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Management of Dissolved Gas Generation in Transformer Insulating Oil Applied to Photovoltaic Solar Power Plants

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ABSTRACT
Photovoltaic systems have emerged as an essential solution for renewable energy generation; however, they require special attention regarding the operation and maintenance of their components, such as power transformers. This article aims to contextualize a topic studied in the MBA in Renewable Energy Management, addressing the management of dissolved gas generation in power transformers used in photovoltaic systems, especially those subjected to large amounts of harmonic currents that are harmful to the equipment. Initially, an overview of transformers was presented, followed by a discussion on insulating oil, including aspects related to operation and maintenance, as well as the K factor of the devices. An exploratory study was conducted in a solar park located in the Mesoregion of the Far West of Bahia, where no maintenance records for the transformers existed, and they were experiencing frequent shutdowns during full-load operation. The investor decided to hire an emergency inspection to perform a general analysis and oil sampling of the transformers to determine the next steps, aiming to implement scheduled maintenance. However, several necessary corrections were identified. In conclusion, it was found that the transformers presented critical issues earlier than expected, resulting from inadequate design conditions and the operation of the park.

***Keywords**: Power transformers; Dissolved Gases; Insulating Oil; K Factor; Solar Park.*

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I. INTRODUCTION

The power transformer is an extremely important piece of equipment for the electrical system and is crucial for the development of renewable energy in Brazil. These are robust assets that undergo trials and testing before entering operation. However, once in operation, they often encounter issues that directly affect the production of renewable energy. As a method and research theme, this study addresses the generation of gases in power transformers applied to photovoltaic systems.

This work provides an overview of the constructive parts of a transformer to explain the functioning of the equipment, the protections coupled to the assets, and explores some of the issues that arise in transformers. It also highlights the differences between dry transformers and oil-insulated transformers, delves into insulating oil, and explains diagnostic procedures and solutions carried out through insulating oil analysis. After presenting this brief diagnostic overview, the study outlines engineering solutions to mitigate the identified problems and discusses actions required when dissolved gases are found in the insulating oil, which often demand significant interventions by stakeholders in the renewable energy sector.

This topic is highly relevant for managers of renewable energy plants, as these problems are common among operation and maintenance teams who frequently face oil analysis reports indicating alarms or recommendations. Such situations often lead to urgent decision-making, which can impact the plant's generation and availability as reported to the national system operator or other regulatory bodies. The researcher aimed to highlight the impacts of gas presence in transformers used in renewable systems, ranging from reduced energy generation to contractual penalties due to unavailability, asset loss, and other consequences depending on the issue causing gas generation.

The chosen approach was qualitative, incorporating exploratory research. Additionally, a literature review and a documentary study were conducted, including access to technical data, electrical tests, and oil analyses of the client's transformers, based on national standards and well-recognized quality guidelines.

The general objective was to contextualize a topic studied in the MBA in Renewable Energy Management, focusing on the administration of dissolved gas generation in power transformers used in photovoltaic systems, particularly those subjected to high levels of harmful harmonic currents. The specific objectives were as follows: to discuss power transformers; to demonstrate the importance of transformer operation and maintenance cycles; to explain how to analyze insulating oil reports; to address harmonic currents and the k-factor in transformers; and to describe maintenance procedures for transformers in a specific company.

This article is structured into four sections. The first section, the introduction, explains the research objectives. The second section presents the research methodologies. The third section consists of the theoretical framework, and the fourth and final section provides the concluding remarks.

