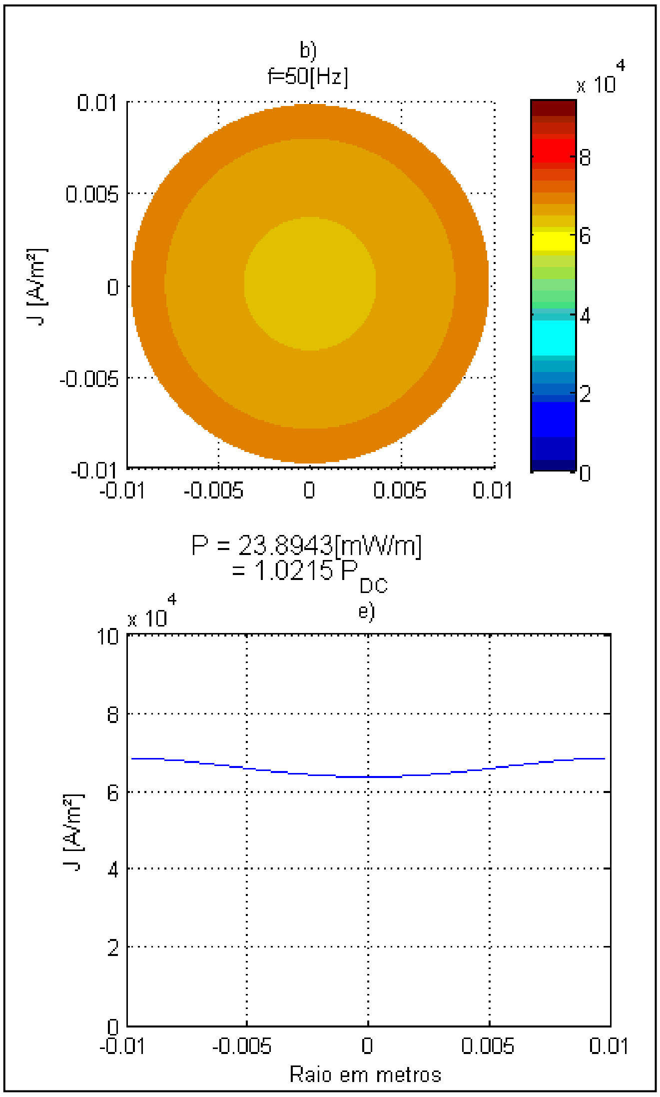

Figure 2 - Skin Effect Simulation on copper conductor with a frequency of 50Hz

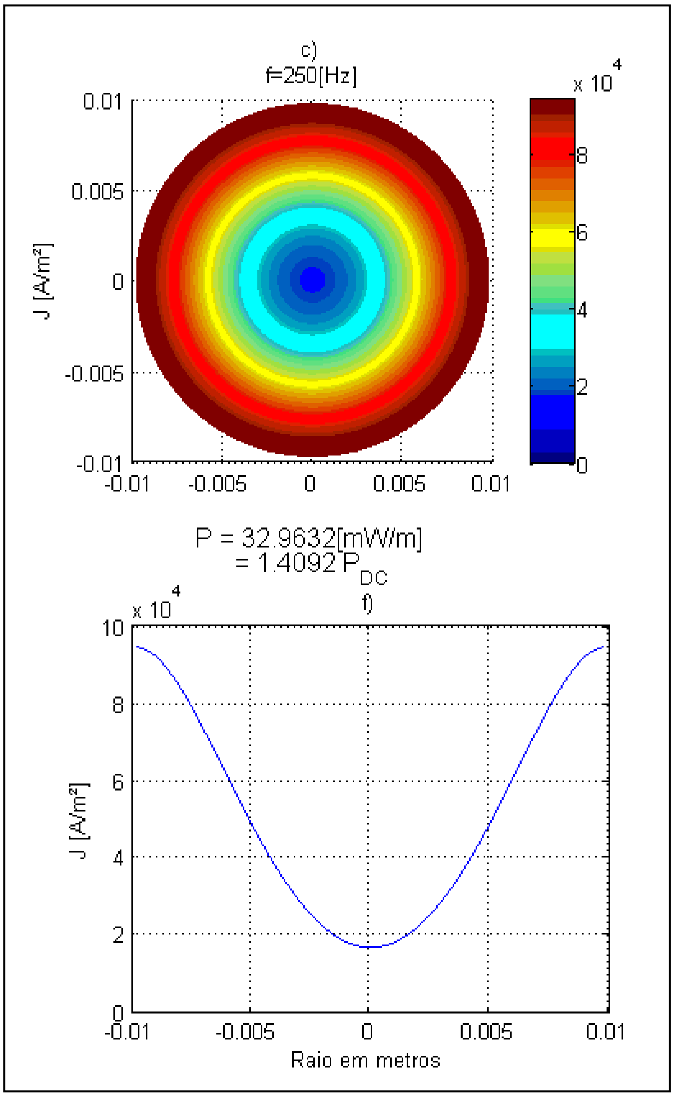

Figure 3 – Skin Effect Simulation on copper conductor with a frequency of 250Hz

In Figure 3 c) one verifies a significant increase of current density towards the periphery of the cable section. In this case one notices a variation of 428.8% between the center of the cable and the periphery. In Figure 3 f) expresses this variation as shown by the slope in the graphical representation.

3 INTERNATIONAL STANDARDS ANALYSIS

There are two international standards related to the operation of distribution transformers with non-linear loads: the European standard (CENELEC) and the American Standard (IEEE/ANSI).

3.1 European Standard – CENELEC

The European standard [1] characterizes the derating of the distribution transformer as the inverse of the factor K, DR_K (7). The factor K can be obtained by (6)[1].

$$K = \left[1 + \frac{e}{1+e}\left(\frac{I_1}{I_{ef}}\right)^2 \sum_{h=1}^{h=h_{max}} h^q \left(\frac{I_h}{I_1}\right)^2\right]^{\frac{1}{2}} \tag{6}$$

$$DR_K = \frac{1}{K} \tag{7}$$

Where *e* it is an estimate that can be obtained by dividing the P_{EC} by the P_{Joule}. In can also be obtained if it considered that the additional losses are majority expressed by the losses due to Eddy currents and the load losses are the reference and in *pu* they have a unitary value. Considering this the estimate can be obtained by (8)

