ANALYSIS OF THE POWER TRANSFORMER OPERATION SUPPLYING A COMBINED NON-LINEAR LOAD IN THE PUBLIC SECTOR - PART II: INFLUENCE OF THE CURRENT HARMONICS

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Abstract: *Much of the technical equipment in energy, industry, commerce and the public sector (electronic equipment, electric motors, furnaces, chargers, uninterruptible power supplies, etc.) are inherently non-linear loads and are sources of harmonic distortion of currents. Non-linear loads adversely affect all components of the power system: they increase losses in transformers and electric motors by thermal loading their windings, increasing dielectric and/or mechanical losses and generally reduce the efficiency of the electrical system. The paper deals with operation of a power transformer that supplies combined non-linear load in a public building.*

KEYWORDS: *ENERGY CONSUMPTION, ENERGY EFFICIENCY, POWER SYSTEM HARMONICS, POWER QUALITY, TRANSFORMERS, ENERGY MEASUREMENT, SMART GRIDS*

1. Introduction

The standard transformers have low temperature tolerances when handling non-linear loads. Until recently, the only solution to power these ones was to choose a larger by power transformer to cope with the additional heating of the windings and the steel core (these states are most often caused by harmonics with number ν = 3, 5, 7, 11 and 13). This solution is economically and technically unacceptable anymore. The degree of handling of such loads and the poor operating results have not been adequately investigated, but it is known that in case of continuous duty with overheating of transformer insulation, the lifetime of the transformer is shortened.

The durability D (in units of time) decreases twice with each temperature rise θ by $\Delta\theta$ about the permissible temperature value for a given insulation class. It has been experimentally found that for Class A insulation $\Delta\theta = 8K.$ For example, at 105^{0}C the insulation is durable $D = 16$ years, at 113^{0}C - $D = 8$ years, at 121^{0}C - $D = 4$ years, etc. In practice, this method of calculation is called the Montzinger rule. For other classes of insulation, $\Delta\theta$ has other values; e.g. for Class B $\Delta\theta = 10K,$ for Class H - $\Delta\theta = 12K,$ etc.

Other disagreeable effects of harmonics are: overheating of neutral conductors and panels, circuit breaker disconnection, grid voltage disturbance, equipment failure, electrical fires, malfunction of controllers, and communication line disruptions.

2. Technical considerations

Electricity is essentially a specific commercial product and as such it must have the necessary qualities. The widespread concept of Power Quality (PQ) means the uninterrupted delivery of electricity to consumers, with grid voltage parameters within certain limits allowing the normal operation of the grid-connected loads. Today, PQ is even more important for two main reasons. They are related to the presence of many modern types of loads, which on the one hand need a good PQ and, on the other, make it worse due to the nature of their action. As an example, it is sufficient to mention the impulse power supplies used in most computer, communication and many other electronic devices, control units of DC and AC motors with variable speed, luminaires, etc. There are numerous areas of human activity where the deterioration of PQ is associated with significant financial losses, notably in continuous production in the industry (according to statistics in the European Union, annual losses in the industry and the public sector due to poor electricity quality are close to € 10 billion The responsibility for the quality of electricity is shared between producers and transmission companies on the one hand and consumers on the other.

A significant and steadily increasing part of the loads, with different functional features, are non-linear, which causes non-sinusoidal currents. This trend makes it increasingly urgent to establish international criteria and a system for assessing the impact of harmonics, but also for recommendations for designers of electrical equipment and technical equipment, because harmonics have long been not a local problem, but rather a global one.

The most significant negative effects of harmonics can be attributed to:

- Zero conductor overload on three-phase groids. The sum of the main harmonic currents of the three phases flowing through it is 0, while the sum of harmonics is not 0 and may even exceed the phase current. According to research, the current in the zero conductor of the electrical grids in public and commercial buildings is 1.5-2 times higher. Undoubtedly, this should be taken into account when designing grids.
- The energy losses in the transformers are increasing, which means additional heating and shortening of the service life.
- Incorrect activation of safety relays and contactors in phases is possible due to increased current amplitude.
- Many control electronic units switch off when the mains voltage goes through zero. In the presence of harmonics, erroneous switch off can occur.
- It is known that the neutral conductor of a three-phase system, which feeds single-phase harmonic-generating consumers, may have a load greater than that of phase conductors (e.g., long three-phase lines, fluorescent lamps without harmonic filters, or a three-phase line that supplies a single-phase switchboard for computers and other office equipment). In such cases, it is necessary to check the cross section of the neutral conductor by collecting the current imbalance between the three phases and the sum of the currents in the three phases of the harmonic components multiples of 3. It is advisable to use four-pole circuit breakers with protection and on the neutral conductor.