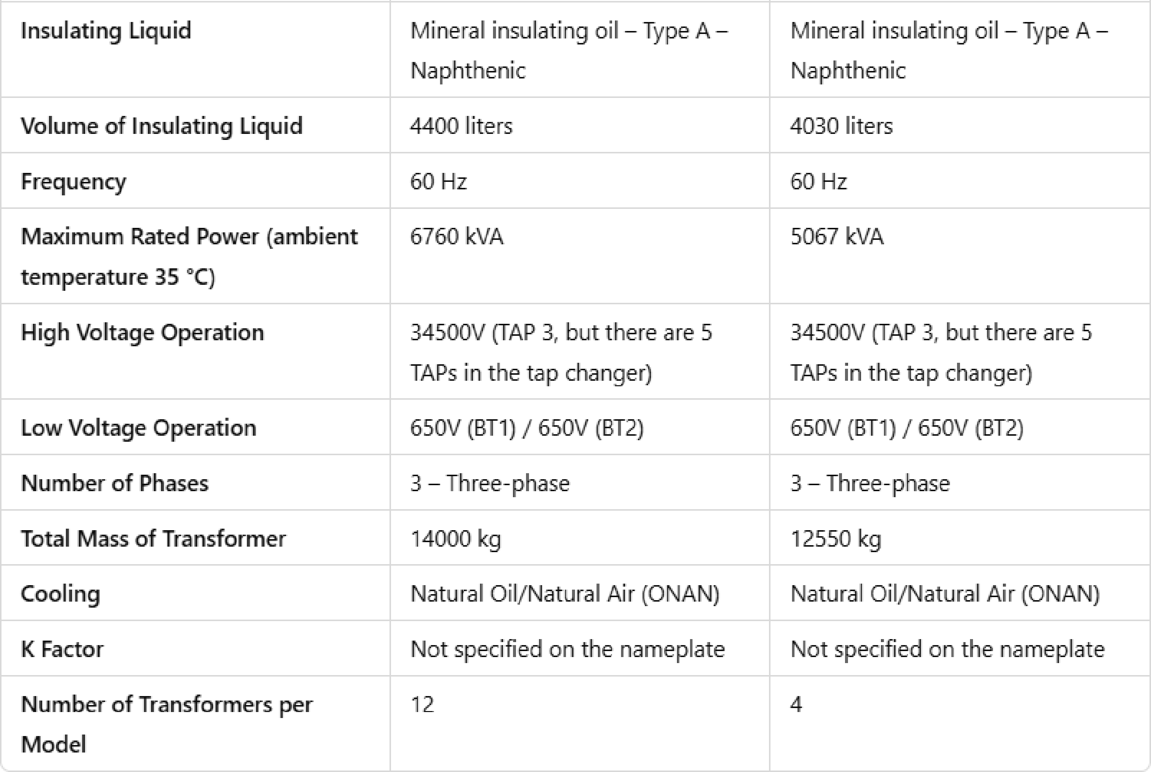
II. MATERIAL AND METHODS

The chosen approach was qualitative, and exploratory research was conducted to familiarize the researcher with the object under investigation. This was achieved through a case study of a solar park located in the Mesoregion of the Far West of Bahia. A maintenance service for transformers was described, which was divided into three stages. At the conclusion of the planned scope, a potential diagnosis of the identified issues was carried out. Additionally, a literature review and a documentary study were conducted, providing access to technical data, electrical tests, and oil analyses of the transformers belonging to these clients, as specified in national standards and high-quality recognized guidelines.

2.1 Enterprise Data and Service Stages

The solar park has a total generation capacity of 116.8578 MWp and spans a total area of 279.48 hectares. It includes 16 transformers of two different models, manufactured domestically, with the following nameplate specifications:

Table 2 – Nameplate Data of Transformers and Related Equipment



Insulating Liquid	Mineral insulating oil – Type A – Naphthenic	Mineral insulating oil – Type A – Naphthenic
Volume of Insulating Liquid	4400 liters	4030 liters
Frequency	60 Hz	60 Hz
Maximum Rated Power (ambient temperature 35 °C)	6760 kVA	5067 kVA
High Voltage Operation	34500V (TAP 3, but there are 5 TAPs in the tap changer)	34500V (TAP 3, but there are 5 TAPs in the tap changer)
Low Voltage Operation	650V (BT1) / 650V (BT2)	650V (BT1) / 650V (BT2)
Number of Phases	3 – Three-phase	3 – Three-phase
Total Mass of Transformer	14000 kg	12550 kg
Cooling	Natural Oil/Natural Air (ONAN)	Natural Oil/Natural Air (ONAN)
K Factor	Not specified on the nameplate	Not specified on the nameplate
Number of Transformers per Model	12	4

Source: Transformer Manufacturer

2.1.1 Stage 01 – Preventive Service

The company's site had no maintenance history available, and various issues arose with transformers shutting down during operation. The client hired a specialized company to perform electrical tests on the transformers, conduct an external general inspection of the equipment, collect physical-chemical and chromatographic oil samples, tighten connections, and perform general cleaning. Below is a summarized report of the first stage carried out in 2023.

