Power transformers supplied by non-sinusoidal voltages or supplying non-linear loads- problems and solutions

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***Abstract*—This article aims to present the power transformers supplied by non-sinusoidal voltages or supplying non-linear loads. A number of factors determine the use of such transformers- the continuous increase of photovoltaic power station, the number of non-linear loads in our homes and industry has also grown significantly over the last decade. On the other hand, more and more consumers need a stable and sinusoidal supply voltage. All these factors pose a number of problems to be solved and affect the operation of the power transformers. The article present the types of non-sinusoidal loads and their influence on the operation of the transformer-increasing the losses and the temperature of the transformer. The types of transformers according to the type of load are presented. Various solutions (with their advantages and disadvantages) to reduce the impact of non-sinusoidal voltages or supplying non-linear loads.**

Keywords— power transformers, non-sinusoidal voltages, supplying non-linear loads, losses and the temperature.

I. INTRODUCTION

In recent decades, the issue of energy efficiency and the replacement of fossil fuels with renewable energy sources has become increasingly important. One way to do this is by putting into operation a set of photovoltaic power station [8], [11]. The quality and quantity of the electricity produced by them is directly dependent on the meteorological conditions and the type and quality of the component from which the photovoltaic power station is built - panels, inverters, batteries and filters. The diversity of consumers in the home and industry is just as great. They set a number of requirement for electricity, but with their own characteristics and parameters they influence it. One of the element through which the connection between the power source and the consumer is made - this is the power transformer. This transformer in turn can be supplied by non-sinusoidal voltages or supplying non-linear loads, which causes a number of problems [3], [5], [7], [10]. To solve these problems, there are many solutions aimed at the transformer itelf. There are many development (theoretical and practical of many scientist from around the world) to improve the quality of electricity produced by photovoltaic power station on the one hand, and on the other to reduce the negative impact of the load.

In the paper are presented the examples of non-linear loads, standards that define k-factor transformers, k-factor determination, the influence of non-linear loads on the transformer (increase in losses and temperature). Various solutions for the reduction of these influences are considered, observing the connection between the source of electricity and the transformer-load.

II. NON-LINEAR LOADS AND THEIR INFLUENCE

In recent years, there has been a significant increase in non-linear loads [2], [5], [6], [10] and the reasons for this are many. In our homes more and more appliances need precise control - washing machines, dishwashers, air conditioners, heat pumps or freezers, this is achieved through inverters. However, these inverters often have parameters that do not meet the required standard. On the other hand, computers and communication equipment are used in every home.

There is also an increase in non-sinusoidal loads in the industry. Today it is almost impossible to create an electric drive without an inverter. These electric drives, which are realized by means of asynchronous electric motors, DC motors or electric motors with permanent magnet, are used to drive water pumps, wood and metal processing machines, welding machines, rectifiers, fans and others.

Achieving higher energy efficiency and the use of more and more renewable energy sources also comes at a price. In the household and industry more and more luminaires are used, which are realized by means of LEDs, but they have specific requirement regarding the current supplying them. Here, too, controllers are needed, which in themselves are sources of harmonics. The need for communication between individual machines and equipment requires a huge amount of communication equipment. The need for a secure and in some cases autonomous power supply in many cases necessitates the use of UPS systems. Charging stations for electric cars, hybrid cars and other vehicles are no less of a problem.

All component of power systems engineering are subject to the harmful effect of non-sinusoidal loads. The losses of electric motors and transformers - thermal, mechanical and dielectric loses [5].

III. DETERMINATION OF K-FACTOR

The k-factor is the ability of transformers to operate at transformers supplied by non-sinusoidal voltages or supplying non-linear transformer that are non-sinusoidal. It is defined by many standards and organizations and regulations-IEEE Std 1100-1992, the standards 1561 and 1562 of Underwriter's laboratory, IEEE C57-110 (different editions) and other [2], [4], [5], [6]. In these literature sources are presented different methods for determining the k-factor based on the different losses in the transformer. In the article they are summarized and presented by expression (1) to expression (4). General explanations based on these literature sources are described.