$$e = \frac{1}{RI_{ef}^{\ 2}} - 1 \tag{8}$$

3.2 American Standards IEEE - ANSI

The IEEE standard C57:110-1998[2] establishes that the losses due to current harmonics can be associated to a factor designated by F_{HL} obtained by (9).

$$F_{HL} = \frac{\sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I_{ef}}\right)^2 h^2}{\sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I_{ef}}\right)^2} \tag{9}$$

This factor is a function of the distribution of the current harmonic content. This way is defined the loss factor on a distribution transformer due to the current harmonics.

For this standard the derating is obtained with the calculation of maximum current allowed in the distribution transformer.

Considering the equations (3), (9), (10) and (11) one obtains the equation (12) which can be manipulated into equation (13)[2].

$$P_{EC} = P_{EC-R} \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I_{ef}}\right)^2 h^2 \tag{10}$$

$$I_{ef} = \left[\sum_{h=1}^{h=h_{max}} I_h^{\ 2}\right]^{\frac{1}{2}} \tag{11}$$

$$P_{load}(pu) = I_{max}^{\ 2}(pu)[1 + P_{EC-R}(pu)F_{HL}] \tag{12}$$

$$I_{max}(pu) = \sqrt{\frac{P_{load}(pu)}{1 + F_{HL} \times P_{EC-R}(pu)}} = DR_{F_{HL}} \tag{13}$$

The obtained result, since it is in *pu*, allows the user to conclude directly which is the derating percentage over the distribution transformer. Although the obtained current is lower than the rated current, by the fact that it is a non-linear load, the transformer has the same losses as the rated losses.

