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Effects of magnetomechanical vibrations and bending stresses on three-phase three-leg transformers with amorphous cores

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This paper explores the influence of bending stresses on the magnetic characteristics of three-phase transformers with amorphous cores. Different types of core structures, including C-cores and toroidal cores, and their magnetic properties are compared using VSM and XRD. The losses in the magnetic core of the three-phase transformer are analyzed using the finite element analysis for both design and measurement. In addition, experimental results indicated that amorphous-core transformers with rectangular corners had higher audible noise and vibration intensities. This is because the condensed distribution of magnetic flux lines in the corners of the core may create high magnetic inductions associated with high magnetostriction. Finally, experiments with three-phase amorphous-core transformers were performed to study the effects of magnetism and magnetostriction on their performance in terms of core loss, vibration, and audible noise. © *2012 American Institute of Physics*. [doi:10.1063/1.3678459]

In recent years, laws have been adopted to protect the environment from energy losses that can occur within amorphous-core transformers used in power systems.[1] As seen in previous research,[2,3] finite element analysis (FEA) is often used to analyze the magnetic properties of power devices. Two types of magnetostriction models with different structures were compared in order to study transformer vibration.[4] The advantages and disadvantages of various magnetostriction models used in understanding the effect of the vibration of the core have been discussed.

In this paper, changes in magnetic hysteresis loss and magnetostriction in amorphous cores due to the core bending stress are investigated. It is known that core loss decreases and magnetic permeability increases with decreasing magnetostriction. From recent works of Chang *et al.*,[5,6] the relationship between magnetic loss and magnetostriction can be represented as

$$\varepsilon_s \propto Hc \propto \sigma \propto K_1 \propto D, \tag{1}$$

where ε_s is the coefficient of saturation magnetostriction of the soft magnetic material sheet, $\propto$ (A/m) is the coercivity, σ is the torsion stress, K_1 is the magnetocrystalline anisotropy of the grains, and D is the average grain size. This indicates that the hysteresis loss is proportional to the variation in magnetostriction. In addition, a higher torsion stress will result in a larger hysteresis loss.

Generally, the fundamental frequency of winding vibration acceleration is 120 Hz, which is twice that of the rated power frequency. The forces of magnetostriction are known to cause core vibrations, and the core vibration acceleration thus induced can be written as[6]

$$a_{core} = -\frac{2\varepsilon_s L U_0^2}{(N_1 A B_s)^2} cos 2\omega t, \tag{2}$$

where L is the length of the sheet; U_0 is the magnitude of the voltage-driving source; $\omega = 2\pi f$, with f denoting the frequency of the voltage-driving source (60 Hz in Taiwan); N_1 is the number of primary turns; A is the cross-sectional area of the core leg; and B_s is the saturation magnetic flux density (tesla). This means that the core vibration acceleration (m/s^2) is proportional to the magnetostriction, i.e., $a_{core} \propto \varepsilon_s$.

For audible noise, a relationship that defines the magnitude of audible noise as a function of the physical properties of the core material audible noise of the core N_c (dB), core weight W_t (tons), cross-sectional length of the core Φ (m), and magnetic flux density B (tesla) is proposed.[5] According to the aforementioned viewpoints, the core vibration and audible noise of an amorphous-core transformer can be reduced through a decrease in the magnetostriction.

For finite element analysis, the electromagnetic forces are calculated from the local magnetic flux density in the power transformer. When the transformer current flows into the windings, the electromagnetic equation is as follows:

$$\nabla \times \frac{1}{\mu}(\nabla \times \vec{A}) = \vec{J}_S - \rho\frac{\partial \vec{A}}{\partial t}, \tag{3}$$

where μ is the magnetic permeability (in H/m), $\vec{A}$ represents the magnetic vector potential, $\vec{J}_s$ is the current density (in A/m^2), and ρ is the conductivity (in S/m); magnetic induction is defined as

$$B = \nabla \times A, \tag{4}$$

Thus, the magnetic flux linkage can be obtained. Two types of magnetizing inductions of different phase are shown in Fig. 1. The 60 Hz magnetizing current of 0.15 A rms at the

