Ways to research and reduce the higher harmonics in the electromotive force from the power transformers for various of loads

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***Abstract*— Regardless of the many factors on which the performance of a power transformer depends, it must be able to reduce the higher harmonics (in the electromotive force in a certain degree), independent of the non-sinusoidal currents that flow through it - determined by the power source or consumer of the electrical energy. The reduction of higher harmonics is particularly important, because they are the cause of the deterioration of the performance of the power transformer - increasing its temperature and losses, and last but not least, reducing its power that can be used. The article provides information on the effect of power transformer loading on the harmonic composition of in the electromotive force on the secondary winding of the power transformer. The studies were done in the area of the rated load of the transformer (at a certain step) and at different loads. Plans are presented for future research that builds on the findings presented in this article.**

Keywords— finite element method (FEM), higher harmonics, power transformer, electromotive force, losses, and rated load.

I. INTRODUCTION

The performance of power transformers depends on many factors. On the one hand, it is the construction of the transformer itself - the type of electrotechnical steel from which the core of the is made, the type and method of connecting the windings - low voltage winding and high voltage winding, as well as a number of structural features. On the other hand, with no less influence on the performance of power transformers are the supply voltages (shape and type), the type of load and the currents that flow through the transformer depending on these factors. They, in turn, depend on the power source, which can be non-sinusoidal - photovoltaic power station or a wind generator, but regardless of the type and presence of an inverter (which, regardless of its good quality, can also be the cause of introducing non-linearity). Due to the goal of reducing conventional and traditional energy sources and replacing them with renewable ones, especially photovoltaic power station [5] or a wind generator, the number of the latter is constantly increasing. The type of load that is connected to their secondary winding (regardless of whether directly or through the power distribution network) has a significant impact on the operation of power transformers. The loads, in turn, are also the most diverse and the reasons for this are as follows - they cover a huge range of applications from homes to offices and administrative buildings to huge industrial manufactores. For this reason, the loads can be the following from LED light bulb in someone's home (consuming a few watts of electrical power) through a UPS system serving the computers in an administrative building (consuming tens of kilowatts of electrical power) to an induction motor located in a factory, which is controlled by inverter (consuming electrical power several megawatts). Sometimes two or more inverters are connected to the secondary winding of the transformer, and they cannot be perfectly synchronized [3]. This, in turn, also causes problems for the power transformer - increasing temperature and losses [1]. What all these loads have in common is that they contain multiple electronic components and this determines the fact that they generate non-linearity and create higher harmonics [1]. Part of the problem is compounded by the fact that non-linear loads are growing more and more [2], [4].

The article is structured as follows:

- information about the power transformer
- power transformer research results
- plan for future work
- conclusions

II. INFORMATION ABOUT THE POWER TRANSFORMER

Technical information about the power transformer, which is the subject of this article, is presented in Table 1. The arrangement of the primary (HV) and the secondary winding (LV) on the core wire of the transformer is shown on Fig.1. A characteristic feature is that both windings are made up of different numbers of parts. The primary is composed of four parts, and the secondary of three. This is done in order that, if necessary, each phase of the transformer (regardless of whether it is a primary or secondary winding) can be located on more than one core of the transformer.

TABLE I. INFORMATION ABOUT THE POWER TRANSFORMER

№	Specification	Data	Unit
1	Rated power	400	kVA
2	Rated high voltage (HV)	20	kV
3	Rated low voltage (LV)	0.4	kV
4	Tapping on HV	± 5	%
5	Frequency	50	Hz
6	Number of phases	3	-
7	Efficiency (100 of load and 0.8 PH)	98.14	%
8	Type of cooling	ONAN	-
9	Installation	Outdoor	-
10	Conductor material (HV and LV)	Copper	-
11	Height	1778	mm
12	Length	1396	mm
13	Width	852	mm

