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Techno-economic comparative evaluation of mixed and conventional magnetic wound cores for three-phase distribution transformers

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ABSTRACT

This paper presents a comparative evaluation of conventional and mixed magnetic wound cores for three-phase distribution transformers. The authors utilize a techno-economic analysis based on an analytical approach in order to determine the variables that differentiate the mixed three-phase transformer from the conventional one. The techno-economic characteristics of two 100 kVA three-phase transformers, a conventional one manufactured of HiB electrical steel and a mixed one manufactured of conventional and HiB steels, are compared using an estimator function and laboratory tests. The authors demonstrate that the mixed three-phase transformer presents improved characteristics over the conventional one for a wide range of sales margins, material costs, magnetization levels, and geometric variables. As a consequence, mixed magnetic wound cores can be an excellent alternative for the E.U. distribution networks where it is necessary to reduce losses, greenhouse gas emissions, and energy costs.

1. Introduction

In the European Union (EU-27), according to strategies for development and diffusion of Energy Efficient Distribution Transformers (SEEDT), losses of distribution transformers are calculated at 33 TWh/year [1,2]. In addition, the reactive power losses and higher harmonics contribute a further 5 TWh/year, resulting in total losses of about 38 TWh/year [1,2]. Moreover, an estimated of 5.5 million of conventional distribution transformers will be installed in the distribution grids of Europe during the next 33 years (2017–2050) [3,4]. The aforementioned represents an additional energy consumption of 72 TWh, a production of 8 Mt of CO_2 emissions, and consequently a negative impact on the environment and the distribution grids.

As a result, utilities, distribution system operators, transformer manufacturers, and individual customers, are all interested in purchasing or manufacturing distribution transformers of the lowest possible total owning cost (TOC) i.e., the sum of the first cost of the transformer and the present value of its future losses, maintenance costs and so on [5]. The minimization of the TOC of a transformer, while satisfying international standards like the IEC 60076, is carried out by optimization procedures that take into account all aspects of the analysis of a transformer, like electromagnetic, thermal and so on, the capitalization of losses, availability of materials like electrical steels and winding materials etc. [6]. However, after the application of the aforementioned optimization processes there is no more room for reducing further the TOC of a transformer. As a result, other solutions and approaches must be sought.

In this paper, such an out of the box approach is used for the reduction of the TOC which is based on experimental evidence concerning the flux density non-uniformity of individual wound cores of conventional three-phase distribution transformers [7]. By using high magnetization grain-oriented electrical steel (HiB) for the wound cores operating at high flux density and conventional electrical steel for the wound cores operating at lower flux density, the overall no-load losses of the mixed three-phase transformer exhibits comparable no-load losses with a conventional distribution transformer [8], but at a lower manufacturing cost i.e., the TOC is reduced.

It is not implied that the optimum mixed three-phase distribution transformer exhibits always a lower TOC than the optimum conventional one or that the conventional optimization procedure should be abandoned all-together. Instead, it is proposed to update the existing transformer optimization procedures in order to include the mixed three-phase wound core topology,

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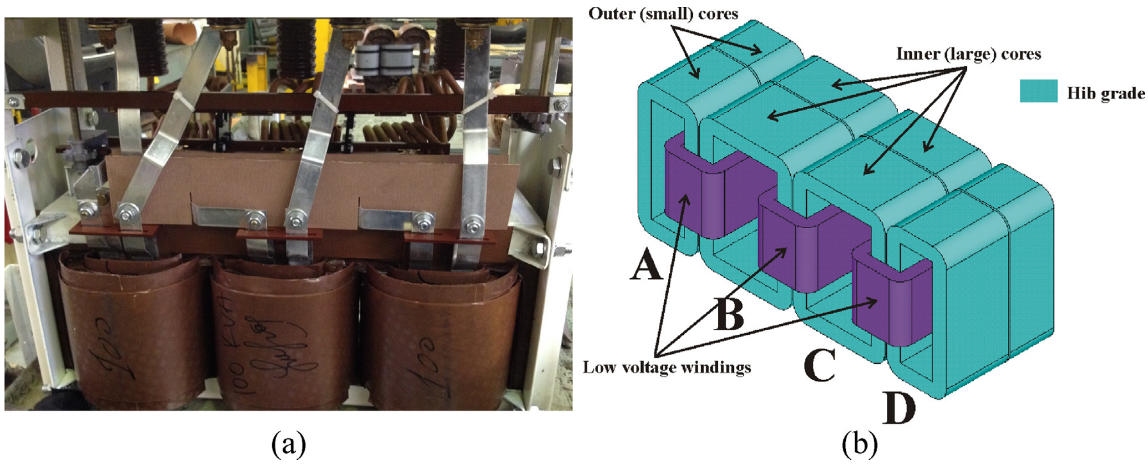

Fig. 1. Conventional three-phase, five-legged, wound core. (a) Active parts. (b) Topology.

then compare the optimum designs of the mixed and conventional three-phase wound core, and finally make the transformer selection decision based on which design presents the lowest total owning value while satisfying international standards, customer needs, and all necessary constraints.