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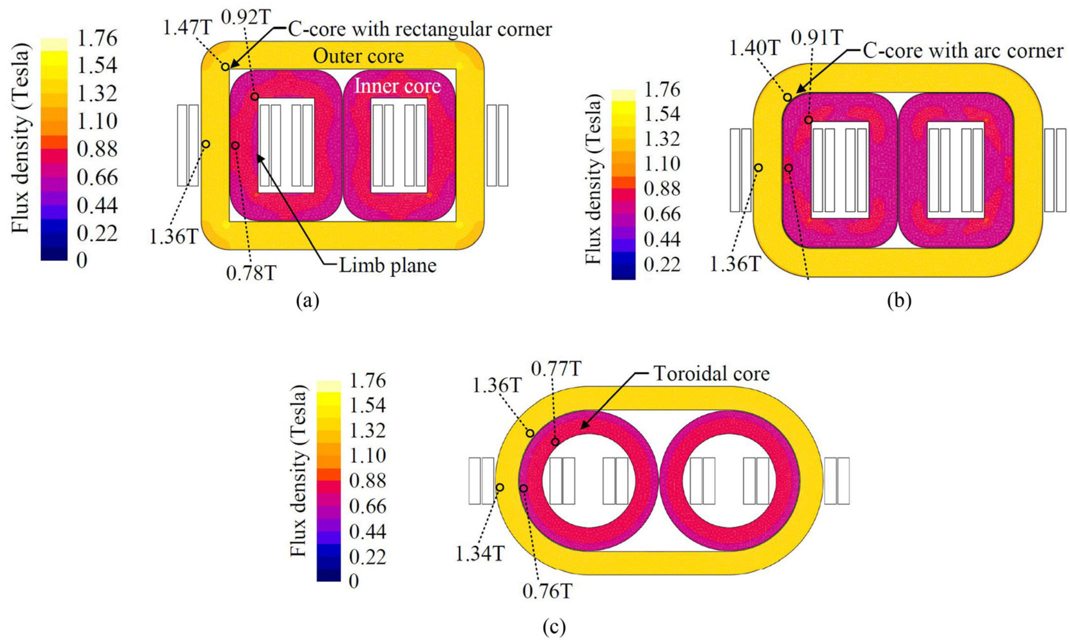


FIG. 1. (Color online) Amorphous-core transformer with different bending structures analyzed using FEA: (a) C-core with rectangular corners, (b) C-core with arc corners, and (c) toroidal core.

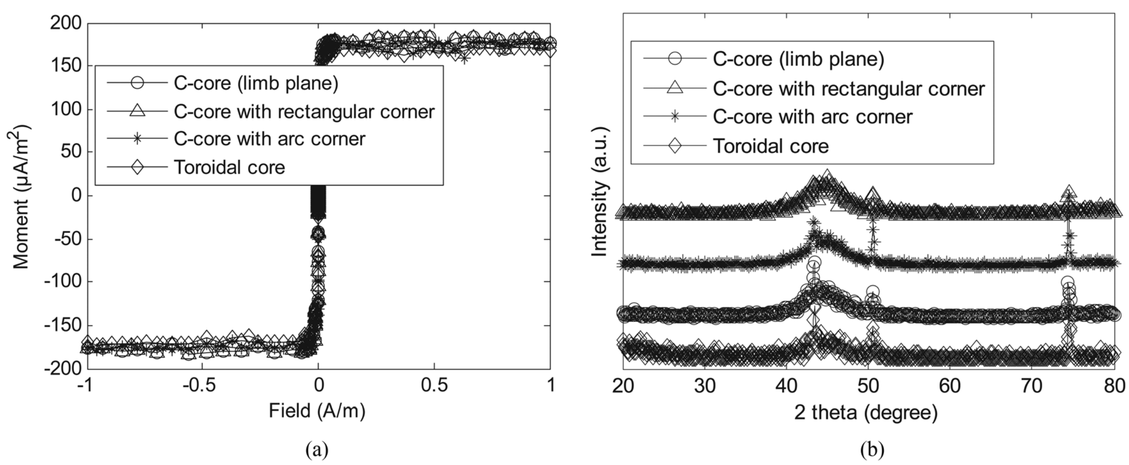


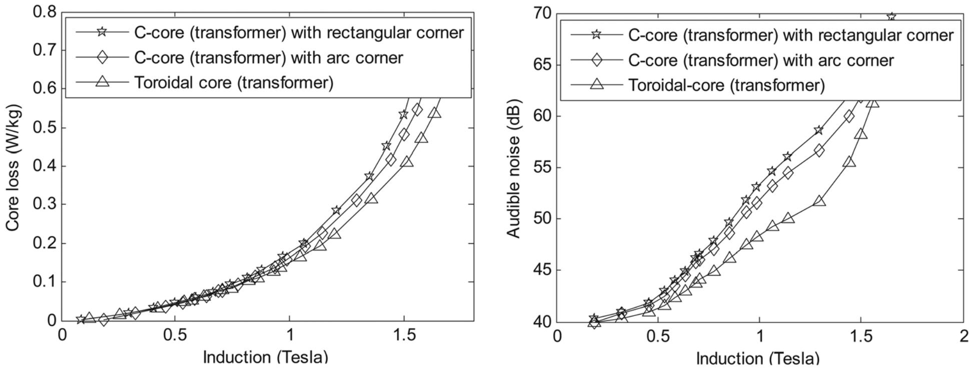
FIG. 2. Measurement results of amorphous alloy SA1 with different bending structures: (a) VSM and (b) XRD.

TABLE I. Magnetic properties of Fe-based amorphous ribbon samples annealed at 350 °C.

