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Economical implications regarding the operation of power transformers in harmonic polluted power systems

Ph.D. Student G.V. Pop, Dr.Eng. M. Chindriş, Ph.D. Student C.O. Gecan
Technical University of Cluj – Napoca
15 C. Daicoviciu St., RO 400020, Cluj – Napoca
Tel: +40264 401408
Gabriel.POP@eps.utcluj.ro
Mircea.CHINDRIS@eps.utcluj.ro
Calin.GECAN@eps.utcluj.ro

Abstract

The segment of loads causing harmonic pollution of power systems is increasing due to the rising volume of electronic and power electronic components. Each non-linear load generates periodic events (e.g. harmonics) that could lead to serious problems within power system networks and its components (e.g. transformers).

If transformers operate in networks where the harmonic spectra exceed a certain limit, they will additionally be heated up and losses are increased, compared to operation under normal conditions.

This paper discusses different effects of harmonics on power transformers, such as increasing power losses, reduction of efficiency, decrease of power factor and derating of transformers.

An economical analysis is performed in order to determinate the life cycle cost of transformers for different rated powers.

Keywords: transformers, power quality problems, harmonics

1. Introduction

Transformer simulation under sinusoidal operating conditions is a well-researched subject and many steady state and transient models are available.

The measurement and calculation methods, required by the standards, accurately determine a transformer's losses and energy efficiency when it supplies *linear* resistive and/or inductive loads. The method used to determine total losses requires the summation of no-load losses and load losses. These losses are determined by performing an open-circuit and a short-circuit tests.

Unfortunately, modern electrical distribution systems typically supply a high percentage of *non-linear* electronic loads. As a result, transformer losses increase and energy efficiencies decrease. The level of deterioration is a function of harmonic voltage magnitudes at a transformer's primary terminals, load-generated harmonic current magnitudes at its secondary terminals and their phase configurations. There are, unfortunately, no recognized standards for determining a transformer losses or efficiency under these *non-linear* conditions.

As a result, it is necessary to investigate more detailed the effects of these new operation conditions on the components of the power systems, especially for power transformers.

2. Transformers efficiency

Distribution transformers are very efficient electrical machines reaching maximum efficiency at the level of 97,5% to 99,4%. Operating efficiency is smaller because transformers do not operate at maximum efficiency all the time (Figure 1).

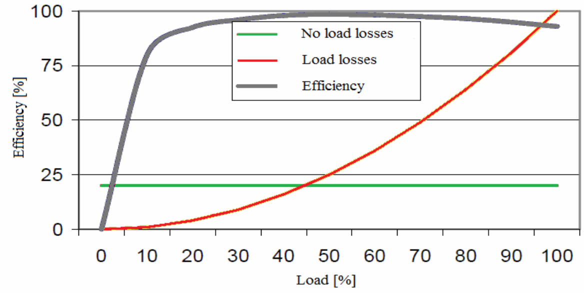

Figure 1. Transformer efficiency

This maximum efficiency point is at the point where load losses proportional to square of transformer load are equal to the no load losses which are constant and appear all the time when the transformer is energized (usually between 40% and 50% loading).

Transformer losses are produced by the electrical current flowing through the coils and the magnetic field

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Keywords: *transformers, power quality problems, harmonics*

alternating in the core. The losses associated with the coils are called load losses, while the losses produced in the core are called no-load losses.

The no-load losses are basically the power required to keep the core energized. These are commonly referred to as “core losses,” and they exist whenever the unit is energized. No-load losses depend primarily upon the voltage and frequency, so under operational conditions they vary only slightly with system variations.

Load losses, as the terminology might suggest, result from load currents flowing through the transformer. The two components of the load losses are the I^2R losses and the stray losses. I^2R losses are based on the measured dc (direct current) resistance, the value of which is due to the winding conductors and the current at a given load.

The stray losses are a term given to the accumulation of the additional losses experienced by the transformer, which includes winding eddy losses and losses due to the effects of leakage flux entering the internal metallic structures.

Auxiliary losses refer to the power required to run auxiliary cooling equipment, such as fans and pumps; they are not normally included in the total losses as defined above.

