A comparative between IEEE and EN in the transformer derating when supplying nonsinusoidal load current. A practical case.

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Abstract. Nowadays, power quality is a challenge for the distribution companies since the new energy policies are directed to a distributed generation system with power electronic based technologies. The reduction of distribution transformers capability when supplying nonsinusoidal load currents has a major impact within capacity reduction in distribution networks produced by technical losses. IEEE Std C57.110-2018, EN- 50464-3 and EN-50541-2 define procedures to derate transformers when supplying nonsinusoidal load currents. The aim of this paper is to compare these procedures through a real case distribution transformer that suffers problems due to high levels of current distortion.

Key words. Distribution transformer derating, current harmonics, harmonic loss factor, k-factor, nonsinusoidal load currents.

1. Introduction

The number of devices that introduce disturbances in the electrical power system is growing due to the great amount of power electronics systems included in those devices. Nowadays, power quality is a challenge for the distribution companies since the new energy policies are directed to a distributed generation system with power electronic based technologies [1,2]. This paper focuses on the power quality problems that can be found in distribution transformers [3,4], particularly in the problems produced by the harmonics [5, 6, 7, 8].

The reduction of distribution transformers capability when supplying nonsinusoidal load currents has a major impact within capacity reduction in distribution networks produced by technical losses [9]. Traditional distribution transformers are designed to manage sinusoidal currents. In practice,

these transformers operate with nonsinusoidal currents, for which are not designed. These nonsinusioidal currents are mainly produced by harmonics. The impact of these harmonics in distribution transformer is very important since increases the losses in the transformers rising their temperature. The losses of a transformer are divided into Joule losses, Eddy-current losses and stray losses. These losses and the type of cooling system will determine the temperature reached by the transformer.

In distribution transformer managing nonsinusiodal currents, Eddy-current losses will increase, producing an additional temperature rise. If this temperature achieve values above operation maximum temperature of the transformer, the thermal protection devices will trip and the life expectancy will be reduced.

IEEE Std C57.110-2018[10], EN- 50464-3[11] and EN-50541-2[12] define procedures to derate transformers when supplying nonsinusoidal load currents. These standards obtain a new value of capacity for distribution transformers managing currents with a level for the harmonic factor exceeding 5 %. Obviously, these capacity reductions produce an inefficient system.

Although, nowadays there are transformers designed to manage nonsinusiodal currents, old distribution transformers frequently have not these characteristics.

It is important for distribution companies to carry out power quality surveys regarding the levels of harmonics in the network. If the harmonic levels in a particular grid increase, it would be advisable to compute the derate of the transformers of this grid in base of the standards mentioned earlier.

The aim of this paper is comparing the IEEE Std C57.110-2018 [10] for dry-type and liquid immersed distribution transformers and the EN-50464-3 [11] and EN-50541-2 [12] for liquid immersed and dry-type distribution transformers respectively. The comparison is made through a real case distribution transformer that suffers problems due to high levels of current distortion.contributions.

2. Comparison of IEEE Std C57.110-2018 [10] and EN-50464-3 [11] and EN- 50541-2 [12]

A. IEEE Std C57.110-2018 [10]

This standard is divided in two options:
- New transformer that is supplying nonsinusoidal currents but it is not only used for a rectifier load.
- Existing transformer designed for sinusoidal current in a distorted current environment.

This standard define two methods that depends on the available information about the transformer. The first method uses full complete information about the losses of the transformer and achieves a high accuracy. The second one uses certified test report data and the accuracy is lower.

1) Transformer capability equivalent calculation using design eddy-current loss data

- Dry-Type transformers:

In this type of transformers, the non winding losses do not affect to the transformer temperature so the stray losses in other parts different than windings are not taking into account. The maximum current with harmonic content that the transformer can manage is defined by:

$$I_{max} = \sqrt{\frac{P_{LL_R}(pu)}{1 + F_{HL} \cdot P_{EC_R}(pu)}} \qquad (1)$$

where
I_{max} (pu) is the max permissible rms nonsinusoidal load current under rated conditions.
P_{LL-R}(pu) is the per-unit load loss under rated conditions.
F_{HL} is the harmonic loss factor for winding eddy currents.
P_{EC-R}(pu) is the per-unit winding eddy-current loss under rated conditions.

