AIP | Journal of Applied Physics

Effects of magnetostriction and magnetic reluctances on magnetic properties of distribution transformers

Chang-Hung Hsu, Chun-Yao Lee, Shan-Jen Cheng, Chao-Ming Fu, and Chia-Wen Chang

Citation: Journal of Applied Physics **115**, 17E718 (2014); doi: 10.1063/1.4870317
View online: http://dx.doi.org/10.1063/1.4870317
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/115/17?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS **115**, 17E718 (2014)

Effects of magnetostriction and magnetic reluctances on magnetic properties of distribution transformers

Chang-Hung Hsu,[1,2] Chun-Yao Lee,[3,a)] Shan-Jen Cheng,[4] Chao-Ming Fu,[5] and Chia-Wen Chang[6]
[1]*Division of Electrical Engineering, Fortune Electric Company Ltd., Tao-Yuan 320, Taiwan*
[2]*Department of Computer and Communication Engineering, Army Academy R.O.C., Tao-Yuan 320, Taiwan*
[3]*Department of Electrical Engineering, Chung Yuan Christian University, Tao-Yuan 320, Taiwan*
[4]*Department of Aircraft Engineering, Army Academy R.O.C., Tao-Yuan 320, Taiwan*
[5]*Department of Physics, National Taiwan University, Tai-Pei 10617, Taiwan*
[6]*Department of Information and Telecommunications Engineering, Ming Chuan University, Tai-Pei 33348, Taiwan*

(Presented 7 November 2013; received 23 September 2013; accepted 17 December 2013; published online 2 April 2014)

This paper analyzes the causes of magnetic reluctance in silicon steel wound cores with multi step-lapped joint structures through the appropriate exploitation of simulated and experimental local flux distributions in an air-gapped core, to propose techniques that can enable the reduction of the resulting core loss and vibration. The magnetic magnetostriction forces in the lap-joint regions, constituting another significant source of permeability, can be controlled by rearranging the step-lapped joint structure. Then, the computed local flux distributions were compared with experimental data. Single-phase pad-mounted distribution transformers with a capacity of 167 kVA were used in this study. It is indicated that the multi-step lap joint can significantly reduce the core loss and exciting power by regulating the configuration of adjacent air-gapped distances. Finally, composite-core structures were also used to validate the reduction of magnetostriction, core loss, and vibrations, corresponding to single-phase distribution transformer. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4870317]

I. INTRODUCTION

Magnetostriction effects play an important role in producing core loss and core vibration in wound-core transformers. Theoretical studies involving magnetostriction equations[1,2] give an insight into the vibration noise spectrum and its harmonics content, but they are of limited practical value. A nanocrystalline soft magnetic composite material was used to fill the step-lap joint gap and was shown to suppress magneto-mechanical vibration and noise levels in transformer cores.[3] The structure of the core step-lap joint as well as of the supporting frame of the transformer tank is manipulated to suppress the noise in a single-phase amorphous HB1-core distribution transformer.[4] Core vibration resulting from the magnetostriction effect,[5] which is also a function of magnetization, was analyzed using finite element analysis (FEA). The proposed modeling methodology can be further utilized in vibration noise spectrum analysis. An efficient computational method was described for establishing the equivalent characteristics of the magnetic joints of transformer cores.[6] The experimental results revealed a useful, practical method of predicting field distributions in various types of overlapping core joints.

However, the aforementioned research does not explore an effective method of overcoming the drawbacks of previous transformer structures. This paper is organized as follows. In Sec. II, the magnetic core design and fabrication are described. In Sec. III, the experimental results are discussed. Conclusions are given in Sec. IV.

II. MAGNETISM THEORY AND MODEL

A. Magnetic circuit and core structures

In this study, a 167-kVA single-phase pad-mounted distribution transformer with a wound-core configuration was used. The geometry of the multi-step lap (MSL) configuration employed in the study is illustrated in Figure 1. Transformer cores were constructed with different step-lap joint structures between the sixth to ninth steps. The silicon steel core (23ZDMH90) is 250 mm in width, 550 mm in length, and has a stacked air gap B_g 3 mm in length. B_J is the length between the half points of the air gaps of two contiguous laminations in the rolling direction, where the length increases with the number of added steps, denoted B_{J+n}. Additionally, B_p is the group formed by a certain number of clusters, and it also depends on the number of steps B_{p+n}. The multi-step core for the single-phase transformer, including the simulation (FEA), prototype experimental setup, and core step-lap joint zoon structure, respectively, are shown in Figure 1.

