Mixed Si-Fe Wound Cores Five Legged Transformer: Losses and Flux Distribution Analysis

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This paper proposes a three-phase five legged wound transformer core constructed of two high permeability Si-Fe wound cores and two conventional Si-Fe wound cores. The two large internal wound cores are manufactured of high permeability, grain-oriented electrical steel. The two small outer wound cores are manufactured of conventional, grain-oriented electrical steel. The specific arrangement is based on experimental evidence concerning the peak flux density non-uniformity of the typical three-phase five legged wound transformer core, constructed of the high magnetization grain-oriented steel. Since the peak flux density of the two outer cores is lower than the two internal cores, low cost, low permeability, conventional grain-oriented electrical steel can be used for the outer cores. Losses, excitation currents, flux waveforms, and their harmonics contents are presented in this paper. A comparison of the mixed three-phase transformer core and the typical one is also carried out.

Index Terms—Magnetic cores, magnetic field measurement, magnetic losses, power transformers.

I. INTRODUCTION

PRESENT energy costs are driving transformer manufacturers to reduce distribution transformer life-cycle costs while maximizing their financial gains [1]. This is because, distribution transformers are the second most energy intensive component of the power grid, since one third of transmission and distribution losses take place in transformers, while almost 70% of the losses take place in the distribution grid [2].

A number of new transformer topologies, novel core joint types [3], and improved electrical steels [4], have been developed in order to improve transformer efficiency. Composite magnetic cores have been proposed for the reduction of the manufacturing and operational cost of distribution transformers without the need to revolutionize the transformer topology or magnetic materials [5]–[7]. A composite wound core is a magnetic core constructed of a combination of conventional grain-oriented and high magnetization grain-oriented electrical steel laminations. Its operating principle is based on the flux-density non-uniformity of wound cores. So far, research studies showed that it is possible to reduce distribution transformer costs and losses by using composite wound cores [7], [8].

This paper proposes a different approach for reducing the manufacturing cost of a three-phase wound core distribution transformer, while limiting its operating cost i.e., iron losses. In particular, it is proposed to assemble the three-phase magnetic core of two large internal wound cores manufactured of high permeability grain-oriented electrical steel and two smaller outer wound cores manufactured of conventional grain-oriented electrical steel.

This arrangement is based on recent experimental analysis of the flux density distribution of the three-phase five legged wound core transformer. According to [9], the peak flux density of the two outer cores is lower than the two internal cores. Therefore, low cost, conventional grain-oriented electrical steel can be used for the outer cores.

The high permeability grain-oriented steel of the two internal wound cores conduct more magnetic flux than the conventional grain-oriented steel of the two outer wound cores. Considering that the iron loss is a function of peak flux density, the iron loss of the mixed three-phase magnetic core is expected to be marginally increased, up to a critical induction level.

II. WOUND CORE DISTRIBUTION TRANSFORMERS

One-phase and three-phase, oil-immersed, distribution transformers are commonly made of wound cores assembled about preformed electrical winding coils. A simplified schematic of a typical wound core and its main geometrical parameters is shown in Fig. 1. Wound cores, are constructed by cutting and spirally winding a flat strip of grain-oriented steel into hundreds concentric turn laminations [10]. Cutting of the electrical steel is carried out so that joints are formed in which overlap is gradual, flux transfer is eased, and flux normal to the sheet is minimized. This joint type is known as step-lap joint, and its efficiency is determined by the overlap length and gap length [10], [11].