- Liquid immersed transformers

In this type of transformers, the losses in elements different than the windings are taking into account because they contribute to the transformer heating.

The first step is the calculation of the top-liquid rise:

$$\theta_{TO} = \theta_{TO_R} \left(\frac{P_{LL} + P_{NL}}{P_{LL_R} + P_{NL_R}} \right)^{0.8} \qquad (2)$$

where

θ_{TO} is the top-liquid-rise over ambient temperature (°C).
θ_{TO-R} is the top-liquid-rise over ambient temperature under rated conditions (°C).
P_{LL} is the load loss (watts).
P_{LL-R} is the load loss under rated conditions (watts).
P_{NL} is the no load loss (watts).

The load loss P_{LL} can be computed as

$$P_{LL} = P + P_{HL} \cdot P_{EC} + P_{HL_{STR}} \cdot P_{OSL} \qquad (3)$$

where

P_{LL} is the load loss (watts).
P is the I^2R loss portion of the load loss (watts).
F_{HL} is the harmonic loss factor for winding eddy currents.
P_{EC} is the winding eddy-current loss (watts).
F_{HL-STR} is the harmonic loss factor for other stray losses.
P_{OSL} is the other stray loss (watts).

The Second step is the calculation of the winding hottest spot conductor rise:

$$\theta_g = \theta_{g_R} \left(\frac{P_{LL}(pu)}{P_{LL_R}(pu)} \right)^{0.8}$$
$$= \theta_{g_R} \left(\frac{I^2(pu)\left(1 + F_{HL} \cdot P_{EC_R}(pu)\right)}{1 + P_{EC_R}(pu)} \right)^{0.8} \qquad (4)$$

where
θ_g is the hottest-spot conductor rise over top-liquid temperature (°C).
θ_{gR} is the hottest-spot conductor rise over top-liquid temperature under rated conditions (°C).

2) Transformer capability equivalent calculation using data available from certified test report

Due to the lack of information about the losses, this method calculate the losses in base on practical values.

- Dry-Type transformers:

First step is the calculation of total stray losses:

$$P_{TSL_R} = P_{LL_R} - P\left[I_R^2 \cdot R_1 + I_R^2 \cdot R_2\right] \qquad (5)$$

where

P_{TSL-R} is the total stray loss under rated conditions (watts)

P_{LL-R} is the load loss under rated conditions (watts)

k is a constant dependent on the number of phases (1 for single phase and 1.5 for three phases)

I_{1-R} is the high-voltage (HV) rms fundamental line current under rated frequency and rated load conditions (amperes)

R_1 is the dc resistance measured between two HV terminals (ohms)

I_{2-R} is the low voltage (LV) rms fundamental line current under rated frequency and rated load conditions (amperes)

R_2 is the dc resistance measured between two LV terminals (ohms)

Eddy-current losses are obtained by:

$$P_{EC_R} = P_{TSL_R} \cdot x \qquad (6)$$

The coefficient is obtained in base of Table I.

Table I. - Estimate of distribution of total stray loss % for dry-type transformers

	Winding eddy loss		Other stray loss
	LV winding	HV winding	
Max self-cooled current rating < 1 000 A or ≤4:1 turns ratio	20	15	65
>4:1 turns ratio	25	10	

In contrast with the previous method, in this method it is obtained the maximum value of the rated Eddy-current losses for each winding.

$$P_{EC_R\,LV} = \frac{x_{LV} \cdot 4 \cdot P_{EC_R}}{k \cdot I_{2_R}^2 \cdot R_2} \qquad (7)$$

$$P_{EC_R\,HV} = \frac{x_{HV} \cdot 4 \cdot P_{EC_R}}{k \cdot I_{1_R}^2 \cdot R_1} \qquad (8)$$

Finally, the maximum admissible current is obtained:

$$I_{max} = \sqrt{\frac{P_{LL_R}(pu)}{1 + F_{HL} \cdot P_{EC_R}(pu)}} \qquad (9)$$

- Liquid immersed transformers

The procedure to obtain the different losses is the same than in the dry-type transformers but with the coefficients of the Table II.

