

Effects of Harmonic Pollution on Electrical Three-Phase Power Transformers

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Abstract—In this paper there are described the effects of the current and voltage variations' distortion on the three-phased power transformers; the methods of evaluating the additional power losses in the three-phased power transformers given by the harmonics and some records necessary for the evaluation and the measurement of the harmonics, corresponding to a consumer powered from a transformer station.

Keywords—harmonics; distortion; magnetic core; three-phase power transformer; power quality

I. INTRODUCTION

The phenomena of current and voltage variations distortion always existed in the power systems. But the interest for its research became greater as these phenomena get more intense due to the wider presence of the power electronics in the power grids. In an ideal power system, the forms of the current and voltage variations are perfectly sinusoidal. But, in reality in the power grids there are non-sinusoidal currents, whenever some loads or elements of the grid have a non-linear variation depending on the applied voltage. The harmonic currents generated by the non-linear loads are circulating in the power grids, generating voltage harmonics in all the impedances.

The resulted non-sinusoidal voltage is applied to all the loads connected to the same grid, loads that shall generate current harmonics, that will circulate through the grid and the loads, even in the situation when they are linear loads. Among the current and voltage harmonics' sources there are the following groups of equipment: the equipment having a magnetic core (power transformers, compensating coils, electric motors and generators); electric arc based furnaces (on alternative current); the electronic equipment and the equipment based on power electronics [1].

II. THE EFFECTS ON THE ELECTRIC POWER TRANSFORMERS

The presence of the current and voltage harmonics leads to important thermal effects (the increase of the winding's and the magnetic core's temperature), produces by the additional active power losses, as power losses in the conductors, power losses in the magnetic materials and power losses in the dielectrics [1], [2].

A. The Increase of the Additional Active Power Posses

He circulation of non-sinusoidal currents in the power transformers' windings lead to additional power losses in the conductive materials, through Joule-Lenz effect, due to the effective increase of the distorter current compared to the sinusoidal one; due to the increase of the conductors' resistance, on the grounds of their frequency dependence (the Kelvin effect).

In the hypothesis of neglecting the continuous component, these power losses can be calculated with the following equation [2]:

$$P_{Cu} = \frac{3}{2} \cdot \sum_{h=1}^M R_h \cdot I_{\max h}^2 \quad (1)$$

where: $I_{\max h}$ is the amplitude of the h grade harmonic, R_h is the electric resistance of that element, calculated for the frequency of the h grade harmonic, and M – is the grade of the harmonic used in the calculations. The electric resistance value R_h is determined based on the Kelvin effect.

The increase of the active power losses in the conductive material of the three-phased power transformers' delta connected windings, given by the current harmonics having a grade multiple of three is absorbed in these windings and is not propagated in the power grid. This circulation current in the delta connected windings, given the current harmonics having a grade multiple of three is to be considered in the calculation of the power transformer [1].

B. The Increase of the Additional Active Power Posses

The presence of the harmonics in the voltage variation leads to additional power losses given by the hysteresis phenomena and the apparition of the rotational currents [1], [2].

$$P_{fe} = a_H \cdot \sum_{h=1}^{\infty} f_h \cdot B_{\max h}^p + a_T \cdot f_h^2 \cdot B_H; f_h = h \cdot f \quad (2)$$

where f_h is the frequency of the h grade harmonic, a_H and a_T – are constants depending on the material; $p=1.5 \div 2.5$ is the Steinmetz constant, its value being dependant on the material, and $B_{\max h}^p$ is the maximal value of the magnetic induction for the h grade harmonic.

The first element of equation (2) is representing the power losses given by the hysteresis phenomena and the second one the power losses given by the rotational (Foucault) currents. The maximal value of the magnetic induction can be calculated by the following equation:

$$B_{\max h} = c \cdot \frac{U_{\max h}}{h} \quad (3)$$

where: $U_{\max h}$ is the amplitude of the h grade voltage harmonic, and c is a coefficient that can be calculated with the following equation:

$$c = \frac{1}{2 \cdot \pi \cdot N \cdot S \cdot f_1} \quad (4)$$

In (4), S is the area of the cross section of the magnetic material, N is the number of turns, and f_1 is the frequency of the fundamental harmonic. By using equations (3), (4) and (2) it can be written:

$$P_{fe} = 3 \cdot \left(c_1 \cdot \sum_{h=1}^{\infty} \frac{U_{\max h}^p}{h^{p-1}} + c_2 \cdot \sum_{h=1}^{\infty} U_{\max h}^2 \right), \quad (5)$$

where:

$$c_1 = a_H \cdot c^p \cdot f_1 \quad (6)$$

$$c_2 = a_T \cdot c^2 \cdot f_1^2 \quad (7)$$

The active power losses in the conductive material are increasing with the increase of the windings' resistance and with the current harmonics' grade. The increase of the power losses in the magnetic materials is given by the increase due to the rotational currents.