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The k-factor depends on the magnitude of the current of each harmonic, which creates a non-linear load, but also the magnitude of the k-factor is greatly influenced by the sequence number of each harmonic. This dependence isrepresented by expression (1) in per-unit system (pu).

$$k\_factor = \sum_{h=1}^{h=h_{max}} I_h^2 h^2 \text{ [pu]}, \quad (1)$$

where h is the number of the harmonic, I_h is the part of the total load root mean square (rms) current for harmonic with number h.

Transformers with a k-factor rating can not be evaluated in use with harmonic loads, where the rms value of the current of any singular harmonic above tenth harmonic is bigger than one tenth from main harmonic of the rms operating current[2].

The k-factor determined by Underwriter's laboratory is using the result of the determination of the k-factor in per-unit system and the rated current of the transformer. When we replace the rated current of the transformer with k-factor it turns out expression (2).

$$k\_factor = \sum_{h=1}^{h=h_{max}} h^2 \left(\frac{I_h}{I_R} \right)^2 = \frac{1}{I_R^2} \sum_{h=1}^{h=h_{max}} I_h^2 h^2, \quad (2)$$

where h is the number of the harmonic, I_h is load root mean square (rms) current, in amperes, for harmonic with number h, I_R is the transformer's root mean square (rms) current at rated load and frequency.

The standard IEEE C57-110 defines and the factor of the harmonic losses-F_{HL} and it is represented by expression (3).

$$F_{HL} = \frac{\sum_{h=1}^{h=h_{max}} I_h^2 h^2}{\sum_{h=1}^{h=h_{max}} I_h^2} \quad (3)$$

The k-factor can be presented by the harmonic losses-F_{HL} and it is represented by expression (4).

$$k\_factor = F_{HL} \frac{\sum_{h=1}^{h=h_{max}} I_h^2}{I_R^2} \quad (4)$$

The F_{HL} is determined by harmonic order of the current, but not determined by relative magnitude. The k-factor determined by Underwriter's laboratory is determined by harmonic order of the current and by relative magnitude. For transformer, which is characterized by the harmonic order of the current is represented by a per-unit system - F_{HL} and k-factor are equal.

After the analysis of each specific load, it harmonic composition can be determined. But according to IEEE Std 1100-1992 transformers are divided into different types according to k-factor represented by expression (5) [6], to which they can eliminate - without overloading them [2]. The k-factor transformers must not work unloaded or lightly loaded. If k = 1 means that the load is resistive.

$$k = 1, 4, 9, 13, 20, 30, 40, 50 \quad (5)$$

The different transformers according to the k-factor are presented on Fig.1 [2], [5].

Load	K-factor
Incandescent lighting (with no solid state dimmers) Electric resistance heating (with no solid state heat controls) Motors (without solid state drives) Control transformers/electromagnetic control devices Motor-generators (without solid state drives)	K-1 K-1 K-1 K-1 K-1
Electric-discharge lighting UPS w/optional input filtering Induction heating equipment Welders PLC's and solid state controls (other than variable speed drives)	K-4 K-4 K-4 K-4 K-4
Telecommunications equipment UPS without input filtering Multi-wire receptacle circuits in general care areas of health care, facilities and classrooms of schools, etc. Multi-wire receptacle circuits supplying inspection or testing equipment on an assembly or production line	K-13 K-13 K-13 K-13
Mainframe computer loads Solid state motor drives (variable speed drives) Multi-wire receptacle circuits in critical care areas and operating/recovery rooms of hospitals	K-20 K-20 K-20
Multi-wire receptacle circuits in industrial, medical, and educational laboratories. Multi-wire receptacle circuits in commercial office spaces Small mainframes (mini and micro)	K-30 K-30 K-30
Other loads identified as producing very high amounts of harmonics (especially in higher orders)	K-40

Fig. 1. Different types of k-factor transformers

IV. PROBLEMS OF POWER TRANSFORMERS SUPPLIED BY NON-SINUSOIDAL VOLTAGES OR SUPPLYING NON-LINEAR LOADS

As described so far, the k-factor determines the number and magnitude of the current of the corresponding harmonic. A non-linear load, however, generates multiple harmonics. In the analysis, the problem is which harmonics to take into account. There are several approaches - analysis of harmonics until the fifteenth twenty-fifth very rarely until the fifties. For the same non-linear load, a different end result can be obtained - according to which harmonics with which numbers will be included in the calculation of the k-factor. It should be have in mind that multiple current with a very small amplitude but with a high harmonic number can seriously change the final result in determining k-factor [5]. The influence of non-linear loads on the transformer will be considered in detail. Because a non-linear load gives rise to many factors (thermal, mechanical and dielectric loses; size, cross section and type of neutral conductor; type and size of insulation materials; possibilities for using the capacity of the transformer), which in turn have a significant impact on the service life of the transformer, and it is very important[1].