Table II Estimate of distribution of total stray loss % for liquid immersed transformers

kVA range	Winding eddy loss		Other stray loss
	LV winding	HV winding	
≤ 300	55	5	40
> 300 ≤ 1 000	40	10	50
> 1 000 ≤ 3 000	20	10	70
> 3 000	25	15	60

Moreover, instead obtain the maximum current, here it is obtained the the top-liquid rise:

$$\theta_{TO} = \theta_{TO_R} \left(\frac{P_{LL} + P_{NL}}{P_{LL_R} + P_{NL_R}} \right)^{0.8} \qquad (10)$$

where

$$P_{LL} = 1 + F_{HL} \cdot P_{EC} \qquad (11)$$

And the hottest spot conductor rise over top-liquid temperature

$$\theta_g = \theta_{g_R} \left(\frac{P_{LL}(pu)}{P_{LL_R}(pu)} \right)^{0.8} \qquad (12)$$

B. EN-50464-3 [11] and EN- 50541-2 [12]

These two standards use the same equation and the same input values for dry-type (EN-50541-2) and liquid immersed transformers (EN- 50464-3).

In a first step, the standards define the harmonic factor as:

$$THD(\%) = 100 \left[\sum_{n=2}^{n=N} \left(\frac{I_n}{I_1} \right)^2 \right]^{\frac{1}{2}} \qquad (13)$$

where

I_n is the current for each harmonic.
I_1 is the fundamental current .

The k factor is obtained by:

$$k = \left[1 + \frac{e}{1+e} \left(\frac{I_1}{I} \right)^2 \sum_{n=2}^{n=N} n^q \left(\frac{I_n}{I} \right)^2 \right]^{\frac{1}{2}} \qquad (14)$$

where

e: ratio between Eddy-current losses by fundamental current and losses by dc current with a rms value equal to the fundamental current at the reference temperature.

n: harmonic order.

I: rms value of all the harmonics including the fundamental value:

$$I = \left(\sum_{n=1}^{n=N} I_n^2 \right)^{\frac{1}{2}} = I_1 \left[\sum_{n=1}^{n=N} \left(\frac{I_n}{I} \right)^2 \right]^{\frac{1}{2}} \qquad (15)$$

q: constant with value of 1.7 for transformers with round or rectangular conductors in LV and HV windings and 1.5 with flat conductors in LV windings.

Once both standards have been explained it is important to focus on the differences. In Fig. 1 a diagram of the procedures is showed.
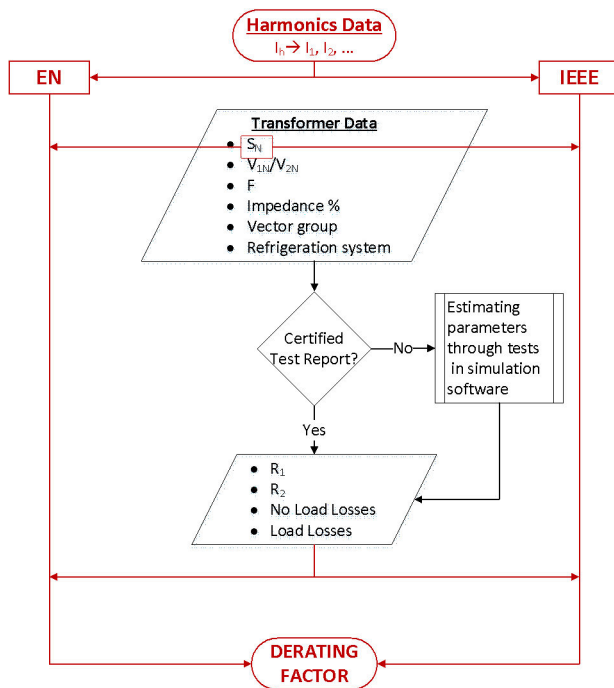
Fig.1 Diagram of the procedures

IEEE standard presents two different procedures for dry-type transformers and for liquid immersed transformers. In the liquid immersed transformers, take into account the losses in the parts different than the windings. In EN standards the procedure is the same for dry-types and for liquid immersed. This point makes the IEEE procedure more accurate. The input data is higher in the case of the IEEE standard for calculation using design eddy-current loss data. Usually, the distribution companies do not have enough information about the existing transformer in the distribution network to implement the calculation using design eddy-current loss data. In practice, it is more usual to implement the IEEE procedure using data available from certified test report or EN procedure.

The real case calculation will allow showing the differences between the procedures.