The magnetic reluctance R of a core in general is given by the ratio of the magnetomotive force (*mmf*) and the magnetic flux intensity φ_A through its cross-sectional area A as

$$R = \frac{mmf}{\varphi_A} = \frac{\int Hdl}{\int BdA} = \frac{l}{\mu_0 \mu_r A}, \tag{1}$$

[a)] Author to whom correspondence should be addressed. Electronic mail: cyl@cycu.edu.tw. Fax: +886-3-265-8888.

0021-8979/2014/115(17)/17E718/3/$30.00

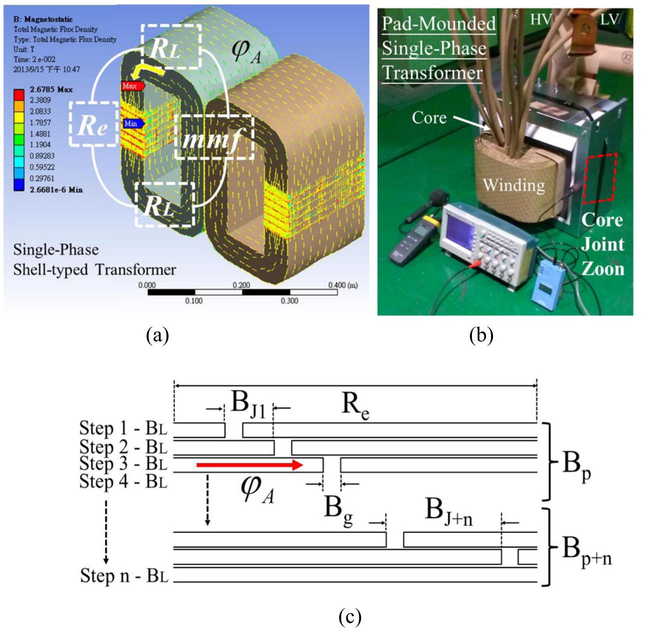


FIG. 1. Single-phase pad-mounted transformer with a wound-type core: (a) FEA results; (b) experimental measurement; and (c) MSL structure.

where μ_r represents the relative permeability and l is the core length. Because the flux must be continuous through a cross section of the step lap joint at B_g and the shutting steel (B_s), the leg lamination flux density (B_L) is given by $2B_g$. This relationship between the flux densities of the leg lamination and air gap is valid only in the regions where the magnetic flux is constant along the rolling plane direction. In joint zones where the magnetic flux is not constant, it is assumed that the reluctance models need to take into account flux variation as a function of l. This involves computing the magnetic flux strength H (A/m) and the magnetic flux density B (Tesla) point-by-point from the FEA simulations:

$$B_L = \frac{B_g + \sum_{k+1}^{n} B_s(k)}{N+1}, \tag{2}$$

where the step lap joint between the sixth and ninth steps is constructed, and the shunting section flux density does not reach saturation. It is clear that the shunting section flux density will never be saturated; therefore, the gap flux density can be assumed to be negligible.

B. Magnetic core losses

It is well known that hysteresis loss P_h (Watt) and eddy current losses P_e (Watt) are the two most important parameters in the computation of transformer core loss P_c (Watt) in joint regions where the magnetic flux density is uniform (most of the lamination length, but excluding the joint zone). In this study, we have used the classic formulation given by

$$P_c = P_h + P_e = k_h f B_m^{1.6} + \frac{1}{24}\sigma(2\pi f)^2 d^3 p L B_k^2, \tag{3}$$

where k_h is a material parameter for eddy current losses in the kth lamination, f (Hz) is the operation frequency, S (S/m) is the lamination conductivity, d (m) is the lamination thickness, p (m) is the lamination width, L (m) is the lamination length, and B_k (Tesla) is the average magnetic flux density in the lamination.