- Electrical Tests: Tests for transformation ratio, winding resistance, and insulation resistance yielded satisfactory results in compliance with the parameters outlined in ABNT NBR 5356.

- External Inspection: It was observed that all low-voltage (LV) bolts were loose, likely due to excessive noise during operation. Along with hot spots, it was identified that two transformers had issues with oil level protections and gas relay, without an evaluation of the root cause of the problem. These issues needed resolution to allow the equipment to return to full-load operation, which was the regular regime of the solar plant.

- Physical-Chemical Analysis Alarms: Three transformers triggered alarms related to dielectric strength parameters specific to the voltage class of the transformers, all belonging to Model 1.

- Chromatographic Analysis Alarms: A total of 12 transformers were diagnosed with chromatographic alarms, as follows: - Overheating (T3): Four transformers, two from each model. - Low-Energy Discharges (D1): Seven transformers presented this alarm, all from Model 01. - High-Energy Discharges (D2): Only one transformer, from Model 01.

2.1.2 Stage 02 – Corrective Maintenance Previously Mapped

The investor contracted the same specialized company to perform corrective maintenance on eleven transformers during the first semester of 2024. The services performed included the following:

- Replacement of Damaged Gaskets: Gaskets were replaced due to damage caused by high temperatures. Although gaskets are designed to last up to 10 years, adverse conditions such as high currents, overheating, and the region's climate accelerated their deterioration.

- Replacement of Bushings: Some bushings were replaced due to cracks, and in some cases, the internal connector of the bushing was made of aluminum while the transformer’s busbar was made of copper. This mismatch created a hot spot, leading to the presence of gases inside the transformer and necessitating replacement. However, due to the large number of bushings that needed replacement, the client did not have enough parts for all the required transformers, leaving this task to the third stage.

- Oil Treatment and Replenishment: As part of the maintenance procedure, oil samples were collected before intervention and compared with the historical data of each transformer. The analysis revealed that the condition of the oil had worsened, and the alarms previously reported had intensified.

2.1.3 Stage 03 – Additional Corrective Services

In the second semester of 2024, the specialized company encountered a different corporate environment, as the initial investor decided to sell the solar park to another operator to handle its operation and maintenance. The new company conducted its own assessment and requested services similar to those performed in Stage 02.

However, the scenarios observed in the transformers had worsened due to adverse conditions, leading to changes in the oil’s chemical parameters, such as discoloration and an increase in the power factor. The services were carried out as described in Stage 02.

However, it is anticipated that, in the future, workshop procedures will need to be performed on these transformers, along with more extensive services to improve the oil’s chemical parameters. These are more costly procedures and may impact the expected payback for the new investor.

III. THEORETICAL FRAMEWORK

This section aims to provide a comprehensive understanding of the key concepts and technical aspects related to the research. The theoretical foundation is structured into four main subtopics:

3.1 Power Transformers – This subsection delves into the fundamental principles, design, and functionality of power transformers, highlighting their critical role in energy generation, transmission, and distribution systems.

3.2 Operation and Maintenance Cycles of Transformers – Here, the focus is on the operational characteristics and maintenance routines of transformers, exploring the importance of preventive and corrective maintenance to ensure efficiency, reliability, and longevity.

3.3 Analysis of Insulating Oil Reports – This subtopic discusses the procedures and significance of analyzing insulating oil, addressing the interpretation of diagnostic results and their implications for transformer performance and safety.

3.4 Harmonic Currents and Transformer K-Factor – This section examines the impact of harmonic currents on transformer operation and explores the concept of the K-factor, emphasizing its role in assessing transformer capacity under non-linear load conditions. By addressing these subtopics, this theoretical framework seeks to establish a solid basis for understanding the challenges and solutions associated with transformer operation and maintenance in renewable energy systems.