3. Real case information

A Plastic production factory suffers from problems of apparent abnormal behaviour of thermal protection in one of its distribution transformers. This protection opens during normal load of only one of the distribution transformers.

The electrical installation is connected to the distribution network in a connection point at 12 kV without neutral conductor. This input supplies four distribution transformers of 12 kV/380 V, Dyn11. Accordingly, the low voltage distribution is made at 380 V with neutral conductor. This configuration may produce circulation of zero-sequence harmonics thought the neutral conductor.

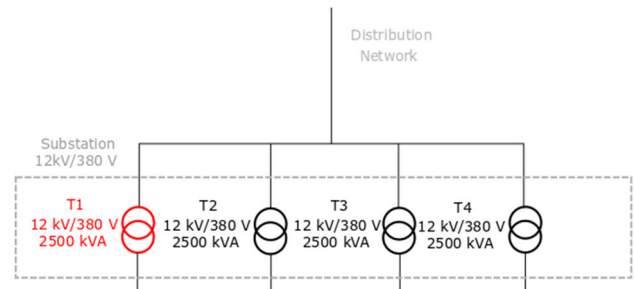The general single-line diagram of the factory is showed in Fig. 2.

Fig.2 General single-line diagram

The problematic transformer is T1. This transformer supplies two lines of the factory (loads) and part of the reactive compensation modules of the factory. The loads of this transformer are mainly three-phase asynchronous motors with static starters but without speed regulation. For these reasons, the loads may be considered as linear loads. This configuration is represented in Fig. 3.
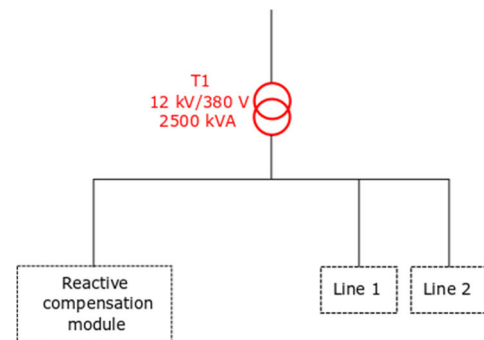

Fig.3 Single-line diagram of the transformer T1 loads

The available information of the transformer T1 is:

- Rated power: 2,500 kVA
- Primary winding voltage: 12,000V
- Primary winding resistance: 0.449 Ω
- Secondary winding voltage: 380 V
- Secondary winding resistance: 0.00015 Ω
- Connection: Dyn11
- Rated Load Losses: 18,900 W
- Rated No Load Losses: 4,300 W
- Cooling system: ONAN

Once the thermal protection of the transformer were analysed and no problems were found, the abnormal trips of the thermal protection of the transformers lead to think that the transformer could be affected by a level of harmonic above the designed. In order to verify this, an analysis of the derating of the transformer with IEEE and UNE standards was carried out.

4. Transformer derating analysis

The first step to analyse the derating of the transformer is to carry out a harmonic study on the secondary side of the transformer. The results obtained in this study show that the voltage THD values go from 5.5 % to 10.2. Considering that the distribution transformers are designed considering a maximum THD of 5 %, it can be concluded that the transformer must be derated. In the case

of the THD of the current it is observed that the current THD values go from around 51 % to around 68.5 %.

In Fig. 4, it is represented the relationship in percentage between the harmonic current and the fundamental current.
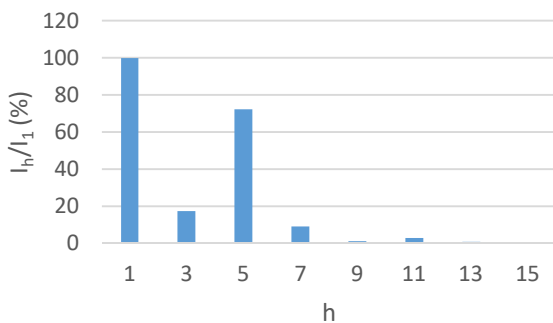

Fig.4 Harmonic content of the current

This shows that 5th harmonic represents the highest value with a 72 % of the fundamental current.

The second step is the application of the procedures defined in IEEE Std C57.110-2018 and EN-50464-3 since it is a liquid-immersed transformer.