For a given excitation power of the transformer, the individual reluctance values for each of the laminations can be combined, which is used to compute an equivalent reluctance R of the entire core. Because the laminations are in parallel, the equivalent reluctance is given by the inverse of the sum of the inverse reluctances of the individual laminations. Thus, the excitation current in amperes per turn is proportional to the average magnetic flux density in the core B_m (Tesla), the core cross-sectional area A_c (cm^2), and the core mean length L_{mc} (cm), which can be expressed as $I_{exc} \propto B_m A_c L_{mc}/R$.

C. Magnetostriction forces and core vibration

A gap peak flux density of around 1.0 (Tesla) would be required to produce a strain of approximately the same magnitude as of magnetostriction, as shown in the following calculation. This can be denoted as $\rho \propto B^2/2\mu_0$. From this equation, it follows that the Young's modulus is proportional to the magnetic flux density, material strain, magnetostriction, and core vibration force F_c. In addition, the core acceleration can also be proportional to the saturation magnetostriction force ε_s, or $F_c \propto \varepsilon_s$. The equation for the core vibration force can be represented as

$$F_c = \frac{F \sin 2\pi 120 t}{m(2\pi 120)^2}. \tag{4}$$

III. EXPERIMENTAL RESULTS

A. Magnetic flux density, reluctance, and core loss

Referring to Eqs. (1) and (2), the effects of the magnetostriction of magnetic reluctances on a single-phase transformer of 167 kVA with an MSL structure is validated by FEA simulation results. To validate the MSL model and FEA-simulated magnetic flux variation results, the cores with MSL joint structures for magnetic flux density depending on magnetic reluctance were analyzed, as shown in Figure 2. Comparisons of experimental results and FEA results for several types of models are presented in Table I. A transformer core with a MSL structure reduced the core loss by approximately 13%.

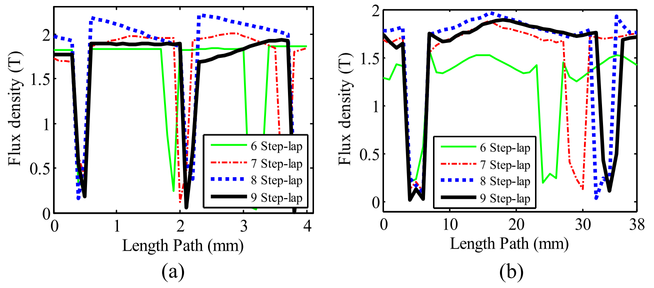
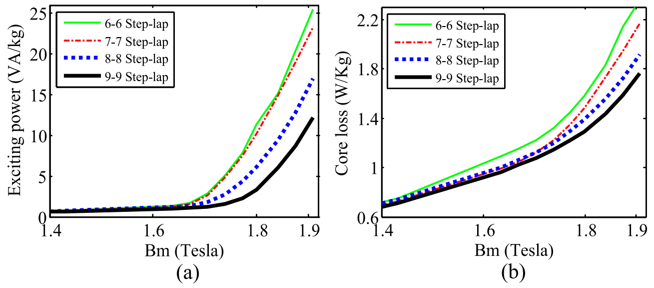


FIG. 2. Permeability variation in MSL core: (a) Adjacent air gap in the horizontal direction; (b) adjacent air gap in the vertical direction.

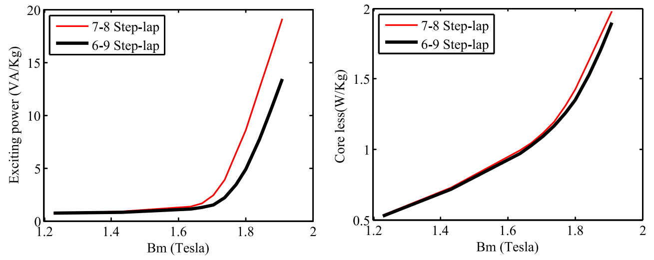
TABLE I. Comparison of the experimental and FEA simulation results.