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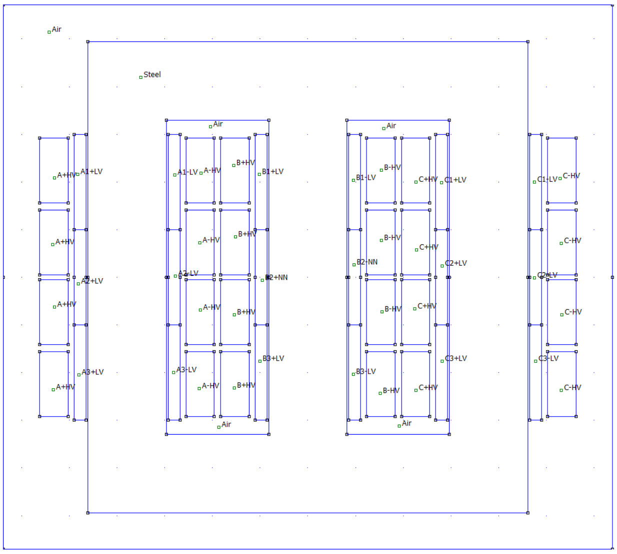

Fig. 1. Arrangement of the primprimary (HV) and the secondary winding (LV) of the transformer.

In this article, in the different parts of the primary winding (identical current densities are set in its four parts). The same applies to the secondary winding (identical current densities are set in its three parts). This creates a transformer with a standard primary and secondary winding.

III. POWER TRANSFORMER RESEARCH RESULTS

The program product FEMM 4.2 was used to study the power transformer. After setting instantaneous values of the current densities (for the primary winding at no load mode and for the two windings at load mode) for a one period of time, the flux linkage is removed. The electromotive force is then calculated, which is then subjected to harmonic analysis. Other characteristic features are that the insulation of the wires of the windings of the transformer is not set, which area in the model. The reason for this is that it would create multiple items, which in turn would increase the time to solve the task. Because core of the transformer to achieve a cross-section that is as close as possible to the circle is made of lamellas that are arranged stepwise, and this cannot be created when compiling a 2D model. For this purpose, an equivalent core created while preserving the volume of the original.

A. Analysis on no load mode

The no-load current of the transformer is essentially its magnetizing current, which does not change when it is loaded. The goal is to determine it so that it can be read when the transformer is loaded, regardless of the degree of load and the type of load.

When determining the idle current, the following features must be taken into account:

- The core of phase "B" is located in the middle of the transformer and for this reason the magnetic flux path of this phase is half of the magnetic resistance of phases "A" and "C". For this reason, the magnetizing current of phase "B" is half of that of phases "A" and "C".
- Since the primary winding is in a delta connected and a third harmonic is closed in it, which must be set in the magnetizing current- I_{h3}=0.176.
- The magnetizing current is determined in the following way (for the most accurate determination) - a value is set for the current density in primary winding until the nominal voltage is obtained in secondary winding (with the corresponding harmonic order).

On Fig.2 shown (for the three phases and secondary winding) the electromotive force curves. The harmonic order of electromotive force (maximum value) is shown on Fig.3 and in Table 2.

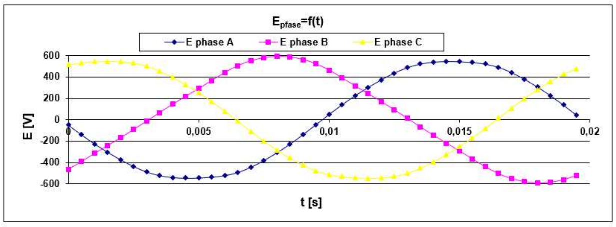

Fig. 2. Electromotive force curves (for the three phases and secondary winding)- no load mode.