3.1 Power Transformers

Based on ABNT NBR 5356 (Part 1), which addresses various topics related to power transformers, it highlights several assets that are crucial for the National Interconnected System (SIN), such as single-phase transformers, three-phase transformers, oil-immersed types, dry-type transformers, reactors, grounding transformers, autotransformers, among other models.

The power transformer is a critical component in the electrical power system (EPS), responsible for voltage transformation. Its function may involve either voltage step-up (as in applications at generating substations, for example) or voltage step-down (in applications within transmission or distribution systems, for instance).

In addition to its evident operational importance, it also carries significant financial value, being the most valuable equipment in an electrical transmission substation. These characteristics make it essential for defining maintenance planning by companies in the energy sector (CIGRE, 2013, p. 8).

3.1.1 Power Transformers Applied in Photovoltaic Plants

According to ANEEL (Normative Resolution No. 1000), photovoltaic generation plants with an installed capacity of up to 3 MW are considered microgeneration or minigeneration, while those above this threshold are considered centralized generation.

However, it is important to note that for large power blocks connected to the National Interconnected System (SIN), transformers are needed to transport the energy generated by the plant. Three-phase transformers are commonly used after the inverters, where they are responsible for stepping up the voltage that will be transported by the internal medium voltage network of the plant to the step-up substation. At the substation, the transformer(s) receive the power generated by the entire complex, step up the voltage again, and dispatch the energy into the SIN, succinctly and efficiently (França et al., 2022).

Each transformer has distinct construction characteristics, varying according to the design, but the insulating medium in most transformers is oil, due to its cost-effectiveness, heat dissipation capacity, thermal efficiency, and superior electrical insulation compared to dry-type transformers (França et al., 2022).

3.1.2 Insulating Oils Applied in Transformers

According to Stocco (2009), mineral insulating oil (MIO) is produced through the fractional distillation of petroleum. This product is used in electrical devices as an insulating and cooling medium. MIO is widely used due to its affordability, easy availability, and excellent dielectric properties.

Its composition consists of hydrocarbons, molecules made up of carbon and hydrogen. In transformers, MIO is used to cool energized parts, facilitating heat dissipation. Additionally, it serves as an electrical insulator within the internal sections of the transformer.

However, MIO is considered toxic and can cause significant environmental damage if spilled or leaked, leading to soil and water source contamination. In contrast to MIO and synthetic insulating oil, vegetable insulating oil (VIO) is always derived from seeds such as canola, soybean, corn, and others. To obtain refined oil, these seeds undergo degumming, neutralization, bleaching, and deodorization (Stocco, 2009).

With a focus on environmental preservation, vegetable oil has a chemical structure composed of ester molecules of fatty acids, which provides a high flash point and reduces the likelihood of fires. Moreover, the smoke generated during combustion is less dense and less harmful compared to that of mineral oil. Furthermore, VIOs are biodegradable and do not contain sulfur compounds, avoiding problems related to the corrosive action of sulfur (Carvalho, 2019).

