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Development of an efficient distribution transformer using amorphous core and vegetable insulating oil

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ABSTRACT

This paper presents the development of an efficient distribution transformer, based on amorphous core and vegetable insulating oil. Significant reduction was obtained in no load losses and guaranteed operation in higher temperatures, along with the fact that the fluid is non-toxic and of fast biodegradation. A distribution transformer design methodology considering the total cost of the equipment is displayed. In this methodology, design parameters, such as induction, number of turns (volts/turn), current density and the aspect ratio of coil form are varied in order to find the best transformer design. Simulation tools of Computational Fluid Dynamics (CFD) using Finite Volume Method (FVM) were applied aiming at proposing innovations to the cooler system taking into account the characteristics of viscosity of the vegetable oil. As result, was developed a prototype unit of 75 kVA, voltage class of 15 kV, primary voltages of 13,800/13,200/12,600 V and secondary voltages of 380/220 V, amorphous core, aluminum wires and vegetable insulating oil.

1. Introduction

The energy efficiency is a very important issue of power systems. In order to assure this goal, highly efficient equipment must be used, from the generation to the distribution of electric power. Regarding that, transformers are the most numerous equipment and fulfill a central role in the power systems, since they are responsible for maintaining the voltage levels among distribution, transmission and generation systems, according to Ref. [1].

Concerning the distribution systems, the losses in the medium voltage transformers represent around one-third of the total of technical losses [1]. This extent of losses points out a great potential to be explored by applying new technologies, such as the use of new materials or new standards that induce the improvement of efficiency in distribution transformers, as reported in Ref. [2].

On that matter, the research and development of more efficient equipment must be a priority, since it represents an important strategy to reduce environmental impacts. The energy efficiency contributes to the preservation of energy and natural resources. By reducing production costs and so providing the market with lower cost and more competitive goods, it consequently reduces the need of investment in infrastructure and energy.

The authors, in Refs. [3–5], discuss the development of amorphous metals and distribution transformers using these metals as cores, and what the future may hold for improvements in these technologies. In Ref. [6], the magnetic flux density of amorphous core is compared to a grain-oriented silicon steel. In Ref. [7], impacts of amorphous alloy on the worldwide energy savings and reduction of greenhouse gas emissions are discussed.

The authors, in Ref. [8], compare the main properties of alternative liquids to show their possibilities for naphthenic oil replacement. The development of dielectric fluids based on vegetable oils is also described and the advantages of these liquids over mineral oil are discussed. In Refs. [9,10] the current status of vegetable oils used as transformer oil is discussed, including their production, processing and characterization. The vegetable oils most used as transformer oils are presented, and their main advantages described in comparison with mineral oil. In Ref. [11], the suitability of vegetable oil as an insulating medium in power transformers is discussed.

The authors, in Ref. [12], investigate several improved designs of ONAN (Oil Natural Air Natural) transformer cooling system by means of advanced numerical heat transfer-fluid flow model. Novel tank designs are examined along with other crucial parameters, as the number and location of the winding cooling ducts, so as to define the best geometry that ensures maximum efficiency of the transformer cooling system. In Ref. [13], a system to improve the cooling process of oil-immersed electrical transformers based on

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heat pipes is presented. In Ref. [14] a prediction and experimental study on the cooling performance of radiators used in oilfilled power transformer applications with non-direct flow (ONAN) and direct-oil-forced flow (ODAN—Oil Directed Air Natural) is presented. Radiator temperature distribution and cooling performance was predicted using theoretical calculations, then validated using CFD simulation results.

In Ref. [15], numerical simulations are performed in a slice model of oil-filled distributor transformer to study thermal transport effects and fluid flow at various nanoparticle concentrations. Natural convection heat transfer is studied using two different nanofluid systems using 3-Dimensional CFD simulations. The effect on the overall heat transfer performance of nanofluids is estimated and compared with transformer oil (base fluid). The authors, in Ref. [16], performed CFD simulations to investigate thermal performance of Oil Natural Air Natural (ONAN) distributor transformer using a slice model. The temperature and velocity profiles were studied at different conditions and the fluid flow pattern was found to be similar in all cases. An optimal mutual configuration of coils and cooling ducts for the effective cooling of a dry-type transformer is presented in Ref. [17] based on the method developed by the author. In the optimization procedure, a Computational Fluid Dynamics (CFD) and a genetic algorithm are combined to optimize the diameters of both the ducts and the coils. The method was applied to cool a special dry-type unit to minimize the hot-spot temperature of the windings.

