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Operational vulnerability indicator for prioritization and replacement of power transformers in substation

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ABSTRACT

This work presents a new methodology for the classification and substitution of power transformers in substations. The paper proposes the use of the operational vulnerability indicator, which consists of two groups of criteria, technical condition and operational condition. This indicator allows identifying which power transformers from a set of substations have priority for substitution, considering technical-operational information available in the substations. The technical condition is composed by the parallelism index, reserve transformer availability, nominal power and transformation ratio. Through criteria such as the parallelism index developed for this work, it is possible to identify the percentage of the load that is assured by a transformer in parallel at the moment of a contingency. The operational condition representing the physical situation of the power transformer, typically found in the literature as health index. It assesses factors such as deterioration of the cellulose paper that makes up the insulation and oil, age of the equipment and loading factor, resulting in a life expectancy for the power transformer. The operational vulnerability indicator can be used as an important guide for the strategic planning of the resource application of electric power companies. The methodology is verified through a case study involving real data from 7 substations and 39 power transformers, belonging to a Brazilian electricity company. In the validation of the method, the effectiveness of the proposed method is compared with the ranking obtained through the traditional health index.

1. Introduction

The electricity distribution companies have a common characteristic of being constituted by several substations, which in turn have numerous power transformers in different states of conservation, ages, configurations and levels of supervision. This diversity makes the decision process of choosing the power transformer to receive maintenance or be replaced complex and subject to many variables. Another point that reinforces this uncertainty at the time of the choice is the high values involved, representing a significant part of the capital of the substation, together with the disturbance caused to the reliability of the electrical system in case an equipment is out of operation, since they are equipment with long terms of manufacturing and delivery. The *Health Index* is an example of methodology adopted during the process of choosing the power transformer to be replaced, approaching factors related to the current condition of the equipment, it assists as a decision parameter indicating the most vulnerable equipment [1–5]. However, the strategic aspect of the substation in which the power transformers are and whether they operate in parallel or have reserves is hardly considered. Factors such as these can delay or indicate the need to advance the replacement of the equipment, contributing to an increase in the safety of the electrical system.

Considering the factors presented, this paper proposes a methodology that presents a priority ranking for maintenance and replacement of power transformers in substations. This ranking indicator involves technical and operational aspects of power transformers to assist the decision maker in this crucial moment. Among the criteria that compose the proposed indicator, we highlight the parallelism index, an innovative calculation method that allows identifying the portion of the transformer load that can be reallocated to the transformer in parallel at times of contingency. The reserve transformer availability is another analyzed criteria. The methodology is verified through a case study involving real data from 7 substations and 39 power transformers, belonging to a Brazilian electricity company named CEEE-Generation and Transmission.

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1.1. Evaluation and monitoring of power transformers

Recent studies aiming at the maintenance and replacement of power transformers have presented the most different methodologies in the solution of this problem [1–11]. Abu-Elanien [7] provides an extensive review of several techniques and methodologies for evaluating and monitoring the condition of the power transformers currently being used. Among the points covered are maintenance plans, aging evaluation, state of health and the expectation of the end of life. The causes for the aging of these equipment's are also explored, such as the action of temperature in the degradation of insulation paper, an extremely sensitive point of a power transformer. Three types of life-span for this equipment are also categorized, the physical life time, which refers to the operation time of the power transformer until it begins to show defects in the components, the technical lifetime, which represents the technological or the operational limit of the equipment, and the economic life limit, related to the accounting depreciation of the equipment, year after year.

In [6] a methodology is presented to calculate the individual failure rate of transformers based on failure statistics, reliability measurements, dissolved gas analysis and furfuraldehyde. The work carries out a case study using a population of 30 transformers, in which it compares the new methodology proposed with the *Health Index* and an asset management tool. The data for the 30 power transformers used by [6] are taken from [2], which presents a new method for calculating the *Health Index* in 69 kV transformers, considering the analysis of dissolved gases, oil analysis and furfuraldehyde, together with the *fuzzy* methodology. Abu-Siada [8] presents a methodology for the critical classification of transformers based on the diagnosis of the analysis of dissolved gases in the transformer oil. It can be seen that [6] presents a different approach, considering fault analysis based on a statistical forecast, in order to identify the most vulnerable transformer for replacement, [2,8] only approach the operational condition of the equipment, estimating the current health condition and aging based on the analysis of data such dissolved gases and oil analysis.