A. IEEE Std C57.110-2018

The first step is to obtain the value of the total stray losses with equation (5):

$$P_{TSL_R} = 18,900 - 1.5[120.3^2 \cdot 0.449 + 3,798.4^2 \cdot 0.00015] = 5,899 \ W$$

The second step is to calculate the rated Eddy-current losses with equation (6) where de coefficient is 0.3 from Table II:

$$P_{EC_R} = 5,890 \cdot 0.3 = 1,769.7 \ W$$

The following step is calculating the stray losses in other points different than windings:

$$P_{OSL_R} = P_{TSL_R} - P_{EC_R} = 5,899 - 1,769.7 = 4,129.3 \ W$$

The values obtained until this point are the estimations of the losses of the transformer. The following step is obtaining the values of losses when supplying nonsinusoidal current. For this purpose, the harmonic factor for the eddy-current losses and the harmonic factor for other stray losses is obtained with the harmonic measurements.

$$F_{HL} = 9.53$$
$$F_{HL_{STL}} = 1.92$$

Finally, the value of the maximum current per unit is obtained:

$$I_{max}(p.u) = \sqrt{\frac{P_{LL_N}}{P_{LL}}} = 0.707$$

This value represent the factor applied to the capability. Accordingly, the new rated power of the transformer is 1,767 kVA.

B. EN-50464-3

This standard requires the value of parameter e, that it is ratio between Eddy-current losses by fundamental current and losses by dc current with a rms value equal to the fundamental current. This value is not typically provided by the costumer of the transformer so it would be necessary to obtain through test in the transformer. There is no possibility to make test in the transformer so the most appropriate solution is to obtain the value through simulation.

PSCAD software is used to model the transformer and calculate de parameter e. This parameter represents the relationship between the Eddy-current losses and the Joule losses in the primary since when a transformer is supplied by dc current the main losses are Joule losses in the primary winding. The e calculation procedure follows the next steps:

1) *Eddy-current losses simulation:* An open circuit test is made in the transformer modeled in PSCAD. The Eddy-current losses obtained in this test are 1,450 W.
2) *Losses with dc current power supply simulation:* The transformer modeled in PSCAD is supplied by a dc current voltage source. The voltage of the source is varied until obtain in the primary winding the rated current. In this condition the losses obtained are 3,100 W.
3) *Parameter e calculation:*

$$e = \frac{P_{EC}}{P_{DC}} = \frac{1,450}{3,100} = 0.468$$

Finally, it is obtained the factor k through the equation (14) with the following conservative value:

$$H = 1.7$$

$$k = \left[1 + \frac{0.468}{1 + 0.468}(0.8)^2 \cdot 9.556\right]^{\frac{1}{2}} = 1.71$$

This means that the factor applied to the capability is 0.58 (1/K). Accordingly, the new rated power of the transformer is 1,456 kVA. This fact constitutes a reduction of the transformer capability of around the 42 %. Taking into account that the top-liquid rise temperature depends on the relationship between the losses with an exponential factor of 0.8 [10] the top-liquid rise temperature may increase with a 1.53 factor due to operate the transformer in its rated power with nonsinusoidal currents.

C. Comparison between results

The results obtained with EN procedure is more conservative than the IEEE procedure. This fact is understandable since the EN procedure is simpler than

IEEE procedure and needs fewer input values than IEEE. In the case of IEEE, the value may be more accurate because the procedure is more complex and use more input values. Moreover, the EN procedure needs some additional test or simulations to obtain some of the values.

Regarding the losses, IEEE procedure takes into account the Eddy-current losses, the Joule losses in the both windings and the stray losses. In the case of the EN procedure the losses taking into account are the Eddy-current losses and Joule losses. For these reasons, the IEEE procedure seems to be more accurate than EN procedure and this last needs to be more conservative.

4. Conclusion

Two standardized methods for derating of distribution transformers that are operating in nonsinusoidal conditions have been analyzed. Both methods provide relatively similar results but with different levels of complexity due to the requested input data.

The results obtained with EN procedure are more conservative than the IEEE procedure. This fact is understandable since the EN procedure is simpler than IEEE procedure and make the calculation neglecting the stray losses.

In summary, the most appropriate standard to derate the transformers is the IEEE procedure if the necessary input data is available. In the case that the input data is poor is more appropriate the use of EN procedure.

Acknowledgement

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