Still in the American community there is an additional derating factor described by the Underwriters Laboratory UL1562 [3] designated by K_{UL}. This can be obtained by (14) [3].

$$K_{UL} = \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I_{ef}}\right)^2 h^2 \tag{14}$$

For this factor the derating will be designated by DR_{KUL} and can be obtained by calculating the additional losses due to Eddy currents. In this case, [3] calculates the P_{EC} by using the equation (15) and (16).

$$P_{EC-C} = \frac{C(P_{AC} - P_{Joule})}{P_{DC} \times T_C^{\ 2}} \tag{15}$$

$$T_C = \frac{T_S + T_k}{T_m + T_k} \tag{16}$$

T_S – The maximum acceptable insulation system temperature rise plus 20ºC;
T_k - Constant, 234.5 for Copper windings and 225.0 for aluminum windings [ºK];
T_m – Ambient temperature in which the losses were measured [°C];
P_{AC} – Short circuit losses in the primary winding, measured at ambient temperature [W];
C – Constant equal to 0.7 for transformers with a transformer ratio higher than 4:1 and with winding current amplitude higher than 1000A. Constant is equal to 0.6 for all others.

With the calculated value of the additional losses due to Eddy currents it is possible to obtain the new estimative *e*. As expressed in equation (13) it is possible to obtain the derating due to the factor K_{UL}.

$$DR_{K_{UL}} = \sqrt{\frac{1 + e}{1 + K_{UL} \times e}} \tag{17}$$

4 INTRODUCTION TO CASE-STUDIES

Along this work one verified that although international standards and the transformers test reports are standardized and comply with assumptions on the European and American Standards, there isn't a direct link between then able to supply direct results. For the development of this work was necessary to cross information from test reports and apply them to the international standards. For this is always necessary to decode the test report of a transformer. Using a current waveform with harmonic content it was possible to execute some simulations and comparisons of the application of the international standards.

4.1 630kVA Distribution Transformer

In this work it was considered a distribution transformer of 630kVA (TD630) with the characteristics described on the Table 1, Table 2 and Table 3.

Table 1 – Electrical characteristics of the transformer TD630

Power [kVA]	630	
Type of Connection	Dyn5	
	Voltage [V]	
Tap	**MV**	**LV**
1	10500	
2	10250	
3 (U_N)	10000	420
4	9750	
5	9500	
Rated Current [A]	36,4	866

Table 2 – No load losses of the transformer TD630

Measurement of no load Losses (P_O) and current (I_O)					**Connection 2U-2V-2W**
U_N [%]	**U_N**	**I_O1 [A]**	**Average [A]**	**I_O [%]**	**P_O [W]**
100	420	2,71	2,36	0,27	849

Table 3 – Short circuit and load losses in the transformer TD630

Measurement of Short circuit Voltage and load losses			
Tap	I [A]	U [V]	P [W]
3	36,28	393,3	4686
P_{CC} I_N	ΣRI^2	P_{AD}	T [°C]
4717	4239	478	19,4
Normalized at 75º C			
ΣRI^2	ΣRI^2	ΣRI^2	ΣRI^2
5165	5165	5165	5165

4.2 Harmonic content of non-linear load current waveform

In this work it was considered the following current waveform with harmonic content.

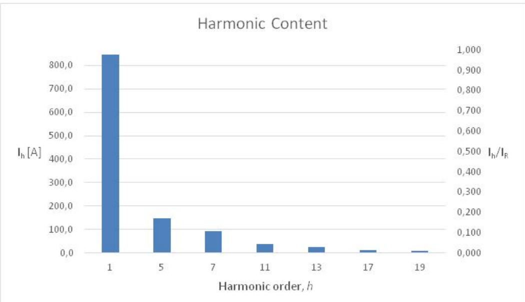

Figure 4 - Graphical representation of the current harmonic content

This waveform presents a root mean square value of 866A, obtained by using equation (11) and it is equal to the rated current of the transformer presented in section 4.1. It has a THD of 21.44%.