The work [9] proposes a method can detect transformer faults in their initial stages. A neural modeling and the local statistical approach is used to diagnose incipient failure. A neural-fuzzy network is used to model the thermal condition of the power transformer in operation in order to identify hot spots. The main purpose is to optimize the asset management decision making and risk reduction, through the fault detection in power transformers. Chatterjee [10] presents an analysis and modeling of the characteristics of the dissolved gases in oil of the transformer, also proposes a Markov model to predict the state of the health of a transformer and to suggest a schedule for a regular filtration of gas, with the objective to extend the life of the power transformer. This model contributes to preventive maintenance, to the quality of the transformer oil and to the anticipation of failures. It also strengthens the importance of the analysis of dissolved gases in the oil to predict the state of health of power transformers.

Studies found in the literature present the *Health Index* as an effective solution in the identification of the end of life of the power transformers, since it collects several data concerning the condition of the equipment in a single value, such as the papers analyzed below.

The paper [3] presents a *Health Index* methodology that uses criteria such as equipment age, loading history, inspection and maintenance, internal failure histories, substation location, transformer manufacturer, dielectric rupture test, amount of water in the oil, analysis of dissolved gases, insulation resistance, winding resistance, winding ratio, winding power factor, oil power factor. In [4] criteria such as insulation resistance, routine visual inspections of the power transformer, thermographic analysis, oil quality, dissolved gas analysis, Tap inspection and testing, dissipation factor analysis (tan δ), excitation current, winding resistance, partial discharges, among others. Dixon [5] used similar criteria together with a real case study involving a group of power transformers. Criteria such as load factor and hours in transformer operation were also added. These indexes use some subjective parameters (e.g., transformer manufacturer, routine visual inspections, Tap inspection and testing), which are difficult to evaluate and implement in a functional method, and some data are difficult to access for lack of registration in some energy companies, such as internal failure histories.

Islam [1] presents a quantitative health index calculation of transformers based on six key measurements, dielectric strength, neutralization number, water content, dissipation factor (tan δ), total dissolved gases and furan, together with General Regression Neural Network (GRNN), which can work with measurements without quantization and present a nonlinear property. This work presents the importance of these criteria in the predict the state of health of power transformers, reinforcing their use in this work. However, they are believed to be insufficient to be used as an indicator of overall power transformers vulnerability in substations.

A work approaching the same problem of equipment *ranking* was carried out by [11], which presents a new methodology for a scale of SF6 circuit breaker prioritization for maintenance in substations. Criteria referring to the basic condition of the equipment and operating conditions are approached, representing the physical and operational conditions of the equipment that may compromise the performance and contribute to the occurrence of failure.

As seen in the works approached, methodologies for fault detection, aging identification and the end of life estimation of power transformers are presented. However, in the event of a fault in a power transformer belonging to a large set of power transformers and substations, some equipment would leave the electrical system more vulnerable than others, since they would not have alternatives to work around the problem quickly, e.g., with a reserve or parallel transformer. These points are not explored in the presented works, being one of the contributions of this paper. What is proposed in this paper is a look not only of the power transformer under analysis, but a strategic view of the surroundings, of all transformers belonging to the substation in which it is located.

1.2. Content and structure of the work

The work developed by [11] contributed to the proposal of this work with the division of the criteria into two main groups, Technical Condition (TC) and Operational Condition (OC). However, the proposal of this paper differs from [11] in the types of equipment addressed (circuit breakers in [11] and power transformers in the presented paper). In addition, the authors consider the importance of equipment for the electric sector, as the existence of power transformer reserve units and transformers in parallel. In this way, the technical aspects of the substation which power transformers are installed are added to the data on the basic health condition of the equipment, that indirectly affect the decision-making process. Working in a complementary way to the Health Index choice process, criteria such as the parallelism index of power transformers and the existence of a reserve transformer are added, which makes it possible to identify critical equipment for the electrical system, thus composing the Operational Vulnerability Indicator (OVI) of power transformers in substations.

In the criterion related to the parallelism index, an innovative calculation method is presented, which makes it possible to identify the portion of the power transformer load that can be reallocated to the power transformer in parallel at times of contingencies, provided that the equipment overload limits are respected. For the composition of the OVI, the *Preference Ranking Organization Method for Enrichment Evaluations* (PROMETHEE), which specializes in the solution of *ranking* problems, together with the *Analytic Hierarchy Process* (AHP), is used to define the weights of the criteria involved, obtaining as a result of mixing basis features of both methods, an operational synergy presented in [12].

The next section presents the OVI in detail, defining each criterion