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INTEGRATED METHOD FOR OPTIMIZING THE PERFORMANCE OF ELECTRICAL EQUIPMENT UNDER THE INFLUENCE OF UNBALANCE AND HARMONICS DISTURBANCES

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Abstract: *Transformers and induction motors are fundamental components of modern power systems, whose performance can be significantly affected by the presence of unbalance and harmonics in electrical networks. These disturbances generate additional energy losses, reduce operational efficiency, and may shorten the lifespan of equipment. This paper presents an innovative integrated method that combines theoretical analysis, numerical simulations, and experimental data to assess and optimize the performance of electrical equipment under disturbed operating conditions. The novelty of the method lies in the integration of multiple disturbance factors into a unified model, capable of accurately diagnosing issues and proposing customized solutions. The validation of the method has demonstrated a reduction in energy losses by up to 15%.*

Key words: *unbalance, harmonics, power quality, transformers, induction motor, new method, integrated.*

1. INTRODUCTION

Voltage and current unbalances, along with harmonics, represent major challenges in the efficient operation of modern electrical equipment. These disturbances are frequently caused by the use of nonlinear loads, improper network connections, and systemic faults. In this context, electrical equipment such as transformers and induction motors become vulnerable to energy losses, overheating, and a significant reduction in lifespan.

Unbalances are disturbances analyzed only in the case of three-phase sinusoidal systems. For these systems to be considered symmetrical, the three phasors must be successively phase-shifted by 120° and have equal peak to peak values. The main causes of unbalance include unbalanced loads, network faults, improper connections, the influence of other disturbances, and inadequate equipment maintenance [1-5].

To define the level of distortion, characteristic indicators, specific to each type of disturbance, are used. In the case of unbalanced loads, there is a difference between the terms addressed by *American standards* [6] and those by *European standards* [7]. The European standard is based on the division of the three-phase system into three single-phase systems, resulting in indicators called the negative unbalance factor k^- and the zero unbalance factor k^0. The negative unbalance factor is the most important indicator in measuring unbalances, with clear limits established at 4-5% for voltage and 20-30% for current [8]. The issue with this standard is that it involves purely sinusoidal quantities, a condition that cannot be met in reality. In the evaluation of unbalances through European standardization, only fundamental quantities are considered [9]. The American standard considers the root mean square (*RMS*) values of the three phases, creating a single unbalance indicator k_s as the maximum among the unbalances in the three phases. When analyzing a current system, American standards do not provide a conclusive response due to the very high harmonic distortions present in the current. Numerically, differences of up to 20% have been found between *European* and *American standardizations* [9].

Harmonics, on the other hand, represent distortions in the waveform of current or voltage, leading to inefficient operation of electrical components. These correspond to a

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deforming or periodically non-sinusoidal regime, characterized by the deviation of the wave from a pure sinusoidal form [1-4, 8]. To define the harmonic level, a series of characteristic terms are used, determined by decomposing a periodic signal into harmonic oscillations. Many of these indicators are well-established in the field of engineering, including *Root Mean Square, average value, crest factor, form factor, total harmonic distortion, distortion factor, harmonic loss factor, and derating factor* [4, 10-12].

In the determination of the harmonic level, there is a difference between *European* and *American standardization* regarding the *derating factor* definition. According to American standards [13-15], the term *"K-factor"* is defined, while European standards [9] defines the term *"Factor K"*. Although these two factors have very similar names, they have different definitions, with *Factor K* also considering certain constructive data of the secondary winding conductor [4]. The values of these derating factors are numerically different. *"Factor K"* is a "total" derating factor (allowing for the direct assessment of maximum power), whereas *"K-factor"* varies for each harmonic (the derating level of the transformer can be determined indirectly using their value) [9]. Numerically, the factor calculated according to the American standard will have a higher value than in the European standard since its calculation does not include the constructive data of the equipment. Thus, the *K-factor* is a more general derating factor, with a larger margin of error compared to *Factor K* [4,16].