The concept of mixed three-phase wound cores differs significantly with existing approaches appearing in research papers and patents in the technical literature. In patent [9] and in research papers [10–12] composite single-phase wound cores are developed. In Ref. [13] the aforementioned composite single phase wound cores are combined in order to manufacture the respective three-phase wound core. Also, in research papers [14–16] the combining of electrical steels is carried out on three-phase, three-legged, stack core transformers whereas in the present paper a mixed three-phase, five legged, wound core is developed that presents a significantly different topology in comparison with the stack core transformers.

The purpose of this paper is on one hand to introduce the concept of the mixed three-phase wound core and on the other hand to determine the variables and conditions that differentiate the mixed and conventional three-phase wound core designs from each other. Afterwards, it is investigated how those conditions and variables, that determine the core selection decision, favor the mixed three-phase wound core design over the conventional one.

2. Working principle of the mixed three-phase wound core distribution transformers

2.1. Brief description of conventional three-phase, five-legged distribution transformer

A large number of the installed three-phase, oil-immersed, distribution transformers are constructed of wound cores assembled about preformed windings. Ratings typically range from 50 kVA to 2 MVA. Fig. 1 shows the active part of a three-phase, five-legged transformer. The transformer core is assembled of two large, inner wound cores (cores B and C) and two smaller, outer wound cores (cores A and D). Typically, all individual wound cores are manufactured of the same grade of electrical steel.

2.2. Experimental findings on flux density non-uniformity in conventional three-phase transformers

Experiments carried out on the conventional five-legged, wound transformer core show that the flux density of the individual cores is not the same [7]. More specifically the flux density of the outer cores is lower than the inner wound cores. Only after a certain magnetization level the flux density of the outer wound cores reaches that of the inner wound cores due to the magnetic saturation of the electrical steel. The aforementioned is valid regardless of the grade of the electrical steel. Fig. 2 shows the peak flux density as obtained experimentally in Ref. [7], of the wound cores of a 100 kVA three-phase transformer core manufactured 100% with HiB steel for two calculated magnetization levels, 1.2 T and 1.6 T. Fig. 2 shows that the flux density of the outer wound cores A and D is significantly lower than the large inner wound cores B and C.

The magnetization level of the three-phase transformer is calculated using a standard method applied in the transformer industry. The specific method considers the connection of the excitation winding and a balanced, three-phase, sinusoidal, voltage source. As a result, and by applying Faraday's law, the magnetization level of the three-phase transformer is given by Eq. (1) in the case of a delta connection. N_s is the number of winding turns of the excitation winding, c_{sf} is the core stacking factor (0.965), E_u is the thickness of the wound cores shown in Fig. 2, D is the axial length of the core, f is the frequency, and V_{rms} is the rms value of the line-to-line voltage.

$$B = \frac{\sqrt{2}}{4 \cdot \pi} \cdot \frac{V_{rms}}{c_{sf} \cdot E_u \cdot D \cdot f \cdot N_s} \tag{1}$$

On the other hand, the peak magnetic flux density of individual wound cores shown in Fig. 2, is obtained experimentally by using search coils and an experimental setup based on a PC equipped with a data-acquisition PCI card of National Instruments (NI6143), current probes based on the Hall Effect, and active differential voltage probes. The captured current and voltage waveforms are post-processed, using virtual instruments created with LabVIEW software, in order to compute iron losses, values of local peak flux density, and the harmonic content of the flux density waveforms [7,8].

Even though, the peak flux density of the outer wound cores is lower than the inner cores, the induced voltage waveform in all of the secondary windings has the same amplitude and it is offset from the others by 120°. This is due to the high harmonic content of the flux density waveforms [17,18] of the outer and inner wound cores caused by the unsymmetrical magnetic circuit topology of the three-phase, wound core, transformer which was first proposed in Ref. [19]. Detailed experimental and theoretical studies of the five-legged three-phase wound core transformer are given respectively in Refs.[7,20].