A. *Losses in the Transformer at non-linear load*

As the non-linear loads increase, so do the losses in the transformer. They can be divided into several types-losses in the transformer's windings, winding eddy-current losses, other stray losses and dielectric loses [4], [6], [7], [9], [10]. A methodology based on [4] and presented by expression (6) to expression (9). was used to recalculate the losses. In non-sinusoidal load, due to the presence of harmonics with different numbers, the total current is represented by expression (6).

$$I = \sqrt{\sum_{h=1}^{h=h_{max}} I_h^2} \tag{6}$$

The losses in the transformer's windings are represented by expression (7).

$$P_I = P_{I\_R} k_{LOAD}^2 I^2, \tag{7}$$

where P_{I_R} are the losses in the transformer's windings at rated load and frequency, k_{LOAD} is is the load coefficient with respect to the rated load value.

The winding eddy-current losses are represented by expression (8).

$$P_{EC} = P_{EC\_R} k_{LOAD}^2 \frac{\sum_{h=1}^{h=h_{max}} I_h^2 h^2}{\sum_{h=1}^{h=h_{max}} I_h^2}, \tag{8}$$

where P_{EC_R} are the winding eddy-current losses at rated load and frequency.

The other stray losses are represented by expression (9).

$$P_{OSL} = P_{OSL\_R} k_{LOAD}^2 \frac{\sum_{h=1}^{h=h_{max}} I_h^2 h^{0.8}}{\sum_{h=1}^{h=h_{max}} I_h^2}, \tag{9}$$

where P_{OSL_R} are the other stray losses at rated load and frequency.

Regardless of the different origins of the different types of losses, they emit in the form of heat.

B. *Increasing the temperature of the transformer and transformer's capacity*

The presence of higher harmonics in the current flowing through the transformer leads to an increase in temperature [5], [7], [10]. It is accepted that the losses in windings caused by the increase in temperature are proportional to the sequence number of the harmonica. The more high harmonics there are, the more the load on the transformer must be reduced. This dependence is presented on Fig.2 [5].

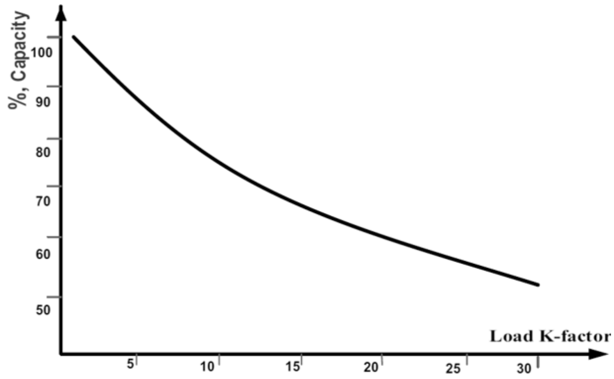

Fig. 2. Load capacity of the transformer according to the $k_{\text{-factor}}$ of the load.

Additional heating of the insulation of the transformer windings represented by expression (10) and expression (11) [5].

$$\Delta\tau = 0.6\tau_n \sum_{h=2}^{h=h_{max}} I_h^2 k_{rh}, \tag{10}$$

$$k_{rh} = \sqrt{h}\tau_{\text{n}}, \tag{11}$$

where τ_{n} is insulation temperature of transformer windings at sinusoidal current

C. *Other problems with transformers transformers supplied by non-sinusoidal voltages or supplying non-linear loads*

At current flowing through the transformer with a strong harmonic order, a current exceeding the nominal current flows through it neutral conductor - it is several hundred times greater than the phase current. In the secondary winding of the transformer is observed skin effect. To reduce it influence, the secondary winding consis9 of several transposed conductors with a smaller cross section, which increases the total surface area of the layers of all conductors [5].