3. Transformer Losses

Transformer losses can be determinate with the following mathematical expression:

$$P_T = P_0 + P_S \quad (1)$$

where:

P_T - total losses in transformer;

P_0 - no-load losses;

P_S - load losses.

3.1. Transformer no-load losses

No-load losses (also referred to as excitation losses, core losses, or iron losses) are a very small part of the power rating of the transformer, usually less than 1%. However, these losses are considered constant over the lifetime of the transformer (do not vary with load), and thus they generally represent a sizeable operating expense, especially if energy costs are high. Therefore, accurate measurements are essential in order to evaluate individual transformer performance accurately.

No-load losses are usually quoted and reported based on a sine-wave voltage excitation. Even with a sinusoidal source voltage, the non-linearity of the transformer core introduces significant harmonics into the excitation current and could result in distorted excitation voltage and flux waveforms. The magnitude of the voltage waveform distortion is usually determined by the output impedance of the voltage source and the magnitude and harmonics of the excitation current. The higher these parameters are, the greater will be the magnitude of the voltage waveform distortion.

No-load losses include losses due to magnetization of the core, dielectric losses in the insulation, and winding losses due to the flow of the exciting current and any circulating currents in parallel conductors.

Hysteresis losses are caused by the frictional movement of magnetic domains in the core laminations being magnetized and demagnetized by alternation of the magnetic field. These losses depend on the type of material used to build the core. Silicon steel has much lower hysteresis than normal steel but amorphous metal has much better performance than silicon steel. Nowadays hysteresis losses can be reduced by material processing such as cold rolling, laser treatment or grain orientation.

Hysteresis losses are usually responsible for more than a half of total no-load losses (50% to 70%). This ratio was smaller in the past (due to the higher contribution of eddy current losses particularly in relatively thick and not laser treated sheets).

Eddy current losses are caused by varying magnetic fields inducing eddy currents in the laminations and thus generating heat. These losses can be reduced by building the core from thin laminated sheets insulated from each other by a thin varnish layer to reduce eddy currents. Eddy current losses nowadays usually account for 30% to 50% of total no-load losses. When assessing efforts in improving distribution transformer efficiency, the biggest progress has been achieved in mitigation of these losses.

There are also marginal stray and dielectric losses which occur in the transformer core, accounting usually for no more than 1% of total no-load losses.

Core or no-load losses is due to the voltage excitation of the core. Even though the magnetizing current does include harmonics, these are extremely small compared with the load current and their effect on the losses is negligible.

3.2. Transformer load losses

These losses are commonly called copper losses or short circuit losses.

Transformer load losses include I^2R losses in windings due to load current, eddy losses due to leakage fluxes in the windings, stray losses caused by stray flux in the core clamps, magnetic shields, tank wall, etc., and losses due to the flowing of current in parallel windings and parallel conductors within windings.

$$P_s = R \cdot I^2 + P_{EC} + P_{SL} \qquad (2)$$

where:

RI^2 - losses due value of the current and resistance of the transformer;

P_{EC} - Eddy Current Losses;

P_{SL} - Stray Losses.

Load losses vary according to the transformer loading; they are composed of:

Ohmic heat losses sometimes referred to as copper losses, since this resistive component of load losses dominates. These losses occur in transformer windings and are caused by the resistance of the conductors. The magnitude of these losses increases with the square of the load current and are proportional to the resistance of the windings. They can be reduced by increasing the cross-section of conductor or by reducing the winding length. Using copper as the conductor maintains the balance between weight, size, cost and resistance; adding an additional amount to increase conductor diameter, consistent with other design constraints, reduces losses.

Eddy currents, due to magnetic fields caused by alternating current, also occur in the windings. Reducing the cross-section of the conductor reduces eddy currents, so stranded conductors are used to achieve the required low resistance while controlling eddy current losses. Effectively, this means that the 'winding' is made up of a number of parallel windings. Since each of these windings would experience a slightly different flux, the voltage would be slightly different and connecting the ends would result in circulating currents which would contribute to losses. This is avoided by the use of continuously transposed conductor, in which the strands are frequently transposed to average the flux differences and equalize the voltage.