C. Other Effects

The increase of the electric current's distortion factor on the magnetisation characteristic's non-linear part. The decrease of the power transformers life duration and efficiency.

III. ELECTRIC POWER QUALITY INDICATORS FOR HARMONICS AND INTER-HARMONICS

A. Electric Power Quality Indicators

The calculation of the electric power's quality indicators, regarding the voltage and current harmonica and inter-harmonics and their comparison with the maximal admissible values is made according to the standards EN 50160 [3], CEI 61000-4-30 [3], CEI 6100-4-7 [3].

According to 50160:2010, the voltage harmonics U_h , can be calculated [1], [4]:

- individually, by their relative amplitude, U_h (%), by dividing the harmonic's amplitude with the fundamental harmonic's amplitude U_1 , h being the grade of the respective harmonics:

$$U_h (\%) = \frac{U_h}{U_1} \cdot 100 \quad (8)$$

- globally, through the total harmonics distortion factor $THDU$, calculated by the equation:

$$THDU = \frac{\sqrt{\sum_{k=2}^{40} (U_h)^2}}{U_1} \quad (9)$$

Similarly, the current harmonics I_h can be calculated:
- individually, by their relative amplitude, I_h (%), by dividing the harmonic's amplitude with the fundamental harmonic's amplitude I_1 , h being the grade of the respective harmonics:

$$I_h (\%) = \frac{I_h}{I_1} \cdot 100 \quad (10)$$

- globally, through the total harmonics distortion factor $THDI$, calculated by the equation:

$$THDI = \frac{\sqrt{\sum_{k=2}^{40} (I_h)^2}}{I_1} \quad (11)$$

B. The Calculation and Measurement of The Harmonics

The use of the standard measurement and calculation methods and procedures for the current and voltage harmonics and inter-harmonics is necessary for the verification of the measured data's compatibility. The main international standards regulating the standard measurement and calculation methods and procedures for the current and voltage harmonics and inter-harmonics are the followings: CEI 61000-4-30:208 [5] and CEI 6100-4-7:2002 [6]. The electric grid's parameters do not meet the periodicity requirement in order to be possible to analyse the distorted voltage and current variations, through Fourier series, because in every moment the electric grid's frequency is modified due to the variation of the loads and the system's parameters. In these conditions, the Fourier transform can be used only for short time intervals, where the grid's operation can be considered constant.

The electric grid's parameter (voltage and current) measuring systems use numerical measurement and processing techniques. For the numerical processing, the input analogic signals are sampled and quantized. For the processing of the samples obtained from the measurements, the Discrete Fourier Transform (DFT) and a fast processing algorithm – known as the Fast Fourier Transform (FFT) are used [1].

The non-sinusoidal parameters of the electric grid are defined through a function having the form:

$$f(t) = c_0 + \sum_{h=1}^{\infty} c_h \cdot \sin(h \cdot \omega_1 \cdot t + \varphi_h) + \sum_{m=1}^{\infty} c_m \cdot \sin(m \cdot \omega_1 \cdot t + \beta_m) \quad (12)$$

where: the first part of equation (11) is regarding the harmonics and the second part regarding the inter-harmonics, considering the modulation of the sinusoidal variations due to the load's variation; c_0 is a continuous, constant component; c_h is the amplitude of the harmonic having the frequency $f_h = h \cdot f_1$; ω_1 is the pulsation of the fundamental component $\omega_1 = 2 \cdot \pi \cdot f_1$; φ_h is the phase alteration of the h grade harmonic, compared to the fundamental component; c_m is the amplitude of the inter-harmonic component having the frequency $f_m = h \cdot f_1$; β_m is the phase alteration of the m grade inter-harmonic compared to the fundamental component.

Considering the above, the Fourier transform can be used for the analysis of the distorted voltage and current variations, only for short time intervals (usually, a time of 10 signal periods), where the power grid's operation can be considered relatively constant [1].