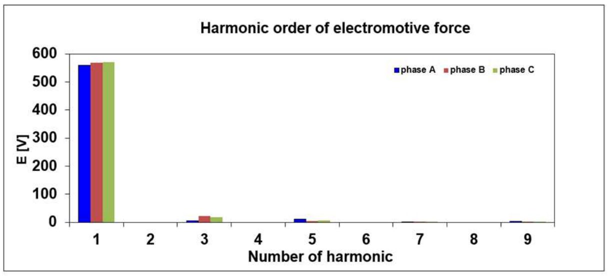

Fig. 3. Harmonic order of electromotive force (maximum value).

TABLE II. HARMONIC ORDER OF ELECTROMOTIVE FORCE (MAXIMUM VALUE).

Harmonic №	phase A [V]	phase B [V]	phase C [V]
1	558,7	569	569,8
2	0	0	0
3	5,116	21,67	18,68
4	0	0	0
5	10,75	4,546	6,262
6	0	0	0
7	1,951	1,477	2,942
8	0	0	0
9	4,059	2,873	1,204
10	0	0	0
11	3,349	2,092	1,255
12	0	0	0
13	2,631	1,872	0,76
14	0	0	0
15	2,536	1,886	0,655
16	0	0	0
17	2,341	1,73	0,614
18	0	0	0
19	2,325	1,707	0,619
20	0	0	0
21	2,289	1,642	0,646

The root mean square value (for the main harmonic) of the electromotive force is shown on Table 3.

TABLE III. TABLE TYPE STYLES THE ROOT MEAN SQUARE VALUE (FOR THE MAIN HARMONIC) OF THE ELECTROMOTIVE FORCE

Harmonic №	phase A [V]	phase B [V]	phase C [V]
1	396,22	403,58	404,13

B. *Analysis on load mode*

The load can be active, inductive or capacitive or (combination of different type of load) and this depends on the angle of the phase difference. The on-load transformer analysis is based on the phasor diagram (in general) shown in Fig.4.

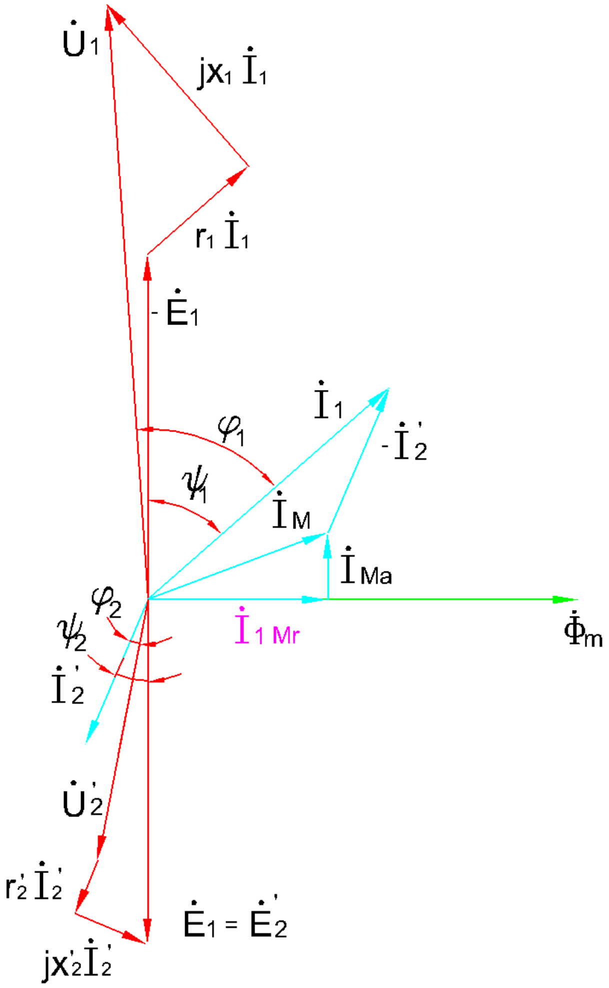

Fig. 4. Phasor diagram of the transformer (in general).