3.3. Transformer losses in sinusoidal operating state

In an ideal clean power system, the current and voltage waveforms are pure sinusoids. In practice, non-sinusoidal *currents* result when the current flowing in the load is not linearly related to the applied voltage. In a simple circuit containing only linear circuit elements - resistance, inductance and capacitance - the current which flows is proportional to the applied voltage (at a particular frequency) so that, if a sinusoidal voltage is applied, a sinusoidal current will flow.

In this state, the losses in transformers can be mathematically determinate by:

$$\Delta P_T = \Delta P_{Cu} + \Delta P_{Fe} \qquad (3)$$

where:

ΔP_{Fe} - losses due magnetization of the core (it is given in the manufactures catalogues);

ΔP_{Cu} - total losses in windings of the transformer.

Total losses in windings are calculated with:

$$\Delta P_{Cu} = \Delta P_{nCu} \cdot \beta^2 \qquad (4)$$

where:

ΔP_{nCu} - copper losses (it is given in the manufactures catalogues);

β - loading of the transformer.

3.4. Transformers losses in non-sinusoidal state

The transformers operation in non-sinusoidal conditions produces supplementary power losses in its components: windings and magnetic circuits.

Losses in transformers are:

- losses due value of the current and resistance of the transformer
- stray magnetic losses in the core;
- eddy current and resistive losses in the windings.

The magnitude of the ohmic losses increases with the square of the load current and are proportional to the resistance of the windings.

If the variation with frequency of the electrical resistance(R) is neglected (it will be the resistance for the fundamental harmonic), power losses in copper can be determinate with:

$$\Delta P_{Cu} = 3 \cdot R \cdot I_{\max 1}^2 \cdot \left(1 + \delta_I^2\right) \qquad (6)$$

where:

$I_{\max 1}$ - maximum value for the fundamental current;

δ_I - total harmonic distortion for current.

There are no test methods available to determine individual winding eddy current loss or to separate transformer stray losses from eddy current losses. Instead, the total stray and eddy current losses are determined by determining the total load losses and subtracting the calculated ohmic losses.

Eddy currents, just like any other electrical currents, are affected by the resistance of the material in which the currents flow. The resistance of any material is inversely proportional to its cross-sectional area.

Out of these, eddy current losses are of most concern when harmonics are presented, because they increase with the square of the frequency.

Before the excess losses can be determined, the harmonic spectrum of the load current must be known.

$$P_{EC} = P_{ECf} \cdot \sum_{h=1}^{h=h_{\max}} \left[\frac{I_h}{I_f} \right]^2 \cdot h^2 \qquad (5)$$

where:

h - harmonic order, 1,2,3, etc.

h_{max} - the greatest harmonic order to be considered

I_h - current at harmonic order h, amperes

I_R - rated current, amperes

$P_{EC,R}$ - eddy current loss at rated current and frequency.

As a result, to reduce power losses, it is necessary to reduce the maximum power load of the transformer or to take extra care in the design stage. Reducing the maximum power load is a practice called “de-rating”.

4. Economical evaluation of losses and life cycle cost of transformers

Transformer losses represent power that can not be delivered to customers and therefore have an associated economic cost to the transformer user/owner.

A reduction in transformer losses generally results in an increase in the transformer’s cost. Depending on the application, there may be an economic benefit to a transformer with reduced losses and high price (initial cost), and vice versa. This process is typically dealt with through the use of “losses evaluations,” which place a EURO value on the transformer losses to calculate a total owning cost that is a combination of the purchase price and the losses. Typically, each of the transformer’s individual losses parameters - no-load losses, load losses, and auxiliary losses - are assigned a EURO value per kW (EURO/kW).