IV. AN EXAMPLE – THE CALCULATION AND THE MEASUREMENT OF THE HARMONICS FOR A CONSUMER POWERED THROUGH A TRANSFORMER STATION OF 400/230 V, 630 kVA

A. The Voltage Recorded on the First Power Grid Line (U_{12}), Is Indicated in Figure I.

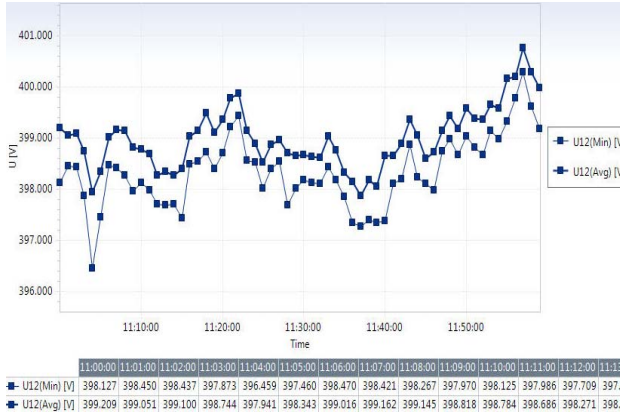


FIGURE I. THE VARIATION OF THE POWER VOLTAGE FROM THE FIRST GRID LINE (V).

B. The Voltage Recorded on the Grid's First Phase (U_{10}) Is Indicated In Figure II.

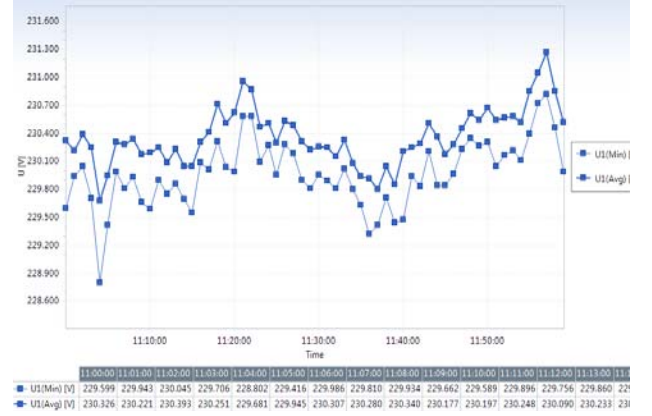


FIGURE II. THE VARIATION OF THE POWER VOLTAGE ON THE FIRST GRID PHASE FOR THE CONSIDERED TIME INTERVAL (V).

C. The Voltage on the Fundamental Component and on the Third and Fifth Grade Harmonics



FIGURE III. THE VARIATION OF THE VOLTAGE ON THE FUNDAMENTAL COMPONENT AND ON THE THIRD AND FIFTH GRADE HARMONICS (%).

D. The Voltage on the Fundamental Component and on the 11, 13 and 17 Grade Harmonics.



FIGURE IV. THE VARIATION OF THE VOLTAGE ON THE FUNDAMENTAL COMPONENT AND ON THE 11, 13 AND 17GRADE HARMONICS.

E. The total Voltage Distort Factors THDU (%) on the Three Power Grid Lines.

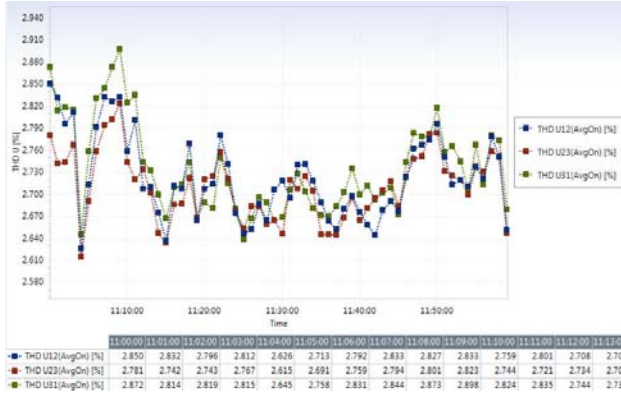


FIGURE V. THE VARIATION OF THE THD (%) FOR THE THREE POWER GRID LINES.

F. The First Current Harmonic



FIGURE VI. THE VARIATION OF THE FIRST CURRENT HARMONIC (A).

G. The First and Third Current Harmonic.



FIGURE VII. THE VARIATION OF THE FIRST AND THIRD CURRENT HARMONIC (%) CURRENT HARMONIC (A).

H. The fifth and seventh current harmonics.

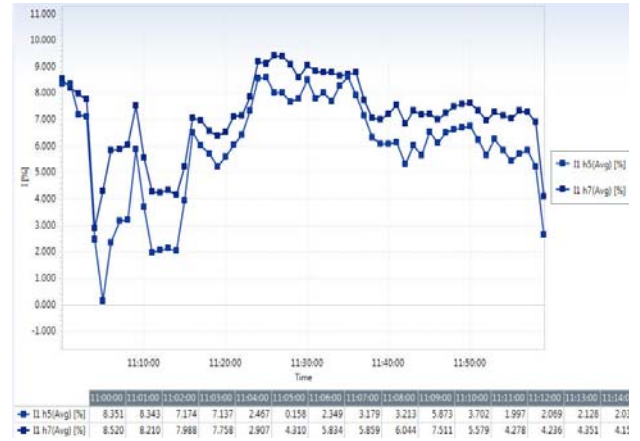


FIGURE VIII. THE VARIATION OF THE FIFTH AND SEVENTH CURRENT HARMONICS (%).