III. SINGLE-PHASE AND THREE-PHASE TRANSFORMER CORES

A. Single-Phase Transformer Cores

Six wound cores, A to F, were used for the experimental analysis of this paper. The dimensions, mass, and electrical steel of each core is shown in Table I. The thickness of the high magnetization (M-OH) and the conventional (M4) grain-oriented steel
TABLE I
WOUND CORES MANUFACTURING DATA

<table>
<thead>
<tr>
<th>Core</th>
<th>Eu (mm)</th>
<th>Fl (mm)</th>
<th>G (mm)</th>
<th>D (mm)</th>
<th>Mass (kg)</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>24.3</td>
<td>57</td>
<td>183</td>
<td>190</td>
<td>18.3</td>
<td>M-OH</td>
</tr>
<tr>
<td>B</td>
<td>24.3</td>
<td>114</td>
<td>183</td>
<td>190</td>
<td>22.1</td>
<td>M-OH</td>
</tr>
<tr>
<td>C</td>
<td>24.3</td>
<td>114</td>
<td>183</td>
<td>190</td>
<td>22.1</td>
<td>M-OH</td>
</tr>
<tr>
<td>D</td>
<td>24.3</td>
<td>57</td>
<td>183</td>
<td>190</td>
<td>18.3</td>
<td>M-OH</td>
</tr>
<tr>
<td>E</td>
<td>24.3</td>
<td>57</td>
<td>183</td>
<td>190</td>
<td>18.3</td>
<td>M4</td>
</tr>
<tr>
<td>F</td>
<td>24.3</td>
<td>57</td>
<td>183</td>
<td>190</td>
<td>18.3</td>
<td>M4</td>
</tr>
</tbody>
</table>

is 0.27 mm. Each core is comprised of 88 steel sheets. The gap and lap length of the step-lap joint are 4 mm and 10 mm. The six cores have been annealed to remove harmful stresses induced by manufacturing processes.

B. Three-Phase Transformer Cores

Two three-phase five legged wound transformer cores were assembled using the six wound cores of Section III-A. The typical three-phase magnetic core was assembled of the high permeability steel cores A to D, Fig. 2(a). The mixed three-phase five legged transformer core was assembled by replacing the outer cores A and D of the typical one with the conventional steel cores E and F, Fig. 2(b). In both cases, the yoke length of the two internal wound cores is twice the yoke length of the outer cores, and the mass of the three-phase transformer core is approximately 80.9 kg.

IV. EXPERIMENTAL SETUP

The experimental setup for single-phase and three-phase transformer core measurements is shown in Figs. 3, 4 respectively. The single-phase transformer cores of Section III-A were magnetized from 1.0 T to 1.74 T by a twenty turn excitation coil supplied with a sinusoidal voltage waveform, 50 Hz, from a programmable ac and dc power supply (California Instruments MX30). In the three-phase experimental setup, three twenty turns excitation coils in delta connection were supplied with a balanced three-phase, 50 Hz, sinusoidal voltage waveform, from the programmable power supply MX30 in order to magnetize the three-phase transformer cores to the same induction levels. Four one-turn search coils (SCs), were wound around the total width of the upper yoke of each core as shown in Fig. 4.

The voltage across the excitation coil terminals was captured using active differential voltage probes. Current probes based on the Hall Effect were used for capturing the magnetizing currents. The output of the probes and the SCs was connected to a noise rejecting BNC connector block (BNC-2110) via passive probes. A noise rejecting, shielded cable connects the data acquisition (DAQ) device directly to the BNC-2110. The DAQ device used was National Instruments (NI) 6143 (8 differential channels, 16-bit resolution, and maximum sampling rate of 250 kSamples/s).

Four virtual instruments (VI) were created with the use of LabVIEW software. The first two were used for capturing the voltage and magnetizing current waveforms for two periods of the fundamental frequency and for the maximum sampling rate of the DAQ device. The last two were used for manipulating the acquired voltage and current data in order to compute, losses, flux waveforms, and their harmonic content.

V. EXPERIMENTAL RESULTS AND ANALYSIS

A. Single-Phase Magnetic Core Losses

Fig. 5 shows the specific iron losses of the six wound cores of Section III-A as a function of the induction level. For 1.5 T the mean loss of the HiB and M4 cores is 0.715 W/kg and 0.81 W/kg. For 1.7 T the respective mean loss is 0.97 W/kg and 1.235 W/kg. The difference in loss for the HiB cores A to D is within
2% for induction levels up to 1.74 T. This is not the case for the M4 cores E, F where the difference in loss at 1.74 T is nearly 10%.