3.2 Operation and Maintenance Cycles of Transformers

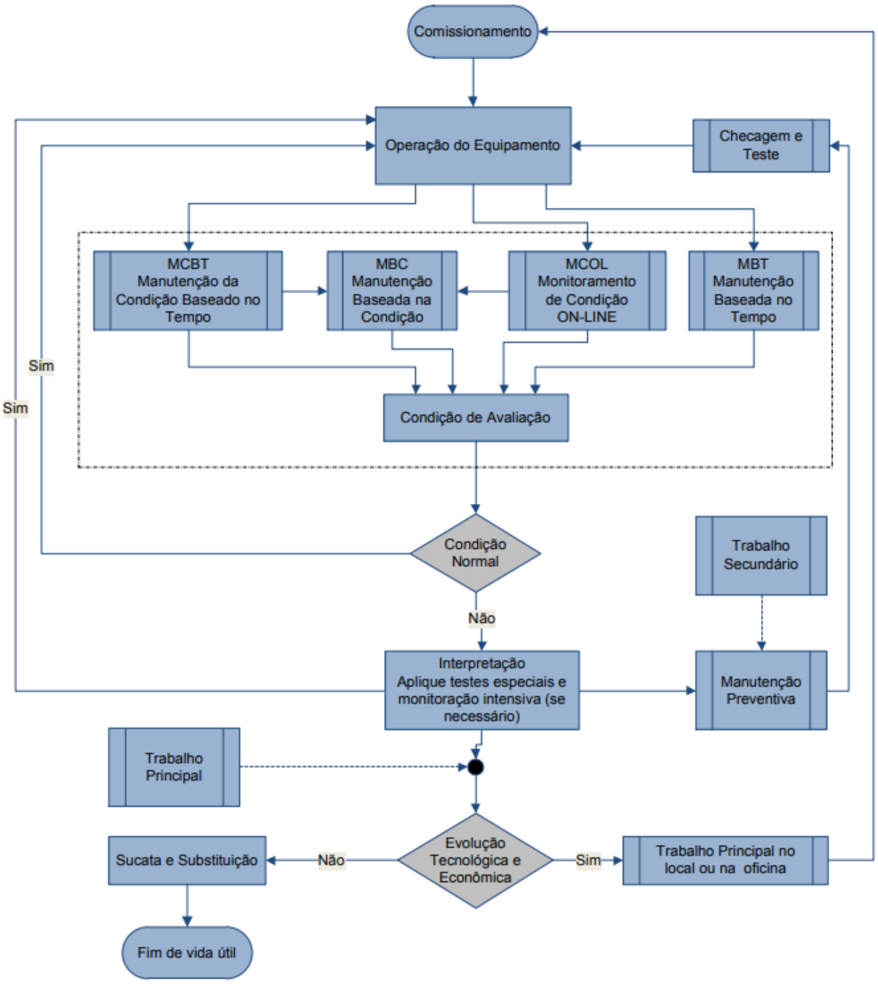
According to CIGRE (2013), a transformer is a robust, highly reliable device that requires relatively simple maintenance. Throughout the lifespan of these devices, it is essential to establish some guidelines. A maintenance strategy that ensures the appropriate level of reliability and maximizes the operational lifespan is crucial.

The operational durability of a transformer begins with the tests conducted prior to installation. Once in operation, a maintenance strategy will ensure the required availability and reliability throughout the equipment's lifespan, at a minimal cost. A manager of a photovoltaic plant (UFV), upon identifying an anomaly, must apply techniques for evaluating and diagnosing the failure.

After determining the severity, it is necessary to assess whether the equipment can be restored to operation, with or without limitations. If needed, corrective action can be taken, or, depending on the condition of the transformer, a more severe intervention may be required.

Finally, it may be decided that it is time to revitalize, repair, or even replace the equipment, based on the results of an evaluation that will consider safety aspects (both for the team of workers and the general population), environmental impacts, and system reliability. Below is a flowchart extracted from the maintenance guide for power transformers developed by CIGRE BRASIL, the Brazilian National Committee for the Production and Transmission of Electrical Energy.

Figure 1 - Operation and maintenance cycle of the equipment, from its commissioning to the end of its useful life.



Source: CIGRE BRASIL (2013)

3.3 Analysis of Insulating Oil Reports

Power generation plants in Brazil that are interconnected with the National Interconnected System (SIN) bear significant responsibility for energy security in terms of supplying energy to consumers, as the National System Operator (ONS) coordinates and controls the operation of electricity generation and transmission facilities within SIN. Therefore, the plant manager must ensure that the complex remains operational, available, and ready for dispatch if necessary (Brazil, 1998).

Transformer manufacturers, when supplying the equipment to the client, explain the guidelines to ensure the transformer’s useful life reaches 35 years, as recommended by ABNT. These guidelines include preventive, predictive, and corrective maintenance, if necessary, to meet this lifespan. Insulating oil collection and analysis, being a proactive maintenance method, can provide data to assess the equipment’s condition continuously and predict potential failures early. Moreover, it is a relatively simple and low-cost procedure compared to the value of the asset, the significant financial losses, the loss of generation, and the potential fines associated with transformer downtime.

3.3.1 Physicochemical Analysis of Insulating Oil

Power transformers are subjected to greater dielectric stresses during transient situations, such as during energization due to inrush current, overvoltages caused by failures in connected systems, and short-circuit currents absorbed by the equipment. In all these situations, it is crucial for the manager to monitor the physicochemical conditions of the insulating oil, as unfavorable conditions can compromise the dielectric withstand capability of the equipment. In extreme cases, this can result in significant losses, especially if it affects the transformer's active part (Dias & Huais, 2022).