The quality of electricity as a specific commercial product is regulated by many standards. For example, EN 50160 "Voltage characteristics of electricity supplied by public distribution systems" is limited to the quality of electricity in low and medium voltage grids and sets acceptable limits for all voltage parameters, i.e. limited to supply facilities without assessing the state of supply and/or impact of loads. There is a need for practical guidance already in the design (or reconstruction) part of energy facilities to address these issues. Such recommendations are given in IEC 60076-7: “Power transformers. Part 7: Loading guide for oil-immersed power transformer ”. European manufacturers and consumers follow the recommendations of IEC standards [1]. Although a member of the IEC, the US has its own standards in this area [2]. UK complies with the strict requirements of their G 5/4 standard (for example, direct connection of inverters with a power exceeding 40 kW is not permitted). Basic evaluation criteria, guidelines and recommendations for limiting the harmonics returned to the grid by non-linear loads are also given in IEEE 519-

1992: “Recommended practices and requirements for harmonic control in electrical power systems” [1, 3, 4]. The standard is practically useful for industrial and public three-phase consumers. Non-linear loads in single-phase grids are beyond the scope of the standard. Their poor impact is difficult to assess because it has a cumulative effect. In [5, 6] a typical composition of the complex load for the domestic sector is given: induction motors with low power - 35% and lighting - 65%.

In a three-phase, four-wire system, the zero conductors can be strongly affected by non-linear loads connected to single-phase circuits with a voltage of 230 V. In a four-wire grid with single-phase non-linear loads attached, the odd harmonics multiples of the third harmonic: third, ninth, fifteenth, etc. - are not zeroed but summed to zero conductor. In systems with many single-phase non-linear loads attached, the current in the zero conductor may in fact exceed the phase current. The result is excessive overheating. There are no current limit switches in the zero conductor. Higher current in the zero conductor can also cause additional voltage drop. Zero bars and conductors are generally sized to carry the full value of the rated phase current. They can be overloaded due to an additional sum of current harmonic multiples of three flowing through the zero conductors [7]. For this reason, the sizing of electrical equipment in industry and the public sector in view of the effects of harmonics should be approached responsibly and their selection adjusted to the full power factor taking into account the presence of harmonics:

$$PF = \frac{\cos\varphi}{\sqrt{1 + THD_I^2}} \tag{1}$$

Transformers are sensitive to current harmonics because all current harmonics generated by non-linear loads flow through them, exerting different effects simultaneously, all with the result of overheating:

- Increasing losses from stray currents in the windings, proportional to the square of the current and the square of the frequency (the main reason for overloading of transformers by harmonics).
- Increasing the losses in the active resistance of the windings as a result of the current flowing, increasing the active resistance of the skin effect at high frequencies.
- Increasing losses in the steel of the magnetic cores.

The transformer industry is considered to be one of the most conservative, although there is also evolutionary rather than revolutionary development. The main directions are reduction of operating and production costs, application of modern structural materials, increase of reliability and improvement of the used insulating and magnetic materials. Transformers become more economical and energy efficient, more technically advanced and become smart. The new smart solid state transformers have a computer chip that can quickly and efficiently regulate the voltage. This allows efficient load management and optimization of electricity consumption. Such transformers can vary the voltage depending on the consumption, include wind turbines, photovoltaic panels or diesel generators in the home grid. Grid congestion will no longer be a problem and energy will be redistributed, increasing it in low cost hours. Smart transformers can combine several energy sources with different characteristics, starting with a low-voltage grid and ending with a diesel generator if needed. Such a grid would provide uninterrupted power supply without additional complex equipment. In addition, the voltage will be maintained with a view to the stable operation of household consumers. In the US, tests with such smart transformers have been conducted, with up to 3% savings in electricity. One feature of smart grids is the ability to "communicate" between the energy system and the energy provider to provide uninterrupted power supply in an emergency.

Experts have identified the following advantages of these new transformers [9, 10]:

- - Weight reduction and reduction in overall dimensions to almost 40%. This enables the use of smart transformers in operating substations without further structural modifications, under light transport conditions.
- - Reduction of up to 90% of nominal load losses, which significantly increases the efficiency.
- - The new transformers have the capability of limiting the short-circuit current, and this in emergency modes would protect the power system.
- - At the expense of significantly reduced reactance, the transformer without regulation will provide voltage stabilization.
- - High resistance to overload without damaging the insulation.
- - Significantly low noise levels at work.

