# Vibration Prediction of Non-Oriented Silicon Iron Power Transformer Core under DC Bias

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**This work focuses on the vibration prediction of power transformer core under DC bias, using a magneto-mechanical approach. A finite element modeling chain is applied under coil current excitation, leading to the core distortion estimation. The constitutive laws of the material use a simplified multi-scale model describing both magnetic and magnetostrictive anisotropies. Magnetostriction is introduced as an input free strain of the mechanical problem to get the deformation and displacement fields. The numerical process is applied to compare the distortion of a given magnetic circuit under different level of DC bias.**

*Index Terms*—**DC bias, Magnetostriction, transformers, vibration, multi-scale modeling, iron-silicon alloys, finite element method.**

## I. Introduction - Objectives

The VIBRATIONS and audible noise of power transformers are becoming a serious issue in electrical industry. One of the sources is the periodic deformation of sheets of the transformer core, caused by magnetostriction and magnetic forces. Although power transformers are normally designed to operated under sinusoidal excitation, in reality, a direct current (DC) component may be superposed in primary or secondary windings. This DC component leads to half-cycle saturation, which increases the losses, creates more harmonics, and generates more vibrations and noise [1]. These effects need to be taken into consideration for the power transformer design. Therefore, a good comprehension of power transformer behavior under DC bias becomes crustial for its optimized design.

This work offers a modeling chain combined with a simplified multi-scale material model, leading to the vibration of the power transformer core. An embedded 'non-cut' triphase power transformer with no air-gap is used as example. Magnetostrictive behavior of the Non-oriented FeSi is first characterized and implemented into the simplified multi-scale model (SMSM). The numerical process is applied to compare the core deformations under mono-phase current excitation, with various DC bias.

## II. Global modeling strategy

### A. Constitutive law

The constitutive law used for the modeling is a simplified version of a full multi-scale magneto-mechanical model (MSM) [2], [3]. In the complete version, the considered scales are the magnetic domain, the single crystal and the polycrystalline (macroscopic) scales. This model allows an accurate modeling of anhysteretic magnetic and magnetostrictive behaviors of ferro/ferrimagnetic materials, and takes the effect of multiaxial mechanical stress into account. The number of internal variables of such model is nevertheless too high to be implemented in a complex structure model with a high number of degrees of freedom. The simplified version (SMSM) where the magnetic material is considered as an equivalent single-crystal (including anisotropy effects) has been recently proposed for that purpose [4]. This single-cristal consisting of magnetic domains is oriented to different directions. Local free energy of a magnetic domain ($\alpha$) oriented in direction ($\vec{\gamma}_\alpha$) is expressed as the sum of three contributions if the stress effect is neglected (weak coupling):

$$W_{tot}^{\alpha} = W_{mag}^{\alpha} + W_{an}^{\alpha} + W_{conf}^{\alpha} \tag{1}$$

$W_{mag}^{\alpha}$ is the Zeeman energy, introducing the effect of the applied magnetic field on the equilibrium state. $W_{an}^{\alpha}$ is an anisotropic energy term related to the crystallographic texture and the magneto crystalline anisotropy. $W_{conf}^{\alpha}$ is a configuration energy term, which allows some peculiar initial distribution of domains (residual stress effect, demagnetizing surface effect...). A Boltzmann like function is used to calculate the volume fraction of domains in different directions $f_\alpha$.

$$f_\alpha = \frac{exp\left(-A_s W_{tot}^{\alpha}\right)}{\sum_\alpha exp\left(-A_s W_{tot}^{\alpha}\right)} \tag{2}$$

where $A_s$ is an adjusting parameter. Macroscopic quantities are finally obtained by averaging the microscopic quantities over the single crystal volume (3)(4).

$$\vec{M} = \sum_\alpha f_\alpha \vec{M}^\alpha \tag{3}$$

$$\boldsymbol{\epsilon}_\mu = \sum_\alpha f_\alpha \boldsymbol{\epsilon}_\mu^\alpha \tag{4}$$

From a given magnetic field $\vec{H}$, the simplified MSM gives then the corresponding free magnetostriction strain and magnetization.

### B. Magnetic resolution with imposed magnetic flux method

One important criterion for power transformer design is power-to-mass ratio (transmitted power per unit mass), which is proportional to the magnetic flux $\phi$ circulating in the transformer core. It is then interesting to make the comparison of the relevance of different materials for the same structure at equal magnetic flux. The partially coupled problem is solved using a sequential approach: magnetic resolution at a given flux first (leading to the local magnetostriction), mechanical resolution in a second step. The magnetic resolution is using an iterative Newton Raphson method: a magnetic flux $\phi$ is imposed; the magnetization $\vec{M}$ is arbitrary defined at the first loop allowing a first estimation of the magnetic field $\vec{H}$. The magnetization is then updated, using the SMSM. The procedure is iterated until convergence. Combined with basic Maxwell equation $div(\vec{B}) = 0$, the re-written constitutive equation in weak formulation is shown in (5). A second equation (6) is obtained from the formulation of total magnetic energy $\phi I = \int_\Omega \vec{T} \cdot \vec{B}\, \mathrm{d}\Omega$, with current potential vector $\vec{T}$ and magnetic induction $\vec{B}$ [5]. $\Omega$ is the integration domain and $\upsilon$ is a test function. A unit current potential vector $\vec{T_0}$ is imposed to get $I\vec{\nabla} \times \vec{T_0} = \vec{j}$. The non-linear problem is solved at a given applied flux leading to current value $\vec{j}$ in the coils (hence magnetic field).