V. Solutions transformers supplied by non-sinusoidal voltages or supplying non-linear loads

There are two approaches to selecting and designing a power transformer whose current have high harmonics. One is to use a standard transformer but with significantly more power. However, this is unprofitable because, how is presented on Fig.2, with a k-factor greater than thirty, the capacity of the transformer may decreases by more than fifty percent. Given that the power of power transformers reaches several hundred megavolt amperes [2], this is economically unprofitable. Another possibility is the use of standard insulation materials, but of a higher temperature class, but increasing only the temperature resistance of the transformer generally leads only to an increase in it cost [5]. The second approach is not to resize the transformer, but to significantly reduce the harmonics or suppress their influence through advanced design solutions. For example, when using hybrid high-temperature insulation, thereby increasing the temperature range and the strength of the structure in mechanical terms. It also reduces the ventilation duct for cooling between the layers, thus the safe achieves better strengthening of the winding's coils [5].

For future research, a power transformer is presented, presented on Fig.3. The low (LV) and high voltage (HV) windings are divided into a different number of sections (LV-3 and HV-4). In this way it will be possible for the winding of each phase to be located on different cores of the transformer. The transformer will be supplied with a voltage that is non-sinusoidal (by setting non-sinusoidal current). Their formation is presented on Fig.4 for k_{factor}=15.65 (I_{h1}=0.7, I_{h3}=0.2, I_{h5}=0.03, I_{h7}=0.02, I_{h9}=0.05). On Fig.5 are presented the value of the different harmonics.

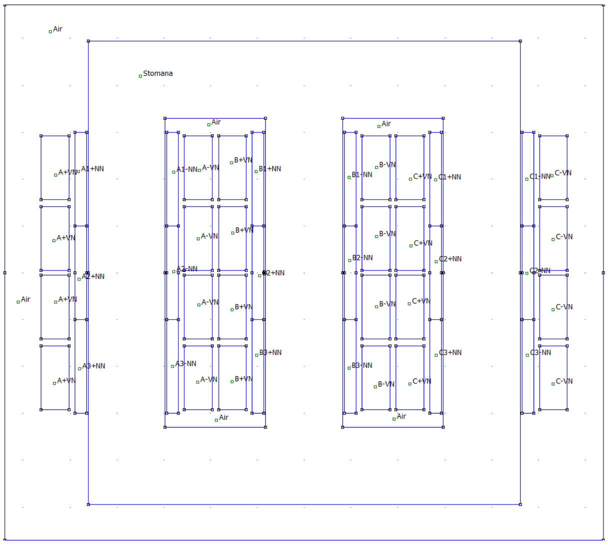

Fig. 3 Construction of a power transformer for future research.

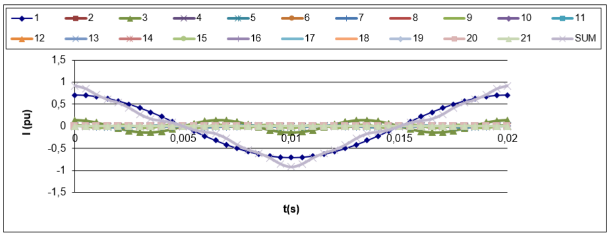

Fig. 4. Harmonic order of the currents for the formation of k_{factor}= 15.65.

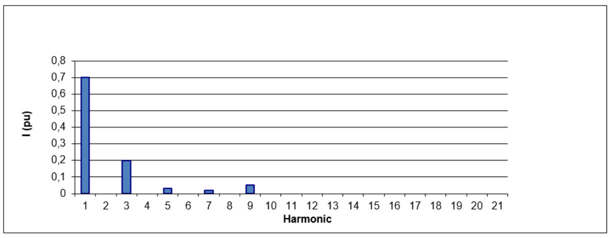

Fig. 5. Value of the different harmonics.

VI. Conclusions

This article present power transformers supplied by non-sinusoidal voltages or supplying non-linear loads. The reasons for the increase of non-sinusoidal loads in recent years are considered and the different types of such loads are described. Various methods for determining the k-factor of a transformer according to existing standards and regulations are presented. Different types of transformers are predicated according to the k-factor and the loads that cause this k-factor. A methodology for determining the losses in different part of the power transformer under non-sinusoidal loading is presented. The influence of the k-factor on the cross section of the neutral conductor, temperature, and capacity of the transformer is analyzed. A plan for future modeling of a power transformer and assembly of the k-factor is presented.

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