In addition, these transformers are environmentally friendly and fireproof. Specialists from Toshiba, Mitsubishi Electric and General electric are working in this field to accelerate their deployment [7, 8, 9, 10].

In order for the K-factor to be correctly determined, each load must be identified by its harmonic spectrum and amplitudes. The choice of acting harmonics is a problem in determining the K-factor of the load. It is important to know that for the same non-linear load, the calculations may vary depending on which harmonics we choose to look at. Even small harmonic currents with a high sequence number substantially alter the end result. In the case of combined power supply of different types of non-linear loads, the K-factor of the power transformer is selected equal to the largest of the non-linear loads (otherwise the operation of the transformer is unreliable and unsafe). The advantage of using K-transformers is that they are usually more energy efficient than using a conventional transformer with higher power and lower load. The choice of a K-transformer for a particular non-linear load, regardless of power, does not mean that it is protected from the harmonic components of the voltage (causing the magnetic circuit to heat up), from mechanical stresses or from the harmful influence of the occurring resonance phenomena.

The approach to determining the K-factor used in Europe and the US is fundamentally different. The European standards EN 50464-3 and EN 50541-2, respectively for oil and dry three-phase transformers, give the following formula:

$$K = \left[1 + \left(\frac{e}{1+e}\right) \times \left(\frac{I_1}{I_\nu}\right)^2 \times \sum_{\nu+2}^{\nu=N} \left(n^q \times \left(\frac{I_1}{I_\nu}\right)^2\right)\right]^{0.5} \tag{2}$$

where: e is the ratio between the 50 Hz sinusoidal winding losses and the DC losses with the same effective value. If not available as a catalog value, it can be assumed to be 0.1; I_1 is the effective value of the first harmonic current, and I_ν - the higher harmonic currents; ν - harmonic number; q is a constant that depends on the design of the windings. If not available as a catalog value, 1.7 for circular or rectangular coil transformers and 1.5 for low voltage foil winding transformers may be considered.

The K-factor calculated in this way takes values between 1 and 2. The maximum continuous power that a transformer subjected to non-sinusoidal currents can be loaded is reduced by dividing its nominal power by the K-factor. In fact, resizing occurs because a transformer with a higher rated one must be selected for a given operating capacity. From the review made so far, it becomes clear how important it is to identify the location, the nature of the manifestation and the influence of different harmonics on the entire power supply grid. In this case, the purpose is to analyze the operation of a power supply transformer for a public-sector object: a public building with non-linear loads.

3. Research results

In [8], a schematic diagram and measurement results were presented to establish the levels of harmonics in operation. Due to the possibly poorly designed connection to the individual phases and the combined manifestation of non-linear loads, the uneven load of the three phases was found. For the sake of complete evaluation, we decide to make a K-rating of the load, to measure harmonic levels, to determine the full power factor and to detect errors in the reading of electricity. Analytical evaluation of the obtained results will show us whether the investment in an energy efficient transformer is justified. This would reduce energy losses and reduce environmental impact, as well as reduce repair and maintenance costs.

The power transformer in question supplies various non-linear loads and has the following data: type TMX 630/20-10/0,4 kV, $u_k\% = 4.39\%$, Dy$_N$5, IP 54, cooling system ONAN. Consumption of energy consumption is two-tariff, low voltage side.

The electrical energy quality analyzer METREL MI 2292 has been used to measure the electrical quantities, with an observed period of 48 hours, counting every 15 minutes. Power, power consumption, harmonic current profile and voltage up to $\theta = 25$ and $\cos\varphi$ are observed for each phase. Consumers in the building are a combined non-linear load for the transformer. The load rating and installed capacity are distributed as follows: lighting - 32 *kW* installed power, K-4; UPS without input filters - installed power 2 *kW*, K-13; servers, computers and peripherals with a total installed capacity of 121.75 *kW*, K-20. There is no indication of the nature of the load on the part of residential customers connected to the separate phases.

The K-rating of the particular combined load is performed according to the recommendations in [1, 2, 5, 8]:

$$P_{LOAD} \times I_{LK} = Index \cdot of \cdot Load \cdot K - ratings \tag{3}$$

Lighting: $32 \times 25.82 = 826.24$

UPS without input filters: $2 \times 57.74 = 115.48$;

Servers, computers and peripherals: $121.75 \times 80.94 = 9854.445$.