According to ABNT NBR 10576, there are essential parameters for decision-making by the manager, which include the following: - Dielectric Strength: Refers to the insulating liquid's ability to withstand electrical stress. A high dielectric strength indicates low water content and solid particles in the oil. If the measured values are low, it suggests that one of these parameters is elevated. This issue can be addressed through a thermovacuum process, resolved on-site, and in some cases, without the need for the equipment to be shut down. - Dielectric Loss Factor: This is a sensitive variable to the presence of soluble polar contaminants, weakening products, or colloids in the liquid. Even with low contamination, parameters should be monitored, especially if they are near the detection limit. To solve this issue, the insulating oil charge should be regenerated or replaced. - Neutralization Index: Refers to the acidity of the oil, based on measuring acidic components present. Acids have a significant impact on the degradation of the insulation paper and on the corrosion of internal metal parts. An increase in the acidity level of an operational transformer indicates the oil’s aging rate. - Water Content: Refers to the parts per million (ppm) of water within the oil. Depending on the amount, temperature, and degree of aging, this water content can influence other parameters such as the dielectric strength of the oil.

Water can enter due to two common causes: humidity from the environment, which can be resolved through a thermovacuum process after leak repair, or water in the cellulose insulation, which should ideally be addressed by drying the active part in an oven. - Interfacial Tension: This test is conducted to analyze soluble polar contaminants and oxidation products. It changes rapidly during the early stages of aging but tends to stabilize when deterioration is controlled. - Other Parameters: Other important parameters, such as color, appearance, density, PCB content, particle count, corrosive sulfur, flash point, viscosity, and others, should be consulted in the ABNT NBR 10576 standard.

Table 1 – Thresholds and limits for physicochemical properties of insulating oils in service equipment

Parameters	**Test Method**	**Voltage Class**			
		• ≤ 36,2 kV	**• > 36,2 kV • ≤ 72,5 kV**	**• > 72,5 kV • ≤145 kV**	**• > 145 kV**
Minimum Dielectric Strength, Cap-type Electrode (kV)	ABNT NBR IEC 60156	40	40	50	60
Maximum Loss Factor (%)	ABNT NBR 12133	• 0,5 (a 25 °C) • 15 (a 90 °C) • 20 (a 100 °C)	• 0,5 (a 25 °C) • 15 (a 90 °C) • 20 (a 100 °C)	• 0,5 (a 25 °C) • 15 (a 90 °C) • 20 (a 100 °C)	• 12 (a 90 °C) • 15 (a 100 °C)
Maximum Neutralization Index (mg KOH/g)	ABNT NBR 14248	0,20	0,20	0,15	0,15
Maximum Water Content (mg/kg)	ABNT NBR 10710	40	40	30	20
Minimum Interfacial Tension at 25 °C (mN/m)	ABNT NBR 6234	20	20	22	25

Source: ABNT (2017)

3.3.2 Chromatographic Analysis of Insulating Oil

As crucial as the physicochemical analysis is, it is equally important to diagnose the dissolved gases in the insulating oil of transformers. Attention must be given to the following characteristic faults, as outlined in ABNT NBR 7274:

• Partial Discharges (DP): A partial discharge is one that traverses the insulation between conductors, potentially occurring within the insulation or near a conductor. This type of discharge may not be easily visible, as it could be located in the cellulose insulation or involve sparking, which induces carbonized holes in the paper.

• Sparking (C1): This occurs between metallic parts and is characterized by dielectric rupture with a high ionization density. This type of fault can cause burnt holes in the insulating paper, which may not be readily visible. Sparks indicate an electrical issue that could affect the integrity of the equipment.

• Low-Energy Discharges (D1): A low-energy discharge occurs in equipment, such as a transformer, without causing significant damage. These discharges can be evidenced by surface carbonization of the insulating paper or the presence of carbon particles in the oil. They are often associated with normal operations, such as tap changer switching, and may be considered partial discharges, though they are of lower energy intensity compared to high-energy discharges, which may cause more extensive damage.