4.3 Algorithm for calculation execution

In this section it will be shown hot to perform the necessary calculations in order o obtain each international standard as well as each factor and its corresponding derating value.

4.3.1 European Standard, Factor K

The factor K is obtained throw the following order:

1º - Obtain the losses by Joule Effect in *pu*, by using Table 3 and execute the division between the losses by Joule effect with the short circuit losses, both normalized at 75ºC.

2º - With the above result, obtain the estimate *e* from equation (8);

3º Obtain the sum of the $(I_h/I_{ef})^2*h^q$ of the harmonic content;

4º - Obtain the square of the division of the root mean square value of the current by the first harmonic of the current;

5º - Apply all the above results to the equation (6).

This way it is possible to obtain a factor K of the transformer, based on the present current waveform and in this case with value of 1.0635.

The derating of the transformer, DR_K is obtained by using equation (7) and in this case has the value of 94%. This means that at 94% of its capacity the transformer will have the same numerical value of losses if at rated power.

4.3.2 American Standard, F_{HL}

The F_{HL} factor is obtained using equation (9) and both the numerator and denominator are retrieved from the harmonic content. In this case the F_{HL} as a value of 2.7255.

The derating of the transformer is obtained using equation (13) considering that:

1º - P_{load}(pu) = 0.9295, obtained using Table 3;

2º - P_{EC}(PU) = 0.0705, obtained using Table 3.

This results in a derating, DR_{FHL}, of 88.29%, which means that the maximum current allowed will be 88.29% of the rated current of the transformer.

4.3.3 American Standard, K_{UL}

The factor K_{UL} is obtained using the equation (14) by directly retrieving the information from the harmonic content of the current waveform. In this case it has the value of 2.7258.

The value of the derating of the transformer, DR_{KUL}, is obtained through the relationship between the calculated load losses and the load losses obtained in test reports. By using equation (17) in this case it was obtained a derating of 94.42%.

4.3.4 *New loss estimative, K_{PT}*

As mentioned in previous section, with the access to a transformer test report (as described in section 4.1 it is possible to perform a derating study by a direct comparison between the theoretical losses with the results obtained in the test report. By using equations (15), (16) and (18)[3].

$$P_{load} = P_{Joule} \times \left(1 + K_{UL} \times P_{EC-C}(pu)\right) \times (T_C) \quad (18)$$

When compared with the test report results, this load losses allows to conclude that the transformer will have a derating, DR_{KPT} of 91.63%.

Table 4 - Results of the study case

De-rating %			
DR_{KUL}	DR_{KPT}	DR_{FHL}	DR_K
94%	92%	88%	94%

For the considered example, the American standard F_{HL}, was the one who showed the more conservative results because it has determined a higher derating (88.29%). This means that in the load conditions the 630kVA Transformer will only have available 556kVA without being overloaded.

5 COMPARISON OF METHODOLOGIES AND SIMULATIONS

As established in chapter 3 by the documents [1],[2],[4] and[3], a distribution transformer is subjected to additional losses when in the presence of current harmonics.

During the execution of the present work, was verified that some comparisons were important to be made. Respectively:

5.1 Influence of the Total Harmonic Distortion

Using three different waveforms (L1, L2 and L3) in which their root mean square value of the current is identical, I_{EF}, but with different THD, applied to the TD630 it was possible to analyze the influence of the THD (Figure 5).