4.1. Cost of annual energy losses

The annual energy losses of a transformer can be estimated from the following formula:

$$W_{loss} = (P_0 + P_S \cdot L^2) \cdot 8760h \qquad (7)$$

in which:

W_{loss} - is the annual energy loss in kWh

L – is the average per-unit load on the transformer

8760 – number of hours in a year [h/year]

To calculate the losses cost, it is necessary to establish their value (in prices) at the moment of transformer purchase, trough capital values. This is called the Total Capitalized Cost of the losses, TCC_{loss}. This can be calculated using the following formula (8):

$$TCC_{loss} = W_{loss} \cdot \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \cdot C_{kWh} \cdot 8760 \quad (8)$$

where:

i – is the estimated interest rate[%/year];

n – is the expected life time of the transformer [years];

C_{kWh} - kWh price [EURO/year];

To perform the economical analysis of a transformer, it is necessary to calculate its life cycle cost.

4.2 Life cycle cost of transformers

Taking in account only the purchase price and the cost of losses, total cost of transformer can be calculated by:

$$TCT = PT + A \cdot P_0 + B \cdot P_{sc} \qquad (9)$$

where:

PT– is the purchase price of transformer;

A – the assigned cost of no-load losses per watt;

P_0 – is the rated no-load losses;

B – the assigned cost of load losses per watt;

P_{sc} - is the rated load losses.

A simple method is proposed for determination of A and B factor for distribution transformers:

No-load losses capitalization (A):

$$A = \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \cdot C_{kWh} \cdot 8760 \qquad (10)$$

Load losses capitalization (B):

$$B = \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \cdot C_{kWh} \cdot 8760 \cdot \left(\frac{I_l}{I_n} \right)^2 \quad (11)$$

where:

I_l – loading current;

I_n – rated current.

Information obtained from such an analysis can be used to compare prices from different manufacturers or to decide on the optimum time to replace existing transformers.

5. Case study

Today the production of transformers is characterized by a large variety of designs, manufactured in relatively short batches to meet the demands of a variety of consumers.

Using the above models to determine power losses and life cycle cost of transformers, a numerical application has been implemented for more oil transformers. The characteristics of the studied transformers are presented in following (Table 1):

Table 1. Transformer characteristics

S_T [kVA]	U_{np} [kV]	U_{ns} [kV]	u_{sc} [%]	P_{sc} [kW]	P_0 [kW]
160	20	0.4	4	1.5	0.87
250	20	0.4	4	2.8	1.1
400	20	0.4	4	3.3	1.45
630	20	0.4	4	6	2
1000	20	0.4	6	9.2	2.3
1600	20	0.4	6	11.8	3.5

The variation of power losses is presented for a transformer witch has rated power equal to 160 kVA. Losses variation, as a function of the total harmonic distortion for currents, is presented below (the load of transformer have different values such as 60%, 80% and 100%) – Figure 2.

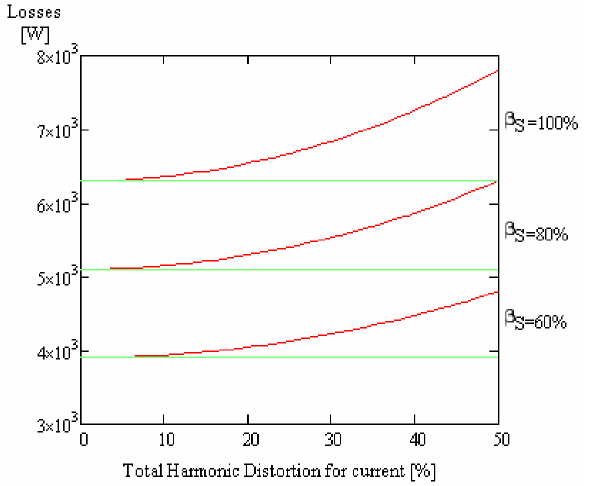


Figure 2. Power losses as a function of Total Harmonic Distortion for current for different loads

Transformers loading conditions are probably most influential as far, for optimum selection of distribution transformer losses.