• High-Energy Discharges (D2): Refers to a discharge that occurs in equipment (such as a transformer) and results in significant damage. These discharges are characterized by extensive destruction and carbonization of insulating papers, metal fusion, and intense oil carbonization. In some cases, the equipment's protection system may be activated due to the high currents associated with these discharges. High-energy discharges (classified as D2 in the standard) represent severe faults that can cause permanent damage to the equipment, and their identification is essential for the safe operation and maintenance of electrical systems.

• Overheating (T1): Refers to a state of overheating where the temperature of the oil and/or insulating paper is below 300°C. Within this temperature range, the insulating paper begins to darken but does not burn. This condition indicates potential thermal problems in the device, which could escalate into a more serious issue if not addressed promptly.

• Overheating (T2): Refers to a state of overheating where the temperature of the oil and/or insulating paper is between 300°C and 700°C. In this temperature range, the insulating paper begins to burn, indicating a more severe degradation compared to overheating T1, which occurs below 300°C. This condition (T2) indicates that the device may be facing serious thermal issues, and if not properly handled, paper burning may lead to more critical failures. A more detailed analysis of the effects of T2 overheating and its consequences is required.

• Overheating (T3): Refers to a condition of overheating where the temperature of the oil and/or insulating paper exceeds 700°C. In this temperature range, there are signs of oil carbonization, metal discoloration at 800°C, or even metal fusion when the temperature exceeds 1,000°C. This is a critical condition that indicates an extreme level of degradation of the insulating material, potentially resulting in catastrophic equipment failure.

It is of utmost importance that the reports are issued by laboratories accredited by INMETRO, in accordance with ABNT NBR 7274. If any alarms are triggered, it is essential to perform re-sampling to confirm the results before taking any action, as the solution to correct the issues that generate gases may be costly and could even require the equipment to be taken out of operation for servicing at a specialized transformer repair workshop.

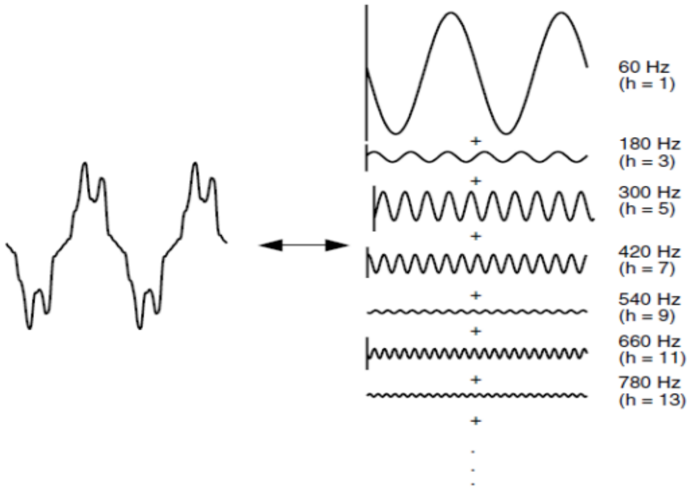
3.4 Harmonic Currents and the K Factor of Transformers

In power generation, clients must adhere to certain predetermined parameters during the study phase, which have been approved by the responsible authorities. However, when operations begin, managers often encounter problems arising from a lack of knowledge during the validation of the executive projects. These problems may include infrastructure issues in the park, construction-related issues in substations, soil stratification problems, and others. Since a power generation park involves various disciplines, it is essential to have trained and qualified personnel to ensure a satisfactory final result without significant rework for the operations team.

Harmonics are sinusoidal components of an alternating voltage or current whose frequency is equal to or a whole multiple of the system's fundamental frequency, which, in Brazil, is 60 Hz. The order of a harmonic is defined by the number of times its frequency is a multiple of the fundamental frequency. Harmonic distortion refers to changes in the waveform of voltages and currents compared to the sine wave of the fundamental frequency. The harmonic order (h) indicates the frequency spectrum relative to a distorted wave, where harmonic frequencies correspond to integer multiples (h) of the fundamental frequency. According to Fourier's theorem, any periodic function can be expressed as the sum of sinusoidal functions. By combining sinusoidal waves, it is possible to create the resulting wave (INEP, 2011; RAMPINELLI; KRENZINGER, 2011; SILVA, 2018).