Measurement parameter	Saturation magnetization, B_s (μA/m^{-2})	Remanent magnetization, B_r (μA/m^{-2})	Coercivity, Hc (A/m)	Resistivity, ρ (mΩ cm)
C-core (limb plane)	179.61	1.37	0.21	0.132
C-core (rectangular corner)	178.35	1.2	0.35	0.115
C-core (arc corner)	175.48	1.45	0.25	0.118
Toroidal core	176.25	1.12	0.26	0.128

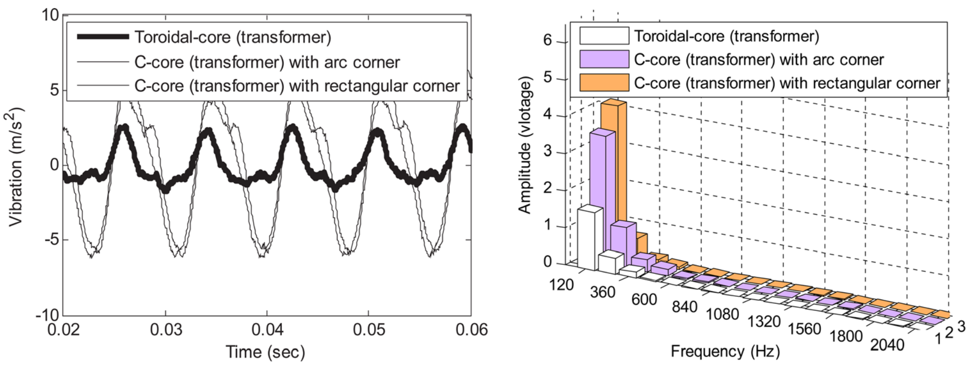
TABLE II. Comparison of FEA results and manufacturer design measurements.

	FEA design values (W/kg)			Measured values (W/kg)
Category	Inner core	Outer core	Total core loss	Core loss
C-core with limb plane	0.358	0.331	0.329	0.352
C-core with rectangular corner	0.349	0.31		
C-core with limb plane	0.356	0.32	0.318	0.326
C-core with arc corner	0.347	0.312		
Toroidal core with limb plane	0.347	0.31	0.306	0.301
Toroidal core	0.346	0.306		



(a) (b)

FIG. 3. Measurement results of amorphous-core transformers with different bending structures: (a) core loss and (b) audible noise.



(a) (b)

FIG. 4. (Color online) Measurement results for three-phase amorphous-core transformers: (a) time-domain data, (b) FFT frequency analysis.

83.5 V side would produce magnetic density of around 1.3 (T). It can be observed that the magnetic flux line passing through part of the C-core corner exhibits a higher magnetic flux density, which means that the increasing core loss is probably induced by magnetostriction variation.

In this paper, the SA1 core is annealed at 350 °C for 2 h, after which the magnetic properties of specimens are measured and taken from the limb plane, the C-core corner, and the toroidal core; all of the samples are depicted in Fig. 1.

From Eqs. (1) and (2), it is clear that both hysteresis loss and variation in magnetostriction play important roles in the magnetic behavior of amorphous cores under torsion stress. The magnetic hysteresis loops (VSM) are shown in Fig. 2(a). The magnetic parameters of the samples are presented in Table I. Regarding XRD measurement results, Eq. (1) indicates that the degree of magnetocrystalline anisotropy is proportional to the magnetic loss. The crystalline phase and grain size of an amorphous ribbon obtained by XRD measurements after annealing are shown in Fig. 2(b).

In reference to Eqs. (3) and (4), a comparison of the different core bending stresses from FEA simulation, accompanied by the corresponding measurement results for core losses, is shown in Table II. Core loss for both the inner (smaller) core and outer (larger) core are compared using FEA. It is significant to observe that the measured results for total core losses of three-phase transformer are almost higher than the corresponding results from the simulation model. This discrepancy is due to the fact that the model ignored all of the joint gaps of the core laminations, which are unavoidable during core manufacture. In Fig. 3(a), according to the FEA simulation and experimental results, it is significant to observe that the C-core with a rectangular corner has higher core loss because the core corner has higher bending stress.

In Fig. 3(b), it is shown that the audible noise for toroidal core transformers is lower than that for other types of C-core transformers owing to a reduction in magnetostriction variation. For the transformer core vibration, Eq. (2) indicates that both time domain analysis and the fast Fourier transform (FFT) to carry out vibration analysis of the transformer with different bending structures were shown in Fig. 4. It is interesting to note that the improvement of audible noise and core vibration in a toroidal core transformer becomes more prominent when the magnetic induction becomes larger.

In summary, this paper discusses the effect of bending stresses on the magnetic characteristics of transformers with different amorphous-core transformer structures. The results of a FEA simulation model of the core are compared with measurements. Three-phase amorphous-core transformers are used for performance comparison in terms of core loss, audible noise, and vibration.

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