Or the average value of the load index is obtained as follows:

$$Total \frac{kVA_{I_{LK}}}{P_{\sum LOAD}} = I_{LKaverage} \tag{4}$$

$$I_{LKaverage} = \frac{10796.165}{155.75} = 69.32$$

Since the power supply grid is already in place, the evaluation of the load rating is “post factum”: the recommended transformer should be less than 630 kVA and K-20.

After processing the data from the specialized equipment, the instantaneous values of the three phase currents can be observed, Fig. 1, and the harmonic composition of each, Fig. 2.

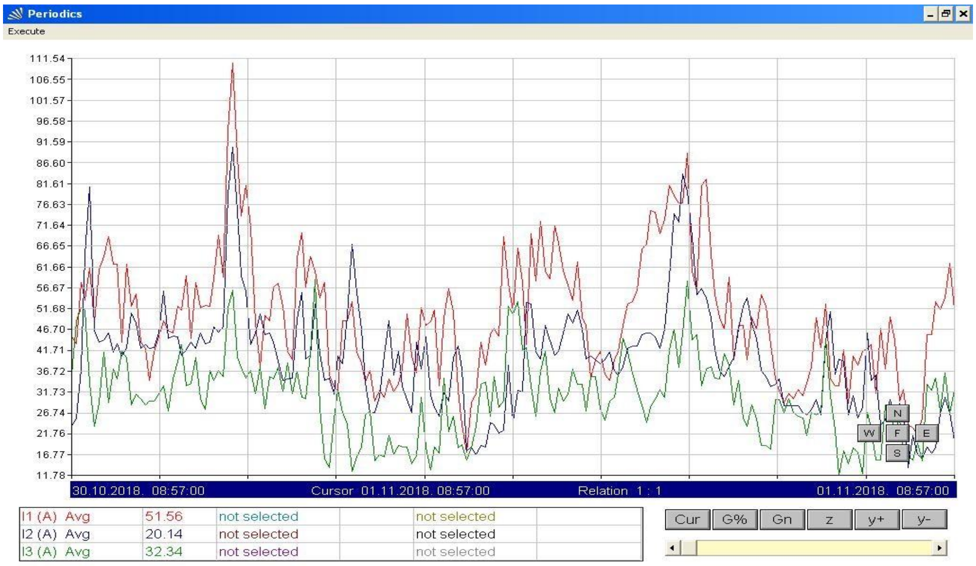

Fig. 1. *Instantaneous values of the observed currents in the three phases.*

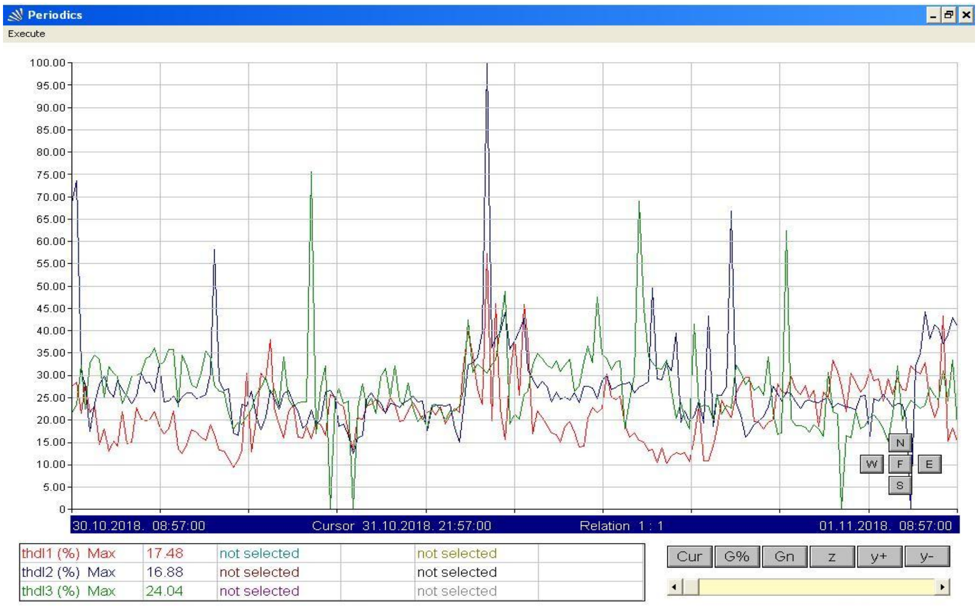

Fig. 2. *Harmonic composition of the three phase currents.*

The data analysis shows uneven loading of the individual phases, close to the limit of moment asymmetry and high harmonic levels, Fig. 3. Phase B is the most disadvantaged: the busiest and with the overall harmonic composition for the observed period $THD_{I2} = 36.94\%$. For this reason, we observe the change in the current and its harmonic composition, Fig. 4.