To simplify the necessary calculations, the following assumptions are made by neglecting the resistance and reactance of the primary and secondary windings of the transformer. Losses in the core are also neglected, meaning that the magnetizing current has only a reactive component. These dependencies are presented by expression (1). Based on these assumptions, the phasor diagram for the active-inductive type of the load is drawn up- Fig.5 and on Fig.6 for the active-capacitive type of the load.

$$x_1 = x_2 = 0 \quad r_1 = r_2 = 0 \quad I_{Ma} = 0 \qquad (1)$$

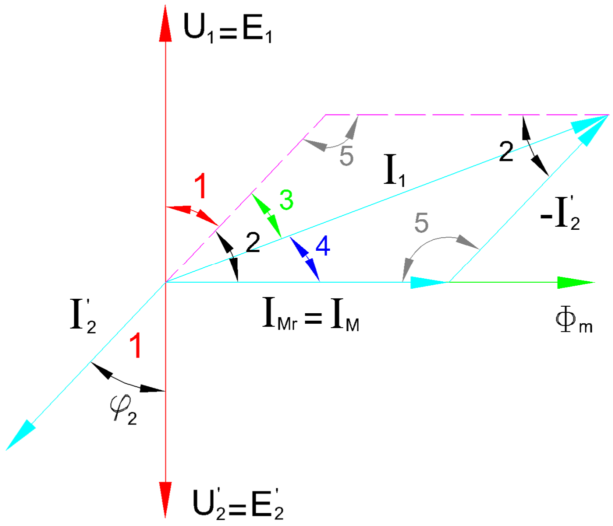

Fig. 5. Phasor diagram of the transformer (active-inductive load).

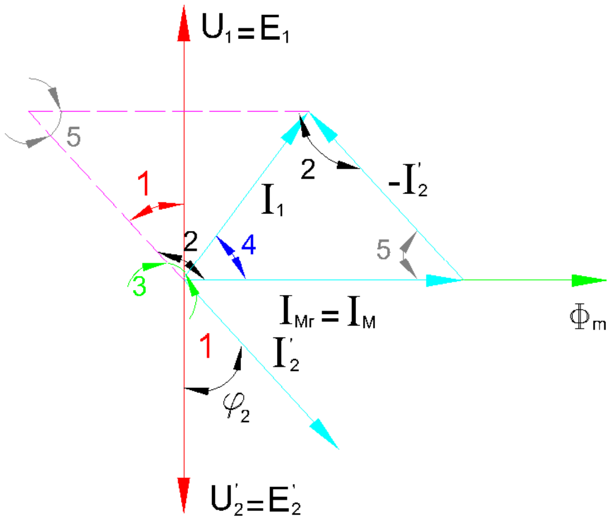

Fig. 6. Phasor diagram of the transformer (active-capcitive load).

The magnetizing current is known from the no-load mode, but it is necessary to determine the angle between it and the current flowing through the primary winding of the transformer (angle 4 -a4). This is done based on the dependencies presented by expression (2) to expression (9).

$$\varphi = a1 - pair\ of\ vertical\ angles \qquad (2)$$

$$a2 = 90^{o} - a1 - active - inductive \qquad (3)$$

$$a2 = 90^{o} + a1 - active - capacitive \qquad (4)$$

$$2 * a2 + 2 * a5 = 360^{o} \Rightarrow \qquad (5)$$

$$a5 = \frac{360^{o} - (2 * a2)}{2} \qquad (6)$$

$$\frac{I_1}{\sin(a5)} = \frac{I_\mu}{\sin(a3)} \Rightarrow \qquad (7)$$

$$a3 = \arcsin\left(\frac{\sin(a5) * I_\mu}{I_1}\right) \tag{8}$$

$$a4 = a2 - a3 \tag{9}$$

Based on expression (2) to expression (9), the angles of the phasor diagram (a1-a5) in Fig.5 are determined in degrees. The results are presented in Table 4. In the area of the rated load of the transformer through a certain step -I*=(0.2, 0.4, 0.6, 0.8, 1) In. On Fig.7 shown (for the three phases and secondary winding) the electromotive force curves (at rated load). The harmonic order of electromotive force (for phase B) is shown on Fig.8 and in Table 2 (for phase A). Fig.7 and Fig.8 show the presence of a third harmonic, which is more pronounced in phase B, because it is located on the middle core of the transformer.