Existing studies have addressed the effects of unbalances and harmonics separately, but their integrated approach is rare, despite being necessary. This paper aims to address this gap by developing an integrated optimization method that considers the simultaneous influence of these disturbances on the performance of electrical equipment. The objective is to identify efficient and practical solutions to reduce the negative impact of these factors. The study is based on a combination of numerical simulations, experimental, and theoretical analyses, creating a comprehensive framework for optimizing the operation of electrical equipment under disturbed conditions. The importance of this research is emphasized by the need to improve energy efficiency and reduce the negative impact on electrical infrastructure. Thus, this paper provides a valuable tool for network operators and electrical equipment designers.

2. THE EFFECT OF UNBALANCES ON ELECTRICAL EQUIPMENT

This chapter provides a synthesis of the effects of unbalances on modern electrical equipment. Practical examples and experimental data have been analyzed from scientific literature to gain a comprehensive understanding of the unbalance problem. The main identified effects include decreased efficiency, increased losses and temperature, as well as variations in torque and slip.

2.1 Effect on Transformers

Transformers are one of the main components of modern electrical networks, ensuring the efficient transfer of energy between different voltage levels. However, transformers are highly sensitive to unbalances, which can generate additional magnetic flux in their core. That extra fluxes cause extra copper and iron losses, increasing the operating temperature and accelerating the degradation of insulating materials.

One of the first aspects analyzed is the influence of different winding connections in three-phase transformers. This design detail leads to different outcomes, a topic that has been studied both experimentally [17,18] and through simulations using MATLAB Simulink [19]. The analysis of physical equipment revealed that the Δ/Δ connection provides the best results in reducing the unbalanced level, with an unbalance level of 5%. However, numerical simulations indicated that Y/Y connections are the most effective in attenuating unbalance.

The most widely used indicator for determining the level of unbalance is the Voltage Unbalance Factor (*VUF*), whose increase leads to detrimental effects. The following section presents numerical results regarding the negative effects of unbalance.

For a 100 kVA transformer with a *VUF* of 12, core losses increased by 22.7%, while copper losses rose by 18.6% [20]. For a 1000 kVA transformer with a *VUF* of 9.2, stray losses increased from 695.53 W under normal conditions to 750.44 W [21]. These loss increases are attributed to rising magnetic flux, which becomes unevenly distributed within the transformer core. Another distinction of the loss increase can be made based on the amplitude and phase shifts of the currents in the three phases. In the simulation of a 315 kVA transformer, the highest losses, reaching 290.84 W, occurred when phase A was in overload, phase B was at nominal load, and phase C was in underload, resulting in the largest numerical differences between phases [22].

Other important aspects to consider include the incorporation of certain environmental factors in the calculation of unbalance levels. Factors such as solar irradiation levels, ambient temperature variations, and exposure to high humidity have been shown to negatively affect the operating conditions of equipment [23,24]. The location of unbalances, whether in the primary or secondary winding, also determines differences in their impact, with studies demonstrating that secondary load unbalance has a significantly greater effect [25].

2.2 Effect on Induction Motors

Induction motors, essential components of electrical systems, are highly vulnerable to the effects of unbalances. The unbalanced loads induce negative-sequence currents, which generate torque pulsations. These pulsations cause fluctuations in rotation speed, leading to unstable operation, reduced efficiency, high temperatures and losses.

As in the case of transformers, the most used indicator is the Voltage Unbalance Factor (*VUF*). An increase in the unbalance factor leads to a decrease in motor efficiency, as illustrated in Fig. 1. For a 3 HP motor, a noticeable efficiency reduction was observed even at low loads [26,27]. If the Total Harmonic Distortion remains constant while only the negative-sequence component varies, conditions of undervoltage or overvoltage will occur. Motor efficiency decreases under undervoltage conditions and increases under overvoltage conditions, while the power factor exhibits the opposite behavior [28].