MSL step-lapcore and composited core	Core loss (Watt) FEA	Core loss (Watt) Measured results	Core vibration (m/s^2) FEA	Core vibration (m/s^2) Measured results
6 and 6 step	325.6	345.1	58.2	56
7 and 7 step	325.3	343.6	58.8	58
8 and 8 step	318.8	322	59.1	59
9 and 9 step	312.6	299.1	60.2	62
7 and 8 step	336.7	335.8	52.8	42
6 and 9 step	315.6	303.4	50.1	38



(a) (b)

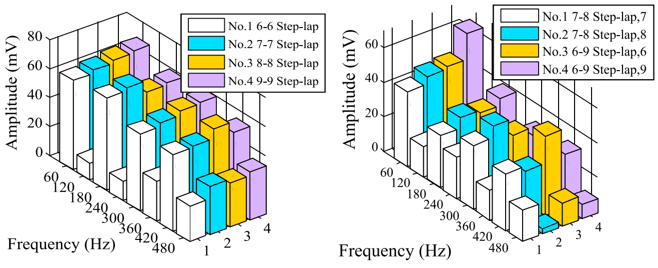
FIG. 3. MSL core-structure, sixth to ninth step lap: (a) Excitation power; (b) core loss.



(a) (b)

FIG. 4. MSL core with composite structure: (a) Excitation power; (b) core loss.

Additionally, the reduction of the excitation power (VA/kg) and core loss (Watt/kg) for a wound core distribution transformer with increasing numbers of step-lap joint groups is shown in Figure 3. It is obvious that the interlaminar flux is exhibited at the overlapped gaps, which yields a compressive off-plane strain, and the magnetic flux lines induced variations between adjacent air gaps with lower step numbers at a shorter distance, much less than with the higher step numbers of the MSL. This is because the multi-stack-structure is used to reduce not only clamping stress effects but also magnetic flux variation when the magnetic flux passes through the lap gaps. In this study, a composite-typed core-structure single-phase transformer is proposed, primarily to reduce off-plane magnetostriction stress (MS) and magnetic flux (MF) variation due to the permeability under a stabile situation, which can induce lower core loss, as shown in Figure 4.



(a) (b)

FIG. 5. Transformer vibration measurement results: (a) Normal MSL core structure; (b) composite core structure.

B. Core vibration and magnetostriction

For the single wound core vibration, the faces of the core induce magnetostriction-forced displacements because $F_c \propto \varepsilon_s$. For a large radial structure, displacements of the normal surfaces can be very significant. One should be able to calculate the core natural frequencies so that the core can be designed to avoid resonances at the harmonics of the core forcing frequencies, i.e., multiples of 120 Hz. Table I indicates that increasing multi step-laps depend on the experiment and FEA results of higher core vibration because the MSL extends each gap distance. Because the core joint lap is closer to the core corner of the two sides, it will induce magnetostriction variation and core vibration. Additionally, this study has found a new method to suppress core vibration using composite-type multi-structure cores, which can decrease core vibration acceleration by more than 40%. In particular, the composite structure in the case of 6–9 and 7–8 step-lap joints is validated, as shown in Figure 5, by decreasing the resonance core vibration by at least 30 percent.

IV. CONCLUSION

This paper proposed a method of reducing the core loss and core vibration for single-phase transformers using an MSL structure, which contains air gaps with adjustable positions. A magneto-mechanical strong coupled model for laminated cores including MS was found. The computed FEA results show that the proposed method using composite cores leads to reduced core loss and vibration compared to most traditional MSL step-lapped methods.

[1] B. Weiser, H. Pfützner, and J. Anger, IEEE Trans. Magn. **36**(5), 3759–3777 (2000).
[2] T. Hilgert, L. Vandevelde, and J. Melkebeek, IEEE Trans. Magn. **44**(6), 874–877 (2008).
[3] L. Zhu *et al.*, J. Appl. Phys. **113**, 17A333-1–17A333-3 (2013).
[4] Y.-H. Chang *et al.*, J. Appl. Phys. **109**, 07A318-1–07A318-3 (2012).
[5] Q. Li *et al.*, IET Electr. Power Appl. **6**(9), 604–610 (2012).
[6] E. Napieralska-Juszczak *et al.*, IEEE Trans. Magn. **47**(1), 244–247 (2011).