TABLE IV. THE ANGLES OF THE PHASOR DIAGRAM (A1-A5) IN FIG.5

$\cos_{\varphi 2}=1$						
I*=		0,2	0,4	0,6	0,8	1
degrees	a1	0	0	0	0	0
	a2	90	90	90	90	90
	a3	5,84	2,92	1,94	1,46	1,17
	a4	84,16	87,08	88,06	88,54	88,83
	a5	90	90	90	90	90

TABLE V. HARMONIC ORDER OF ELECTROMOTIVE FORCE (MAXIMUM VALUE- FOR PHASE A)- LOAD MODE.

$\cos_{\varphi 2}=1$						
I*=		0,2	0,4	0,6	0,8	1
electromotive force [V]	h1	578	577,5	577	577,9	577,7
	h2	0	0	0	0	0
	h3	41,96	41,95	41,89	42,41	42,45
	h4	0	0	0	0	0
	h5	18,13	18,26	18,26	18,37	18,38
	h6	0	0	0	0	0
	h7	0,507	0,544	0,591	0,668	0,7
	h8	0	0	0	0	0
	h9	1,676	1,447	1,441	1,474	1,496
	h10	0	0	0	0	0
	h11	0,792	0,613	0,573	0,56	0,562
	h12	0	0	0	0	0
	h13	0,807	0,583	0,523	0,511	0,507
	h14	0	0	0	0	0
	h15	0,588	0,333	0,255	0,235	0,235
	h16	0	0	0	0	0
	h17	0,516	0,244	0,154	0,121	0,12
	h18	0	0	0	0	0
	h19	0,503	0,188	0,078	0,048	0,073
	h20	0	0	0	0	0
	h21	0,492	0,158	0,048	0,041	0,08

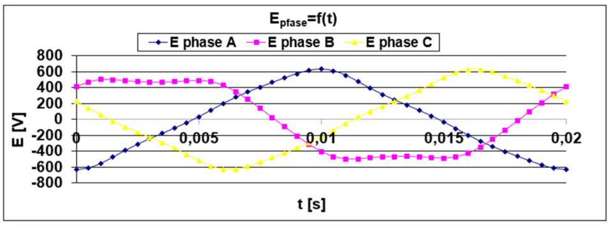

Fig. 7. Electromotive force curves (for the three phases and secondary winding)- load mode (at rated load).

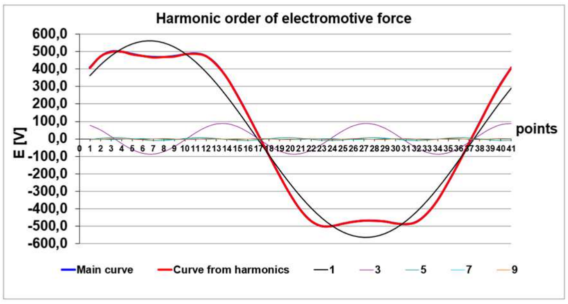

Fig. 8. Harmonic order of electromotive force (for phase B)- load mode (at rated load).

IV. CONCLUSIONS

This article gives information about different types of loads that cause non-sinusoidal currents to flow through the power transformer. A model of the transformer was created using a computer program based on the method of finite element method. In no load mode, the magnetizing current was determined and the harmonic order of the electromotive force also. Simplified vector diagrams of the transformer for active-inductive and active-capacitive type of load are created. In load mode of transformer (with active type of load and the area of the rated load of the transformer through a certain step) the harmonic order of the electromotive force. Based on this research and created phasor diagrams, a future researches of the transformer at different loads, phase difference and k-factor is possible.

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