Total Capitalized Cost of the losses for studied transformers, when the loading range between 10% and 100%, is presented in Figure 3:

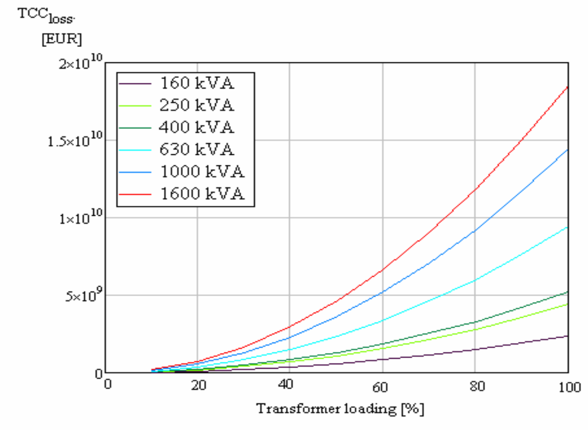
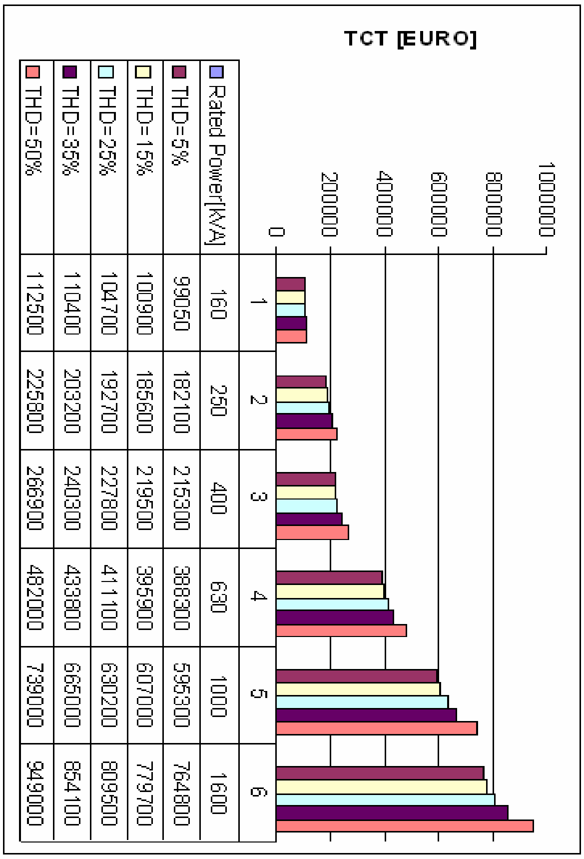


Figure 3. TCC of losses for different transformers

Lifetime is a crucial component of TCT calculation. Transformers are durable and have long life cycle.

The Total Cost (TCT) for studied transformers is presented in the following (Figure 4); the loading of transformer is considered 60% and total harmonic distortion for current (THD) takes different values (5, 15, 25, 35 and 50 %).



	1	2	3	4	5	6
Rated Power[kVA]	160	250	400	630	1000	1600
THD=5%	99050	182100	215300	388300	595300	764800
THD=15%	100900	185600	219500	395900	607000	779700
THD=25%	104700	192700	227800	411100	630200	809500
THD=35%	110400	203200	240300	433800	665000	854100
THD=50%	112500	225800	266900	482000	739000	949000

Figure 4. Total cost of transformers for different values of THD

Conclusions

The non-linear consumers are the consumers that generate non-sinusoidal evolution in three-phase systems. The presence of harmonics components has a bad influence on the transformers: the technical efficiency is reduced.

Ensuring a sinusoidal operation state allows, for the same volume of supplied energy, minimum of power losses.

Because the losses are higher, the operating temperature of the transformer is higher and the lifetime is considerably shortened. Even moderately loaded transformers supplying IT loads will have much lower lifetimes than expected unless proper precautions are taken.

The economic effects of harmonics are shorter equipment lifetime and reduced energy efficiency.

Equipment such as transformers is usually expected to last for 30 or 40 years and having to replace them in 7 to 10 years can have serious financial consequences.

The business risk posed by power quality problems is a real one with even ‘low tech’ industries being exposed to serious financial losses. On the other hand, prevention is relatively cheap ranging from simple good practice design techniques to the installation of widely available support equipment.

Such a complete technical and economical model is useful through its ability to stress opportunities and technical measures to support the strategies aimed to increase the efficiency of distribution industry.

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