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Voltage distribution constant versus losses in medium-voltage distribution transformer: A polynomial interpolation approach

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ABSTRACT

This paper aims to calculate an estimate of the initial stress voltage distribution in the transformer windings through their losses (that can be reduced by varying the construction parameters such as conductor section and size of the core window) through the numerical interpolation applied in capacitances of distribution transformers 30, 45, 75 and 112.5 kVA, 15 kV class. The calculations of the projects were organized into sets, with simultaneous variation of three construction parameters, totaling analysis of 10,648 projects of each power transformers arranged in three-dimensional arrays. The equation of the constant voltage distribution (α-factor) according to the losses through the quadratic polynomial and cubic splines for the of LV and HV windings is formulated.

Introduction

The medium voltage transformers are indispensable equipment for electricity distribution. At the electricity grid, transformers are exposed to electromagnetic disturbances, which can damage or shorten the life of such equipment. Equivalent circuit models have been proposed to describe the behavior of the transformer's response to various bandwidth. Models like "black box" are suitable in the absence of the construction parameters of the windings and are often based on the frequency domain [1].

In this context, techniques such as frequency response analysis has been applied to determine the types of electrical faults that occur in the coils. [2,3]. Numerical techniques are also applied aiming to study the diagnosis of the frequency response of the windings with the possibility of extracting the equivalent circuit parameters, as in the case of applying bacterial swarming algorithm [4]. In the same way, the sweep frequency response analysis method (SFRA) can be applied to check the presence of short circuit between turns [5]. The model based on transfer function to detect mechanical displacement axial or radial in the coil due to short circuit or shipping purposes streams is proposed in [6].

The aim of describing the coils model is to determine the internal behavior of equipment due to the surge wave during operation. In [7] is proposed a coil's model to analyze the voltage distribution against of fast electromagnetic transients. An estimate of the voltage distribution profile in the windings can be obtained from the measurements of the response data combined with the simulation of the two models: analytical and physical data [8]. The first portion of the transient surge, microsecond fraction of the currents that flow are the displacement currents in the windings capacitances. In this context it is possible to describe the initial voltage stress distribution through the constant voltage distribution (α-factor) [7,9,17]. It is worth to point out that the initial constant voltage distribution is applied to the first transient time interval. This interval is characterized by very fast wave front and thus after analyzing the α-factor arises the study of the transformer insulation system design behavior.

The losses in the transformers can be adjusted according to the dimensions of the elements that constitute core and windings [10,11]. The optimization of transformer designs may have the functions to be minimized, as total cost, total mass, losses and efficiency. The application of Covariance Matrix Adaptation Evolution Strategy proposed in [12] proved suitable for optimization of the manufacturing cost, the total mass and losses. Methods based on neural networks to forecast no-load losses is presented in [13] is a technique for evaluation of the technical features. The reduction of the losses has been studied in [14] with the goal of increasing the utility efficiency, achieve the reduction of greenhouse gas emissions and improve economic viability.

The capacitances of a distribution transformer are determined numerically through constructional details, such as coil radius, gap between coils, permissiveness of the materials and distance

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between the coil and inner surface of the tank. In the absence of these parameters, an alternative that this paper proposes is to calculate an estimate of the initial stress voltage distribution in the transformer windings through their losses, since they can be determined by laboratory tests, apart from being a data of the equipment specification. In this case, there is the relationship between the magnitudes of industrial frequency and transient state, in other words, losses and α-factor.

This article aims to describe the results of the initial stress distribution through the numerical interpolation applied in capacitances of distribution transformers 30, 45, 75 and 112.5 kVA, 15 kV class. The applications of numerical interpolations were performed in 10,648 transformers designs, with different levels of losses and capacitances. The article is divided into: initial parameters, which deals with the transformer design, the concept of initial stress distribution constant and polynomial interpolation; the α-factor versus losses which describes in the equation of the initial voltage distribution according to the load losses of the transformer; discussion of results and conclusion. The algorithm in this paper was developed in MATLAB©.

Initial parameters

Transformers features

The reduction of losses in transformers can be obtained by varying the construction parameters such as conductor section and size of the core window. The capitalization of losses is carried out through the total cost equation and the optimization applied to the equation through minimization of the cost function indicates efficient transformer design. It means that the optimum design of distribution transformer has lower technical losses in the power distribution system and economic feasibility, as payback less than 4 years [18,19].