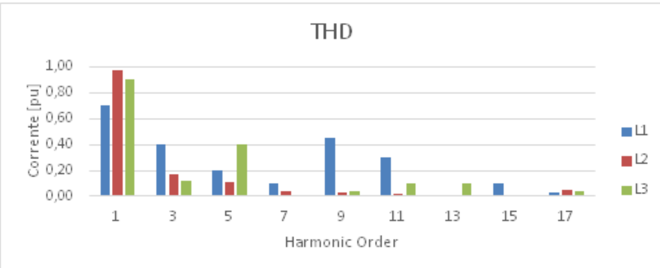

Figure 5 - Harmonic content of three examples with the same I_{EF}

Table 5 - Obtained results

	I_{ef}	THD	K_{UL}	F_{HL}	Factor K
L1	864	102 %	33,22	33,11	1,26
L3	861	50 %	8,45	8,37	1,13
L2	861	22 %	2,46	2,45	1,06

Table 6 - Derating of the transformer - percentage of the rated power

De-rating %				
	DR_{KUL}	DR_{KPT}	DR_{FHL}	DR_K
L1	55 %	45 %	53 %	79 %
L3	81 %	77 %	76 %	88 %
L2	95 %	93 %	89 %	95 %

Analyzing the Table 6 - Derating of the transformer - percentage of the rated power Table 6 it is possible to conclude that between the international standards, the American standard are the ones who accentuate the derating of the transformer when it is affected by a high rate of harmonic distortion.

This simulation allows also the conclusion that the derating of the transformer may not be estimated only by knowledge of the current root mean square.

5.2 Influence of the Current root mean square

Using three different waveforms (L4, L5 and L5) in which their THD is identical, but with different current root mean square, applied to the TD630 it was possible to analyze the influence of the I_{EF} (Figure 6).

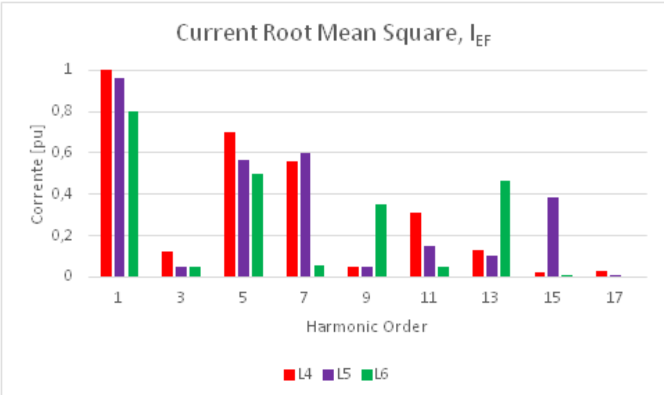

Figure 6 - Harmonic content of three waveforms with the same THD

Table 7 - Obtained Results

	I_{ef}	THD	K_{UL}	F_{HL}	Factor K
L4	1197	97%	43,79	22,62	1,38
L5	245	97%	54,32	43,82	1,41
L6	48	97%	64,38	36,08	1,48

Table 8 - Derating of the transformer - Percentage of the rated power

	De-rating [%]			
	DR_{KUL}	DR_{KPT}	DR_{FHL}	DR_K
L4	50%	38 %	60%	73%
L5	46%	33 %	48%	71%
L6	43%	30%	51%	68%

Analyzing the results of Table 8 it is possible to conclude that the current root mean square influences the results. All the factors are directly proportional to the current value. With the decrease of the current value one verifies the increase of the transformer derating.

5.3 Influence of the root mean square *versus* the amplitude of the first current harmonic, I_1

In the course of this work, it was necessary to clarify which of the variables should be used in the calculations. For example, in the European standard there is a reference for both variables while for instance in the American standard there is only reference to the amplitude of the first current harmonic.

Using the data of the current waveform described in section 4.2 it is possible to ascertain which variable is more accurate or produces better results.