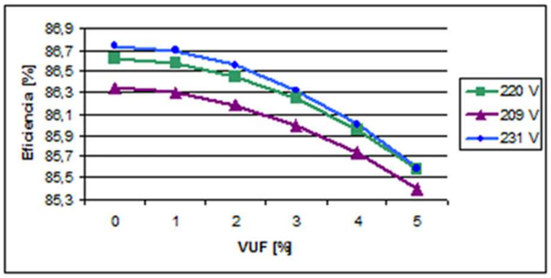

Fig. 1. Variation of a 3HP Induction Motor Efficiency as a Function of VUF [26]

Analyzing the losses, it was observed that stator winding losses are not dependent on the motor load and increase proportionally with the negative-sequence voltage component, while rotor losses increase proportionally with the positive-sequence component. An analysis conducted on two induction motors of 132 kW and 220 kW with a *THD* of 8.45% found that for the 132 kW motor, rotor losses increased by 23%, while stator losses increased by 18%. For the 220 kW motor, rotor losses increased by 18%, while stator losses increased by only 2% [29]. Analyzing other situations of unbalance, it was found that as the unbalance level increases, the overall losses also increase.

Voltage unbalance also affects the mechanical characteristics of the motor. A *VUF* of 6% determines the lower limit of the starting torque, which decreases by up to 25% compared to the case of a symmetrical voltage supply. Additionally, the pull-out torque experiences a reduction of approximately 70% under unbalanced conditions, which lowers the operational safety margin of the motor. As a result, rotor slip increases, leading to additional rotor losses. Regarding thermal influence, a *VUF* of 4% causes a temperature rise of 15°C [30,31]. By testing all types of unbalances, it was concluded that temperature increases in all cases, except when one phase is under voltage while the other two remain at nominal value, in which case the temperature decreases [32].

A new indicator has been introduced in the scientific literature for a more accurate evaluation of losses. This term is called the unbalance coefficient, denoted as *f*, and is defined as the ratio between the *VUF* and the angle $cos(\theta)$ between the positive-sequence and negative-sequence components [33].

$$f = \frac{VUF}{\cos(\theta)} \qquad (1)$$

3. THE EFFECT OF HARMONICS ON TRANSFORMERS

This chapter provides a synthesis of the effects of harmonics on transformers. Practical examples and experimental data have been analyzed from specialized scientific literature to gain a comprehensive understanding of harmonic issues. The main identified effects include decreased efficiency, increased losses and temperature, and a reduced lifespan.

It has been demonstrated that current harmonics have a greater impact on total losses than voltage harmonics [35]. An example of loss analysis was conducted on a 100 kVA three-phase transformer, where for a *THDi* of 12%, copper losses increased from 1575 W to 1711 W, eddy current losses rose from 50 W to 63.34 W, and magnetic flux density increased from 0.424 T to 0.466 T [36].

A key aspect explored in studies is the influence of each harmonic component on transformer load unbalance. It has been found that the fundamental harmonic (H1) has the greatest impact, accounting for 84% of the total neutral current. Third-order harmonic multiples are the next most significant, contributing substantially to the increase in neutral current and load unbalance. Other harmonics, particularly the 5th , 7th , and 10th orders, also have considerable effects, though with much lower amplitudes. Analyzing the contribution of each harmonic individually, it was determined that not only the amplitude of the harmonic should be considered but also its angle and phase [37-39]. Losses increase when harmonics are in phase (0°) and reach their minimum when they are in phase opposition (180°). For a voltage *THD* level of 21%, the difference between minimum and maximum losses in this scenario is 18%. [40].

New terms have been introduced in the specialized literature to estimate disturbances alongside the well-established indicators. The Equivalent Current Index (*Ieq*) converts the effect of harmonic currents into fundamental current terms. *Ih* represents the amplitude of the harmonic component of order *h*. The *Harmonic Impact on Transformer Loading (HITL)* measures the percentage increase in transformer loading due to the presence of harmonic currents [41].

$$I_{eq} = \sqrt{\sum_{h=1}^{\infty} (I_h^2 \cdot h^2)} \qquad (2)$$

$$HITL = \frac{I_{eq}^2}{I_{rms}^2} \qquad (3)$$

4. THE DEVELOPMENT OF AN INTEGRATED OPTIMIZATION METHOD

The proposed method introduces an innovative analytical framework that assesses the combined effects of multiple disturbance sources on electrical equipment. Its primary objective is to analyze, diagnose, and optimize the performance of equipment affected by unbalances and harmonics. Designed to accommodate various operational scenarios, the optimization method provides a comprehensive evaluation of real-world conditions. It incorporates the analysis of negative-sequence currents and voltages, zero-sequence components, and harmonic effects to quantify their overall impact on performance. The main components of the method are:

4.1 Data Collection

Data collection is the first critical stage of the developed method, providing a solid foundation for identifying and analyzing disturbances in the examined electrical networks. This process involves continuous monitorization of operating parameters, including voltages, currents, and harmonic distortions, using advanced sensors and integrated monitoring systems.