I. the Total Current Distortion Factor tddi (%), of the Load Being on the First Power Grid Line.



FIGURE IX. THE VARIATION OF THE TDD (%) OF THE LOAD BEING ON THE FIRST POWER GRID LINE.

J. The Total Current Distortion Factor of the Load TDDI (%).

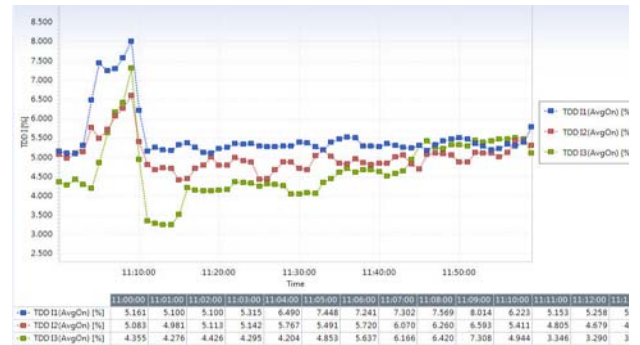


FIGURE X. THE VARIATION OF THE TDDI OF THE LOAD ON THE THREE POWER GRID LINES.

From the analysis of Figures I-X, we can deduce that in the low voltage grids the individual voltage harmonic's limit values are observed, for grades of less than 25% compared to the fundamental component of the voltage U_1 (the standards: EN 50160; CEI 61000-2-2), and there are also observed the limit values for the current harmonics in the low voltage grids of three-phased equipment (the standard CEI 61000-2-4).

The harmonic measurement method is according to CEI 61000-4-30 (the Metrel Power View, v.3.0 measurement tool has been used).

V. THE CALCULATION METHOD FOR THE ADDITIONAL POWER LOSSES GIVEN BY THE HARMONICS

A. The "K" Factor Method, Used in the USA

This method is based on the calculation of an increase factor for the power losses given by the rotational currents and on the indication of a power transformer designed to overcome them [1]. This factor is defined through the equation [7]:

$$K = \sum_{h=2}^{h_{\max}} h^2 \cdot \left(\frac{I_h}{I} \right)^2 \quad (13)$$

where: h is the harmonic's grade, I_h is the h grade harmonic's r.m.s. value, I the r.m.s. value of the distorted load current (1). When the load is linear, the K factor is 1. A greater K factor means that the Foucault current power losses are K times higher compared to the fundamental frequency component. In this case, a power transformer dimensioned for a certain H factor has reduced Foucault current power losses when operating in sinusoidal conditions (1).

Actually, the majority of the electric power quality measurement tools are determining directly the K factor of the load current. Once the K factor known, the choice of the proper power transformer from the standardised power transformers, marked for the K factor of: $K = 4, 9, 13, 20, 30, 40, 50$ [7].

B. The Power Transformers' Denomination

Another method is used in Europe [1] and is about how much is necessary to decrease the power of the transformer's load when it is powering non-linear loads, without exceeding the power losses defined for the non-distorted operation. This is called the transformer's *denomination* or *demarcation*.

In this case a denomination factor, also called K factor, is calculated based on the equation:

$$K = \left[1 + \frac{e}{1+e} \cdot \left(\frac{I_1}{I} \right)^2 \cdot \sum_{h=2}^{h_{\max}} h^2 \cdot \left(\frac{I_h}{I} \right)^2 \right]^{1/2} \quad (14)$$

where: h is the harmonic's grade, e is the ratio between the Foucault current power losses and the resistive power losses for the fundamental component and for the reference temperature; I_h is the r.m.s. value of the h grade harmonic current; I_1 is the r.m.s. value of the of the current's fundamental component; q is a constant depending on the winding's parameters and on the

frequency. The typical values are: 1.7 (for power transformers with conductors having circular or rectangular section) and 1.5 for low voltage power transformers [1].

VI. CONCLUSIONS

The rotational currents do have a high importance in the calculation of the three-phased power transformers' thermal processes given by the harmonic components. The power losses due to the rotational currents are usually approximatively 10% of the Joule power losses at nominal voltage and are increasing with the current's and the frequency's squares. The increase of the power losses lead to a higher temperature of the operating windings, which can lead to the decrease of the life duration. For maintaining the life duration, there is necessary to decrease the load and the use of the power transformer at a lower power (its denomination or demarcation) [1].

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