The three-phase distribution transformers designs applied in this paper are 30, 45, 75 and 112.5 kVA, 13.8 kV/380 V, connection of windings Δ–Y, 60 Hz, involved core. The high voltage windings (HV) and low voltage (LV) are copper and arranged in helical layers. The LV winding consists of a rectangular wire (thickness × width) and the HV winding is of circular section. The LV and HV windings are spaced by a gap of oil.

The calculations of the projects were organized into sets, with simultaneous variation of three construction parameters, totaling analysis of 10,648 projects of each power transformers. The algorithm for analysis calculates designs through three-dimensional matrices for each set of parameter variation. Thus, the structure of the algorithm worked with 4 main arrays with dimension $11 \times 11 \times 22$. The arrays are organized into: (1) variation of the width LV conductor, (2) variation of the thickness LV conductor; (3) variation of the width of the LV conductor and circular cross section of the HV conductor; and (4) variation of the thickness of the LV conductor and circular section of the HV conductor.

The sets were arranged according to the simultaneous change of constructional parameters, in order to produce an efficient transformer design [19]. The sets are consisted of varying: (a) current density of the HV winding, gap between HV and LV winding and height of the core window; (b) current density of the LV winding, insulation thickness of the paper and magnetic induction; (c) current density of the HV winding, insulation thickness of the paper and magnetic induction; (d) current density of the HV winding, current density of the LV winding and insulation thickness; and (e) current density of the HV winding, insulation thickness and gap between the coils [20].

Fig. 1 shows the surface that relates the no-load losses, the load losses and constant voltage distribution (α-factor) for winding LV to designs ranging width LV conductor and the thickness of the insulation paper that coats the conductor of LV and the winding layers. Consequently, it will occur a variation in the core window, according to the increasing of LV coil for 75-kVA transformer. The surface of Fig. 1 has a horizontal slope which changes direction each section, that is, the tilt angle is changed every section.

The term Standard Transformer in this study refers to the transformer with losses around 28.8% lower than the limit of the losses established in Brazilian standards [21]. The losses levels for the standard 30-kVA transformer are 139.69 W for no-load losses and 294.88 W for the load losses. The no-load losses and the load losses are respectively 166.91 W and 586.26 W for a standard 45-kVA transformer. Regarding the 75-kVA transformer, the no-load losses and the load losses are 254.06 W and 868.48 W, and to the 112.5-kVA transformer, the no-load losses are 313.16 W and the load losses, 1525.64 W. Table 1 presents a summary of the power losses for each of the standard transformer designs applied in this study.

Voltage distribution constant

The initial voltage distribution constant at the windings or α-factor describes voltage gradient at the terminals of the windings and the degree of deviation between the initial and final voltage distributions in the transient analysis. The α-factor can be seen at the governing equation of the transient model [15]. Eq. (1) defines the α-factor, which is the square root of the ratio of the capacitance between the winding and the ground (C_{wg}) and the series capacitance (C_s) [9,16].

$$\alpha = \sqrt{\frac{C_{wg}}{C_s}} \tag{1}$$

Therefore, by varying the construction parameters of the coil, the capacitances are also changed and hence the constant of initial voltage distribution.

For example, consider 45-kVA three-phase distributions transformers. The capacitance between HV winding and ground increase up to 121.48% to the set of designs with change width of LV conductor and isolation thickness is 50% higher than standard value. For this case, the no-load losses increase up to 21.8% while the load losses are reduced up to 53%. For the set of design mentioned, the capacitance between LV winding and ground increase up to 181.82%. For the set of design with change in the width of

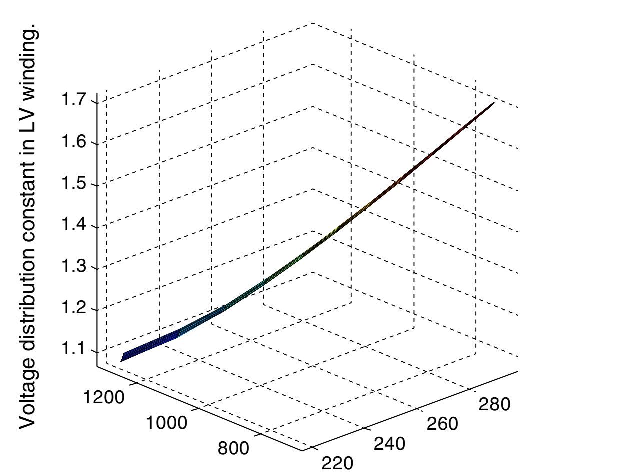

Fig. 1. Surface voltage distribution constant in LV winding for the 75-kVA transformer.