Before measuring the parameters of the analyzed electrical equipment, certain additional data must be recorded beyond the nominal specifications. The equipment's age should be known beforehand, as its performance may degrade over time, with losses increasing by up to 15% in worn-out equipment. As a transformer ages its insulation layer can deteriorate, leading to higher resistance and reactance values compared to an unused transformer.

Another important factor is the utilization level of the equipment in relation to its location. Equipment operating in areas with predominantly linear loads, such as residential zones or office buildings, will experience lower losses and a longer lifespan. Conversely, equipment used in environments with strong nonlinear loads, such as industrial plants or technical university laboratories, will be subject to greater disturbances, increased losses, and a reduced lifespan. A particular aspect of three-phase transformers is the influence of different winding connection type configurations. These connection characteristics significantly impact the transformer's ability to mitigate unbalance, a subject that has been extensively studied.

A set of detection algorithms classifies disturbances by their type and determine their amplitude. For transformers, critical points in the magnetic core and windings are identified where additional magnetic fluxes lead to significant energy losses. The main parameters measured in transformers include input and output voltages and currents, magnetic fluxes in the core, and the temperatures of the core and windings. Examples of measurement devices for these parameters include current and voltage sensors, magnetic probes, and thermocouples.

In the analysis of induction motors, the main measured parameters include phase currents and voltages, input voltages, grid working frequency, torque, power factor, stator and rotor temperatures, and mechanical vibrations. Examples of measurement devices for these parameters include current and voltage sensors, thermocouples, infrared sensors, and accelerometers. For harmonic level determination, spectral analysis using Fast Fourier Transform is applied, while the level of unbalance is assessed by analyzing the negative-sequence component of current and voltage.

It is important to note that in harmonic measurement, in addition to amplitudes, phase angles must also be considered. The phase angles of harmonics play a crucial role in determining core losses, with losses reaching their maximum when harmonics are in phase (0°) and decreasing significantly when they are in phase opposition (180°).

In addition to these operational data, environmental factors will also be considered to provide a more accurate and comprehensive assessment of the equipment. Indicators such as ambient temperature variations, solar irradiation levels, humidity, and the presence of electromagnetic fields are considered. For example, in solar farms, it has been observed that due to solar irradiation levels, losses during summer are 8% higher than in winter.

An advanced, modern, and efficient method for data collection is the use of *SCADA* (Supervisory Control and Data Acquisition) systems and *IoT* (Internet of Things) based solutions. These technologies enable real-time and remote monitoring of equipment without requiring user intervention. One of the key advantages of this approach is the ability to store and process data in the cloud, facilitating the development of predictive analysis algorithms based on machine learning. The implementation of *SCADA* and *IoT* systems enhances energy efficiency, reduces intervention time, and optimizes equipment operation.

4.2 Data Analysis

Data analysis is a fundamental stage in the developed optimization method, playing a crucial role in interpreting the collected information. The collected data is processed using mathematical models and simulation algorithms that enable the identification of critical areas affected by disturbances. This stage involves processing electrical signals, determining unbalance and harmonic indices, and correlating the results with mathematical models specific to each type of equipment.

Harmonic analysis involves decomposing a periodic signal into harmonic oscillations, specifically through Fourier series expansion. This decomposition separates the signal into its fundamental component and the individual harmonic components. By determining these elements, specific indicators for evaluating the harmonic distortion level can be established, such as *Root Mean Square (RMS) value, harmonic level, Crest Factor (CF), Form Factor*

(FF), Total Harmonic Distortion (THD), and the Derating Factor.