For a clear understanding of the problem (at what times during the whole observed period the influence of which harmonics is the most unfavorable) and to determine the frequency of manifestation of the individual harmonics with a cumulative assessment of their influence, we solve the constructive Pareto diagram, Fig. 5. The analysis shows the following: the hours during which highly non-linear loads are included are from 8:30 am to 1:00 pm and 1:15 am to 6:15 am; capacities for daytime consumption are in the range 38.8 *kW* up to 92.45 *kW*; capacities for nighttime consumption with a strong non-linear load are in the range 30.62 *kW* up to 40.12 *kW*. With the highest values, harmonics with numbers $\nu = 3,5,7,9,11$ are above the recommended values.

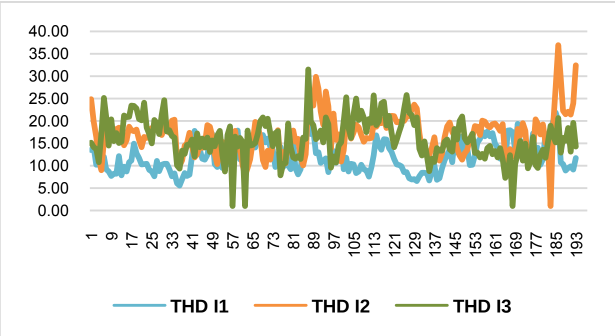

Fig. 3. *Total harmonic distortions for all three currents* $THD_I\,\%$.

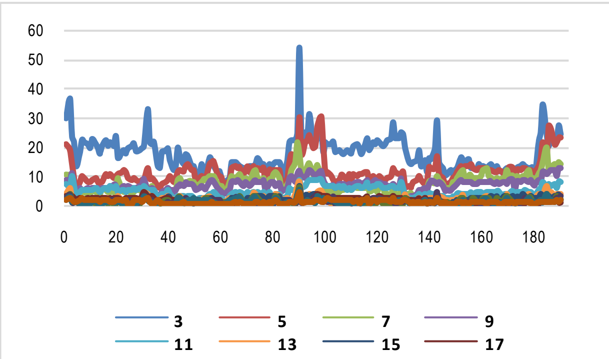

Fig. 4. *Variation of harmonic components (* $\nu = 3$ *to* $\nu = 25$ *) of the current of the second phase* I_2*, [A].*

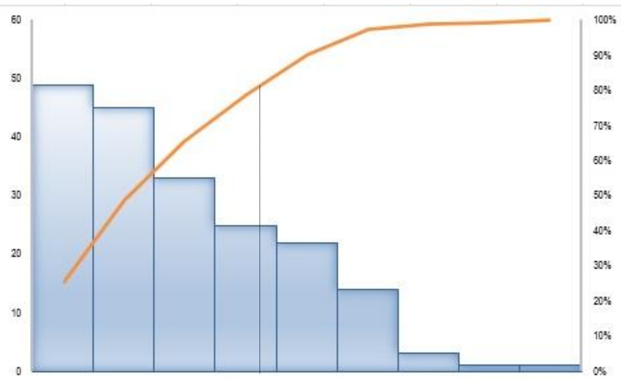

Fig. 5. *Pareto diagram for the distribution of data according to the frequency of manifestation with the cumulative line.*

4. Conclusions

The treated transformer supplying the combined non-linear load operates at load level $\beta = 4.86 \div 14.67\%$ at $THD_{I1\max} = 39.88\%$, $THD_{I2\max} = 68.45\%$, $THD_{I3\max} = 64.45\%$ or there is a classic case of a oversized transformer. In case the track is to be reconstructed and other single-phase users will be connected to the individual phases, it is recommended to choose a transformer with less power and a K-factor 20 with a uniform phase load.

Since transformers are very expensive equipment and in order to avoid the constant inconvenience for consumers of wasting money and energy, it is necessary to determine the winding losses at going current values. Losses in the windings due to eddy currents are generated due to skin and proximity effects and have not yet been determined. It is recommended to use filters to suppress the influence of the harmonics.

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