In Ref. [18] three methods of reducing distribution transformer losses are examined. The first method analyzes the effects of using aluminum electromagnetic shields in a distribution transformer to reduce the stray losses. The possibility of reducing the dielectric losses was shown through experiments in the second method. And the third method of this work analyzes the behavior of wound-cores losses in distribution transformers, as a function of joint configuration design parameters. In Ref. [19] an approach for building a fuzzy load model is proposed. In the first stage of the proposed method, customer class load profiles are constructed. Different from previous load profiling techniques, customer hourly load distributions obtained from load research are converted to fuzzy membership functions based on a possibility-probability consistency principle. With the customer class fuzzy load profiles, customer monthly power consumption, and feeder measurements, hourly loads of each distribution transformer on the feeder are estimated. The load data is not represented by a unique value, but by intervals with confidence levels.

Taking into consideration the energy efficiency, the conservation of energy and environmental concerns, this work aims at developing an efficient distribution transformer, with reduced weight/power ratio and that is environment friendly.

In order to achieve that, amorphous core technology is applied, resulting in a significant reduction in no load losses. It is also applied the vegetable insulating oil, reducing the risk of environmental accidents in case of oil leakage and improving the efficiency of the cooling system, as attested by a Computational Fluid Dynamics (CFD) analysis using Finite Volume Method. The electrical project of the transformer is optimized by changing parameters of the project, such as: inductance, current density, number of turns (volts/turn) and the aspect ratio of coil form (diameter/height ratio of wires). Hence, the main contribution of this paper is the concomitant use of these technologies and analysis techniques for low power transformers (distribution), highlighting the following:

(i) concomitant employment of new technologies in distribution transformers, such as amorphous core and vegetable insulating oil;
(ii) approach for projecting transformers with both amorphous core and vegetable insulating oil, considering the typical load profile of the network at the point of installation and total cost of the equipment;
(iii) utilization of the finite volumes method in thermal simulations of cooling systems of distribution transformers.

As result, a prototype unit of 75 kVA, voltage class of 15 kV, primary voltages of 13,800/13,200/12,600 V and secondary voltages of 380/220 V, amorphous core, aluminum wires and vegetable insulating oil was developed.

It is found that in constructive terms there is no significant evolution for distribution transformers, especially regarding the use of new materials. In this sense, the main contribution of this work is the concomitant use of these technologies and analysis techniques for low distribution transformers, through the concomitant employment of new technologies in distribution transformers, such as amorphous core and vegetable insulating oil, approach for projecting transformers with both amorphous core and vegetable insulating oil, and utilization of the finite volumes method in thermal simulations of cooling systems of distribution transformers, having as final result a prototype unit.

For a better understanding, this paper is organized as follows: Section 2 deals with the materials used in the core of transformer and the materials used as dielectric and coolant fluid. Section 3 presents the technical and economic feasibility study. Section 4 presents the methodology of project of distribution transformers with amorphous core and vegetable insulating oil. Section 5 presents the study of a thermal dissipation system in order to determine the best configuration to keep the operating temperature within the limits established in the standard. Section 6 shows the development of the prototype unit. Section 7 presents the experimental validations of the prototype unit. Section 8 presents the conclusions of this paper.

2. Materials

2.1. Amorphous core

The performance and efficiency of transformers are directly related to the type of material used in the production of the magnetic core. Throughout the years, the discovery of new materials and the enhancement of isolation and manufacturing techniques have led to substantial improvements of the performance of the transformers.

The most common metallic alloys used in the core of transformers, such as silicon electrical steel, usually present crystal atomic structure, in which the atoms are arranged in an orderly and repeatable network. In contrast to these alloys, the amorphous metals present the atoms randomly distributed and devoid of any order in long distance, as in glasses, which easily allow the magnetization of the material [20,21].

One of the advantages of the amorphous core transformer is the lower magnetization current, when compared to the conventional transformers of silicon electrical steel. Besides, amorphous metals present some advantageous features to establish the magnetic induction, a narrow hysteresis loop and high magnetic permeability, despite having a lower saturation flux density. These characteristics guarantee lower hysteresis losses in comparison to the silicon electrical steel. Therefore, the project of the magnetic circuit of the amorphous core transformers assures lower magnetization current and higher efficiency [20,21]. In Fig. 1, it is possible to compare the hysteresis loop of an amorphous alloy to the hysteresis loop of a Grain Oriented Electrical Steel.

The high electrical resistivity, a desired characteristic for the transformers core, and the thickness of the strips of amorphous metal (around ten times thinner than the strips of silicon electri-