The *RMS* value is one of the most straightforward indicators to analyze, as an increase in this value indicates the presence of disturbances. To obtain a truly accurate *RMS* value, harmonics of higher orders up to the 50th must be considered. The most critical analyzed parameter is *Total Harmonic Distortion*, which represents the ratio between the distortion residue and the *RMS* value of the fundamental harmonic. According to current standards, for harmonic effects to be negligible on electrical equipment, voltage *THD* (*THDv*) should be below 5%, while current *THD* (*THDi*) should be below 8%. A *THDv* exceeding 5% leads to an increase in magnetic core losses by up to 20%, causing a 30% reduction in loading capacity. A *THDi* above 8% results in a rise in winding losses by up to 15% and increases winding temperature by 5-10°C.

In addition to these well-established terms, specialized studies have introduced new indicators that enhance the characterization of disturbances. The *Equivalent Current Index (Ieq)* (2) is used to convert the effect of harmonic currents into fundamental current terms, providing an equivalent measurement of overheating caused by harmonics. A higher value of this index indicates increased losses due to harmonic distortions. If this index exceeds one, it is considered that total losses surpass the maximum allowable limits. The *Harmonic Impact on Transformer Loading (HITL)* measures the percentage increase in transformer loading. If *HITL > 1*, the transformer is significantly affected by harmonics and requires corrective measures. *HITL* extends the analysis by expressing the percentage increase in total loading, considering both harmonic losses and total *RMS* current. These two new indices provide a more detailed perspective on the actual impact of harmonics, offering a solid foundation for harmonic effect analysis.

In the analysis of unbalanced operating conditions, two primary indicators are used to measure the level of unbalance: the *negative-sequence component* and the *Voltage Unbalance Factor*. Studies show that increases in these values are correlated with higher losses and temperature rises. A new term introduced for analysis is the *unbalance coefficient f* (1), an indicator that considers the angle between the negative-sequence and positive-sequence components. It allows for a more efficient estimation of total losses, showing distinct variations depending on their value. If *f* is less than 1, the motor operates under unbalanced undervoltage conditions, leading to an increase in copper losses by up to 15%. If *f* exceeds 1, the motor functions under unbalanced overvoltage conditions, causing rotor temperature to rise and reducing efficiency by up to 8%, although copper losses in this case are lower than in the undervoltage scenario. The most critical situation occurs when *f* exceeds 1.2, as stator core losses increase significantly, requiring the application of a derating factor to prevent equipment failure.

Another analyzed parameter is the *Hot Spot Temperature (HST)*, which affects the loading capacity of transformers. Higher-order harmonics contribute to an increase in *HST*, with a current *THD* of 22% leading to a temperature rise of 30°C compared to nominal conditions. This temperature increase is also correlated with the accelerated aging process of electrical equipment. Regarding unbalance, a *VUF* of just 4% causes a 15°C increase in winding temperature.

In the evaluation of unbalances, a three-phase system is always analyzed, meaning that the unbalance level will vary across each phase introducing specific characteristics. Studies have found that the highest losses occur when one phase is in overload, one is at nominal value, and one is in underload. This maximum loss level is due to the large differences between phases, ranging from a minimum level (underload) to a maximum level (overload). In addition to losses, the derating factor is also influenced by the distortion level on each phase as well as the *THDv*. A correlation has also been established between phase unbalance levels, the unbalance factor, and stator temperature. For any variation in unbalance, temperature will increase during motor working time , except in cases where a single phase is in underload along with a high *VUF* exceeding 15%, in which case the temperature decreases.

Analyzing the variation with the negative-sequence voltage component, it has been observed that it is lower under undervoltage conditions and higher under overvoltage conditions. Conversely, the power factor gradually decreases as the negative-sequence voltage increases, showing higher values in undervoltage conditions. Torque is a critical parameter that requires significant attention, as it is one of the key characteristics of an induction motor. A *VUF* of just 6% can lead to a reduction in starting torque by up to 25%, which is a considerable decrease. In addition to this reduction in starting torque, other negative effects include a decrease in steady-state speed, distortion of the torque-speed curve, and an increase in motor slip. The phenomenon of torque ripple is measured using the *Torque Ripple Factor (TRF)*, which is defined as the ratio between the maximum torque variation and its average value. *TRF* increases with *VUF*, meaning that even for a relatively small *VUF*, *TRF* values can be significantly high. For an unbalance of 5%, the torque ripple factor can reach as much as 63.82%.