Table 9 - Results obtained with Root Mean Square, I_{EF}

K_{UL}	K_{PT}	F_{HL}	Factor K
36,08	-	36,08	1,29
De-rating %			
DR_{KUL}	DR_{KPT}	DR_{FHL}	DR_K
54 %	43 %	51 %	78 %

Table 10 - Results obtained with the amplitude of the current of the first harmonic, I_1

K_{UL}	K_{PT}	F_{HL}	Factor K
69,86	-	36,08	1,87
De-rating %			
DR_{KUL}	DR_{KPT}	DR_{FHL}	DR_K
41 %	28 %	51 %	54 %

As showed in Table 9 and Table 10 the K_{UL} is the one who demonstrates the most difference between the two cases. The factor F_{HL} as it depends only on the harmonic content and not in their amplitude, produces the same results on both cases.

The factor K as it uses both variables shows a difference between the results.

5.4 Comparison between two distribution transformers

For this comparison it was necessary to collect the electrical data of an additional distribution transformer designated by TD1600. Both transformers where subjected to the same current waveform (as per section 4.2).

Table 11 - Results obtained using TD1600

K_{UL}	K_{PT}	F_{HL}	Factor K
2,726	-	2,725	1,108
De-rating %			
DR_{KUL}	DR_{KPT}	DR_{FHL}	DR_K
91%	77 %	81 %	90 %

Table 12 - Results obtained using TD630

K_{UL}	K_{PT}	F_{HL}	Factor K
2,726	-	2,725	1,064
De-rating %			
DR_{KUL}	DR_{KPT}	DR_{FHL}	DR_K
94 %	92 %	88 %	94 %

The obtained results allow concluding that the factors of the American standards are not affected by the characteristics of the transformers. Using the same waveform, the results will be the same. The European standard as it uses the loss estimate, *e*, it has different results for each transformer.

Although for the calculation of the transformer derating the electrical characteristics of the transformer are crucial for this analysis. From the obtained results it is possible to affirm that with the increase of power occurs and increase of the derating.

With these results it is possible to conclude that the European standard has a selective approach and personalized since it depends on the transformer. The American standards base their calculations only on the current waveform in order to obtain their factors, considering only the characteristics of the transformer to calculate the transformer derating.

6 CONCLUSIONS

From the several simulations and calculations developed throughout the present work, it is possible to conclude that in order to obtain the results it was necessary to create a connection between a test report from a transformer with the international standard in which it will be applied.

From the comparison of methodology between European and American standards it is possible to conclude that the factor K_{UL} depends on the distribution of the current harmonic content. Its value depends on the rated current on the secondary of the transformer. In case the values are calculated in *pu*, both K_{UL} and F_{HL} have the same numerical value.

From the analysis of the influence of the total harmonic distortion it is possible to conclude that an increase of about the double of the THD value leads to an increase of derating in about 15% to 20% in the American factors. In the European factor it is also noticed a difference in results although is not considered to be significant. From the analysis of the influence of the current root mean square it is possible to conclude that all the factors are directly related to its value.

From both analyses it is possible to conclude that the THD has a higher influence over the transformer derating.

From the comparison between the current variables it is possible to conclude that the factor F_{HL} depends only on the harmonic content not being influenced by any of the variable, demonstrating the exact results in either case. The factor K has the particularity of using both variables. Its relationship with the harmonic fundamental influences the transformer derating. However, the difference obtained between the variables, allows to conclude that the current root mean square is the one who best represents the amplitude of the transformer current.

Using the two distribution transformers we were able to conclude that the American factors aren't affected by the characteristics of the transformer subjected to the non-linear load. The European factor produces different results as in it equation it uses the losses obtained in the test reports.

Nevertheless, for the calculation of the transformer derating the electrical characteristics of the transformers is crucial. From the obtained results it is possible to affirm that with the increase of power occurs and increase of the derating. With these results it is possible to conclude that the European standard has a selective approach and personalized since it depends on the transformer. The American standards base their calculations only on the current waveform in order to obtain their factors, considering only the characteristics of the transformer to calculate the transformer derating.

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