$$\int_\Omega \mu_0 \vec{\nabla}\omega \cdot \vec{\nabla}\upsilon \,\mathrm{d}\Omega + I \int_\Omega \mu_0 \vec{T_0} \cdot \vec{\nabla}\upsilon \,\mathrm{d}\Omega = -\int_\Omega \mu_0 \vec{M} \cdot \vec{\nabla}\upsilon \,\mathrm{d}\Omega \tag{5}$$

$$\int_\Omega \mu_0 \vec{\nabla}\omega \cdot \vec{T_0} \,\mathrm{d}\Omega + I \int_\Omega \mu_0 \vec{T_0} \cdot \vec{T_0} \,\mathrm{d}\Omega = \phi - \int_\Omega \mu_0 \vec{M} \cdot \vec{T_0} \,\mathrm{d}\Omega \tag{6}$$

### C. *Mechanical resolution*

The free magnetostrictive strain $\boldsymbol{\epsilon}_\mu$ calculated from the SMSM is then transformed into an equivalent force density $\vec{f_{eq}}$ as a body force of a classical plane stress mechanical problem. This equivalent force density is calculated from $\boldsymbol{\epsilon}_\mu$ thanks to: $\vec{f_{eq}} = -\vec{\nabla} \cdot (\mathbb{C} : \boldsymbol{\epsilon}_\mu)$, where $\mathbb{C}$ is the stiffness tensor of the medium. Mechanical resolution is carried out for each harmonic component of this equivalent force density obtained with a Fast Fourier Transformation (FFT) method. Inverse FFT after resolution leads to the deformation at each node of the transformer core over the time.

## III. Application of power transformer core under DC bias

Here we chose an onboard three-phase power transformer as an example. These small transformers are usually made of Non-Oriented (NO) FeSi with an ideal '8'-shape structure (no air-gap). Magnetostrictive behavior of NO FeSi is first characterized in rolling direction (RD), transversal direction (TD) and 45 degree of RD. Parameters of SMSM are then deduced, using the measured magnetostrictive behavior. Fig. 1 allows to compare the measured and SMSM modeled magnetostrictive behaviors in three directions for NO FeSi (Parameters of the SMSM for both materials will be given in the full paper).

For simplification reasons, the three-phase power transformer is excited here only by a central coil imposing a sinusoidal flux which leads to a maximum induction of $B = 1.4$T. Amplitude of the current in central coils and core displacement as a function of time are then solved. A series of simulations are carried out with a DC component, in addition to the sinusoidal flux. DC component of the magnetic flux is set

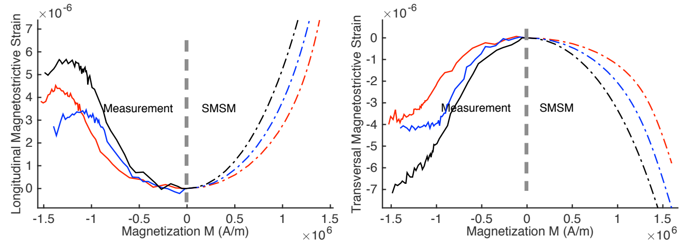


Fig. 1. Measured and SMSM modeled anhysteretic magnetization curves in longitudinal (left) and transversal (right) direction for NO FeSi (red: $\vec{H}//RD$; blue: $\vec{H}$ at 45° of $RD$; black: $\vec{H}//TD$).

as 0%, 10%, 20% and 30% of the maximum flux. With the finite element resolution, this corresponds respectively to DC current bias of 0At, 18 At, 26 At and 108 At in the secondary coils. Excitation current in primary coils and spectrum of displacement amplitude at particular point of the core are given in Fig.2.

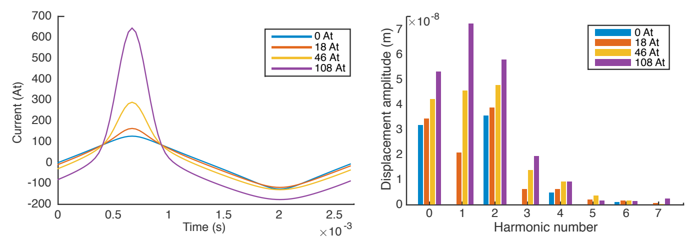


Fig. 2. Excitation current in primary coils (left); Spectrum of displacement amplitude at particular point of the core

With the presence of DC component, the transformer core is highly saturated in the first half period. As the DC component rises, the current in coils becomes more distorted with harmonics. With a DC bias at $108At$, the excitation current rises dramatically in amplitude. In terms of core distortion, magnetic saturation of the first half period creates relatively large magnetostriction, which generally rises the amplitude of displacements of all harmonics. Core distortion is much higher in the the half period than it in the second half period, which induces odd harmonics of the vibration. Harmonics at higher frequency are found with the increase of DC bias, which may be close to resonance. Comparisons between simulation and measurement on power transformer core will be given in the full paper.

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