4.3 Parameters Optimization through the Design of Optimization Solutions

Based on the analysis results, the proposed method integrates a series of solutions to mitigate disturbances. This study examines the two main types of disturbances, unbalances and harmonics, each requiring specific mitigation strategies. The objective is to combine these solutions to ensure the proper operation of electrical equipment under any disturbance conditions. The most direct approach is balancing and optimizing the load input; however, this method is often impractical, necessitating more complex procedures. Therefore, the following methods are proposed.

A new method is proposed [42] that converts the distorted waveform into an equivalent sinusoidal wave by using the absolute mean value of the applied voltage. This technique enables the application of Bertotti's equation for estimating core losses, providing more accurate results than traditional methods that do not account for the phase angle effects of harmonics. Compared to classical methods, which have significant limitations at high *THDv* levels (up to 30%), the proposed method offers improved accuracy [42].

To minimize unbalances, a new transformer model has been proposed, featuring an additional coupling winding on the secondary side of each phase. Simulation results have shown that the proposed transformer is more effective in reducing both voltage and current unbalances compared to the original design [43].

By introducing power factor correction capacitors, losses can be significantly reduced. These capacitors can be installed on either the high-voltage or low-voltage side, with studies showing that low-voltage capacitors are more efficient, reducing losses by up to 20% [35].

Another effective method for loss reduction is the use of filters, a rapidly evolving researched field with continuous improvements. The most advanced filters have successfully reduced disturbance levels from 29.5% *THDi* to 3% and from 10.59% *THDv* to 5% [44]. In addition to these specialized filters, conventional active filters are also widely used. Studies have shown that for effective harmonic level management, using a single filter does not yield optimal results, with the ideal number of filters being three.

One of the primary solutions for reducing unbalance is the implementation of load balancing schemes for unbalanced consumers, specifically through the use of single-phase transformers. These single-phase transformers are usually Scott or V type and have been the subject of numerous studies. Research has shown that the Scott transformer maintains the unbalance ratio below 5%, even under significant load variations, while the V-type transformer registers higher unbalance values in the same scenarios.

Another type of transformer used for this purpose is the *On-Load Tap Changing (OLTC)* Transformer, which is applied in the three-phase regulation strategy. This approach involves using phase and voltage amplitude regulation transformers controlled via *OLTC*. Voltage phase adjustment is achieved through a specialized phase-shifting transformer that modifies the angles between phases, ensuring a constant 120° phase difference. Voltage amplitude is regulated using series-connected tap-changing transformers, each controlled by automatic voltage regulation relays. Figure 2 illustrates the amplitude regulation process for this strategy [45].

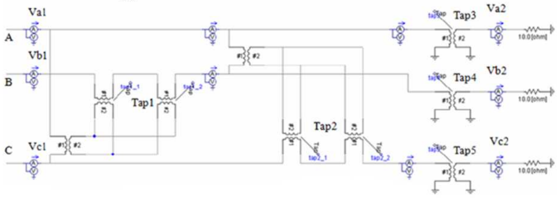

Fig. 2. The scheme for three-phase regulation strategy with OLTC Transformers [45]

Apart from the use of new equipment or load optimization, another solution for mitigating the effects of disturbances is the application of specific mathematical models. In harmonic reduction, advanced algorithms integrate frequency-domain analysis with digital filtering techniques. The algorithm operates in real-time, reducing harmonic-induced errors from 5% to 0.5%. This type of mathematical models can be created on specific platforms and softwars like MATLAB/Simulink, PSCAD/EMTDC, ETAP, DIgSILENT PowerFactory, and many more.

A frequently addressed issue in specialized studies is the differentiation between short-circuit faults within stator windings and faults caused by unbalances. To tackle this problem, a new detection system has been developed, consisting of current and voltage sensors, low-pass filters, and an artificial neural network *(ANN)* for data analysis and fault type identification [46].