### B. Three-Phase Magnetic Core Losses

Fig. 6 shows the specific iron losses of the typical and the mixed three-phase transformer cores as a function of the induction level. Also, it shows for comparison the sum of the single-phase losses of the A, B, C, D and E, B, C, F wound cores. For 1.5 T and 1.7 T the loss of the typical and the mixed three-phase transformer cores is 1.02 W/kg, 1.05 W/kg and 1.43 W/kg, 1.56 W/kg respectively. The building factor at 1.5 T for the typical and mixed three-phase transformer cores is 1.45, 12. For 1.7 T the building factor is 1.49 and 1.51 respectively. Fig. 7 shows the specific iron loss increase percentage of the three-phase and single-phase transformer cores, as a function of the induction level. In both cases the increase in losses is exponential. The increase in losses of the mixed three-phase transformer core is limited to less than 5.4% up to 1.6 T. For 1.7 T the respective increase percentage is 9.4%. This suggests that a critical induction level exists, where after that the increase in loss is unacceptable.

### C. Comparison of Flux Waveforms and Their Harmonics

Fig. 8 shows flux density waveforms of the typical and mixed three-phase transformer cores for 1.2 T and 1.6 T. Those were obtained by the four search coils of Section IV. The flux waveforms of cores A, D and E, F are in phase and out of phase by 120° with cores B, C [9]. For 1.2 T, the peak flux density of E, F cores is lower than cores A, D and cores B, C. Also, the peak flux density of the cores B, C of the typical three-phase transformer core is lower than cores B, C of the mixed three-phase transformer core. This is because cores B, C of the mixed transformer core conduct more flux due to the low permeability of cores E, F. For 1.6 T and in both cases, the peak flux density of the outer cores reaches that of the internal cores due to the saturation of the HiB grain-oriented steel of cores B, C.

Fig. 9 shows the peak flux density harmonics contents of the typical and mixed three-phase transformer cores for 1.2 T and 1.6 T. The peak amplitude of the 1st harmonic component is larger than the induction level due to the phase angle of the
higher harmonic components relative to the fundamental. The mixed transformer core has larger 3rd and 5th harmonic components than cores A, D and B, C. This explains the increased losses of the mixed three-phase transformer core.

### D. Three-Phase, Line, Excitation Currents

Fig. 10 shows the line excitation rms currents of the typical and mixed three-phase transformer cores as a function of the induction level. In both cases the rms value of the excitation currents of phases L2, L3 is smaller than the phase L1. This is because phases L2, L3 link via the delta connection of the excitation coils, one internal and the adjacent outer core whereas the L1 phase links the two outer cores. The line excitation currents of the mixed three-phase transformer core are significantly larger than the typical one. For 1.5 T, the L1 rms current of the typical and mixed transformer cores is 0.97 A and 1.15 A. The respective L1 rms current for 1.7 T is 1.45 A and 2.625 A.

### VI. CONCLUSION

Considering that the cost of the M4 grain-oriented steel is 19% less than the HiB grain-oriented steel, the financial gain of using a mixed wound three-phase transformer core would be 8.6%. This is a significant percentage considering that from the various materials required to manufacture a transformer, the electrical steel comprises the largest investment.

Increase in loss is limited up to a critical induction level, due to the lower peak flux density of the outer cores, the higher magnetic flux conducted by the HiB internal cores, and the low loss characteristics of the HiB steel. As a result, increase in loss is limited to less than 5.4% up to 1.6 T.

Line excitation current is an important transformer design constraint. Increased line excitation current is a drawback of the mixed three-phase wound transformer core. For 1.6 T the excitation currents are increased by 35%.

### REFERENCES