Poorly designed photovoltaic inverters can cause significant problems due to harmonic distortion caused by the integrated electronics in their construction models, as outlined below: • Increase in temperature: Harmonic distortions can raise the temperature of electrical cables, reducing their lifespan. • Equipment burnout: Harmonic currents can cause the burning out of electrical equipment and components. • Errors in meters: Harmonic currents can lead to errors in induction disc electricity meters. • Relay interference: Harmonic currents can disrupt control devices, such as relays used by electric utilities. • Vibrations and noise: Harmonic currents can cause vibrations and acoustic noise, especially in electromagnetic devices. • Increased consumption: Harmonic currents can increase the effective current in the grid, resulting in unnecessary consumption increases. • Sizing issues: Harmonic currents can cause problems related to the sizing of cables and transformers. • Waveform distortion: Harmonic currents add to the fundamental current, distorting the original waveform of the grid. Below is the representation of the Fourier series of a distorted waveform.

Figure 2 – Signal Decomposition into Harmonic Frequencies



Source: Dugan (2002)

According to the manufacturer ITAIPU (2023), transformers are also affected by the effects caused by harmonics, which can lead to increased losses, heating, audible noise, reduced lifespan and efficiency, as well as the risk of core saturation. To minimize the issues mentioned earlier during the design phase, it is essential to inform transformer manufacturers that the transformers will be subject to non-linear loads, and they must determine the required K factor for that specific application. It is important to highlight that cost considerations should be evaluated to achieve a successful outcome at the end of the project's useful life.

- K Factor = 1: A transformer classified in this way is designed to only withstand the thermal effects caused by eddy currents and other losses associated with load in a 60 Hz sinewave current. This type of transformer may or may not be designed to manage the temperature rise resulting from harmonics present in its load current. Its applications include motors, incandescent lighting, resistance heating, and motor generators (without solid-state inverters).
- K Factor = 4: This classification refers to a transformer designed to provide the rated KVA without the risk of overheating when handling a load that includes 100% of the standard 60 Hz fundamental current in a sinewave form, in addition to: 16% of the fundamental current at the 3rd harmonic; 10% of the fundamental at the 5th harmonic; 7% of the fundamental at the 7th harmonic; 5.5% of the fundamental at the 9th harmonic; and smaller proportions up to the 25th harmonic. The number "4" represents the transformer's ability to withstand four times the eddy current losses compared to a K-1 rated transformer. Its applications include HID lighting, induction heaters, welding equipment, uninterruptible power supplies (UPS) with optional input filters, PLCs, and solid-state control systems.
- K Factor = 9: A K-9 transformer can handle 163% of the harmonic load that a K-4 transformer can support.
- K Factor = 13: A K-13 transformer, in turn, can support 200% of the harmonic load equivalent to a K-4 transformer. These transformers are used in various circuits, including medical assistance environments, UPS systems without optional input filtering, and production or assembly equipment, among others.
- K = 20, K = 30, K = 40: The maximum value in each of these K-factor categories demonstrates the ability to withstand increasing volumes of harmonic load without the risk of overheating. Some transformer models are applied in variable-speed inverters with SCR, circuits with data processing equipment, intensive treatment installations, and hospital operating rooms.

IV. DISCUSSION AND CONCLUSION

In conclusion, the research fully addressed the proposed approach, shedding light on several aspects of renewable energy plant management, which is the focus of the aforementioned MBA program. This study discussed a scenario that investors and/or managers often overlook or fail to give due importance to, even though it can have significant long-term impacts.

The research highlighted that, considering that 100% of transformers have already undergone some form of critical intervention in less than five years of operation, a transformer has an estimated lifespan of more than 20 years, according to the ANBT NBR 5356 standard.

Therefore, it is recommended that academic institutions establish partnerships with manufacturers and major investors to evaluate solutions for reducing harmonics caused by inverters and conduct financial studies comparing the maintenance costs of transformers with a K factor of 1 and the acquisition of transformers with a K factor greater than 1 during the project phase, depending on the needs of the installation.

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