4.4 Implementation and Validation of Solutions

The final stage involves testing and comparing the performance of optimized equipment with its nominal values using numerical simulations and experimental data. The experimental analysis must confirm that *THDi* is reduced below 8% and *THDv* is below 5%, leading to a significant decrease in power losses and operating temperatures. The implementation of optimization solutions for electrical equipment affected by unbalances and harmonics requires an integrated approach that combines operational parameter adjustments, the use of compensation equipment, and continuous monitoring. The measures outlined in the previous chapter are progressively implemented and validated through numerical simulations and experimental tests, utilizing predictive mathematical models based on the *unbalance coefficient f,* the *Voltage Unbalance Factor (VUF)*, *Total Harmonic Distortion (THD)*, and the *Harmonic Impact on Transformer Loading (HITL).*

The selection of optimal solutions for minimizing the effects of unbalances and harmonics must be tailored to the specific characteristics of each piece of equipment and the severity of disturbances. The authors recommend customized approaches for harmonic compensation and unbalance minimization, a principle reflected in the application of the previously described methodologies, such as using passive or active filters for transformers, optimized frequency converters for induction motors, and other techniques. Depending on the operating parameters, the combination of these solutions may vary, ensuring an optimal balance between efficiency, cost, and the reliability of the electrical system.

5. POSSIBLE RESULTS, ADVANTAGES, AND BENEFITS

The developed model provides a structured sequence of actions to offer a comprehensive assessment of the impact of disturbances on modern electrical equipment. The application of the proposed method provides the following advantages and benefits:

- Reduction of energy losses in transformers, cables, and induction motors by up to 15%. Increase in operational efficiency, with analyzed equipment demonstrating efficiency improvements of up to 10%.
- Extension of equipment lifespan by up to 20%, achieved through lower operating temperatures, thereby minimizing insulation degradation.
- Adaptability, as the method can be applied to a wide range of equipment and operational conditions, offering flexibility in implementation.
- Enhanced reliability and sustainability of electrical systems, contributing to improved

power quality, more efficient energy consumption, and long-term stable operation of equipment.

- Automatic Detection and Compensation of Disturbances by utilizing advanced spectral analysis algorithms (FFT) and intelligent systems. The system can quickly identify the type and severity of disturbances, applying optimized compensation solutions in real-time.
- Increasing the Reliability and Sustainability of Electrical Systems. The method contributes to maintaining a high power quality, ensuring more efficient energy consumption and a more stable operation of equipment in the long term.

6. CONCLUSIONS

This paper has proposed an integrated approach for analyzing and optimizing electrical equipment exposed to disturbances caused by unbalances and harmonics. Unlike traditional methods, which address these two types of disturbances separately, the proposed method provides a comprehensive and correlated evaluation, enabling precise diagnostics and the implementation of optimized solutions for each specific piece of equipment.

By combining theoretical analyses, numerical simulations, and predictive models, critical points have been identified, allowing for the application of effective solutions. The obtained results demonstrate that, through the implementation of the integrated method, transformer losses can be reduced by up to 15%, induction motor efficiency can increase by up to 10%, and equipment temperature can be maintained within optimal limits, extending the lifespan by up to 20%.

The flexibility of the method allows for a clearer adaptation of solutions based on the specific characteristics of the equipment and the level of disturbances. This enables each operator or designer to select the most suitable measures for their application. In conclusion, the study is a practical tool for optimizing the performance of electrical equipment, providing customizable solutions for reducing energy losses and enhancing the reliability of modern electrical networks.

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Metoda integrată de optimizare a performanței echipamentelor electrice sub influența nesimetriilor și armonicilor

Rezumat: Transformatoarele și motoarele asincrone sunt componente fundamentale ale sistemelor electroenergetice moderne, a căror performanță poate fi semnificativ afectată de prezența nesimetriilor și armonicilor în rețelele electrice. Aceste perturbări generează pierderi suplimentare de energie, reduc eficiența operațională și pot scurta durata de viață a echipamentelor. În această lucrare, este prezentată o metodă integrată inovatoare care îmbină analiza teoretică, simulările numerice și datele experimentale pentru a evalua și optimiza performanța echipamentelor electrice în condiții de funcționare perturbate. Noutatea metodei constă în integrarea mai multor factori perturbatori într-un model unitar, capabil să diagnosticheze cu precizie problemele și să propună soluții personalizate. Validarea metodei i a demonstrat o reducere a pierderilor energetice cu până la 15%.

Cuvinte cheie: *dezechilibru, armonice, calitatea puterii, transformatoare, motor cu inducție, metodă nouă, integrat.*

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