A New Algorithm to Consider the Effects of Core Losses on 3D Transient Magnetic Fields

P. Zhou, D. Lin, C. Lu, N. Chen and M. Rosu
ANSYS Inc
225 W Station Square Dr, Suite 200, Pittsburgh, PA 15219 USA
ping.zhou@ansys.com

***Abstract*—As a follow-up to our previous efforts to take into account the effects of steel lamination core losses on 3D transient magnetic fields, a new algorithm is proposed to eliminate possible convergence problem and improve computation efficiency when strong eddy loss component is involved.**

***Index Terms*—Magnetic losses, transient analysis, eddy current**

I. Introduction

The steel lamination core loss with sinusoidal excitation is commonly computed based on loss separation, which breaks the total core losses into static hysteresis loss, classical eddy current loss, and excess loss in the frequency domain [1]. In order to apply the method to the time domain, an equivalent elliptical loop (EEL) method was presented to model the hysteresis loop [2], and therefore, the instantaneous core losses at each time step can be predicted in the transient FEA. However, the instantaneous core loss presented in [2] is derived as a "post process", that is, it did not consider the feedback of the core losses on the transient magnetic fields. To this end, an attempt was made in [3] to consider the effects of core losses through introducing an additional **H** component which is derived from the instantaneous static hysteresis loss, classical eddy current loss and excess loss in an iterative manner. Excellent results are achieved. However, it is shown from some applications that if the component of classical eddy current loss is very strong, the solution may become diverged.

The possible divergence is caused by the fact that the derived eddy current loss component is very sensitive to any numerical error due to its proportional to the *square* of (dB/dt) where B is just a guess of the true value during the iteration. When such a component is used as an additional source component in the right hand side, the error will propagate and accumulate with time, which is very much prone to unstable behavior during an iterative process. To this end, in this paper, a new algorithm is proposed to incorporate the feedback of classical eddy current loss component directly into magnetic field equations through introducing an equivalent permeability. As a result, the iterative process for considering eddy-current loss effects is completely eliminated, and both stability and computation efficiency are significantly improved.

II. Basics of Core Loss Feedback on Magnetic Fields

For the sake of conciseness but without loss of generality, we take 3D T-Ω formulation as illustration example in the following discussion. When the effects of lamination core loss on fields are taken into account, according to [3] we have

$$\mathbf{H} = \mathbf{H}_{re} + \mathbf{H}_p = \mathbf{H}_s + \mathbf{T} + \nabla\Omega \tag{1}$$

where

$$\mathbf{H}_{re} = \mathbf{H} - \mathbf{H}_p = \nu\mathbf{B} = \mathbf{B}/\mu \tag{2}$$

is the reversible component of the magnetic field associated with normal B-H curve without hysteresis loop and $\mathbf{H}_s$ is the source field component produced by either known current or unknown current associated with the voltage excitation or connected with external circuit; on the other hand,

$$\mathbf{H}_p = \mathbf{H}_{ph} + \mathbf{H}_{pc} + \mathbf{H}_{pe} \tag{3}$$

is an additional irreversible field component which is introduced to consider the effects of the total core loss on **H** field. Here $\mathbf{H}_{ph}$, $\mathbf{H}_{pc}$ and $\mathbf{H}_{pe}$ are associated with individual effect of static hysteresis loss, classical eddy-current loss and excess loss, respectively.

According to Maxwell equations, we have [4]

$$\begin{aligned} \nabla\times(\frac{1}{\sigma}\nabla\times\mathbf{T}) + \frac{\partial}{\partial t}\mu(\mathbf{T}+\nabla\Omega) &= -\frac{\partial}{\partial t}\mu(\mathbf{H}_s - \mathbf{H}_p) \\ \nabla\cdot\mu(\mathbf{T}+\nabla\Omega) &= -\nabla\cdot\mu(\mathbf{H}_s - \mathbf{H}_p) \end{aligned} \tag{4}$$

Unlike the source component $\mathbf{H}_s$ that is either known or solved together with voltage and/or circuit equations, the handling of additional component $\mathbf{H}_p$ is not so straightforward since the determination of $\mathbf{H}_p$ is solely dependent on field solution **B** which is available only after solving. For the completeness, let us have a brief overview of the algorithm developed in [3].

The basic concept for deriving the contribution from each core loss component to $\mathbf{H}_p$ field is to factor individual core loss expression in the form of $k\cdot\partial B/\partial t$. In such a way, k is just the individual component of $\mathbf{H}_p$, which can be derived as

$$\mathbf{H}_{pc} = \frac{k_c}{2\pi^2}\cdot\frac{\partial\mathbf{B}}{\partial t} \tag{5}$$

$$H_{ph} = \frac{k_h}{\pi}B_m\cos(\theta) \tag{6}$$

$$\mathbf{H}_{pe} = \frac{k_e}{C_e}\left[\left(\frac{\partial B}{\partial t}\right)_m\right]^{-0.5}\frac{\partial\mathbf{B}}{\partial t}. \tag{7}$$

In (6), each coordinate component is computed separately. Since all $\mathbf{H}_{ph}$, $\mathbf{H}_{pc}$ and $\mathbf{H}_{pe}$ depend on field solution **B** which is not available until it has been solved. Thus, an iteration process has to be involved:

1. Using the value of the additional source component $\mathbf{H}_p^{(t_0)}$ at the last time step t_0 as the initial guess of $\mathbf{H}_{p_{(0)}}^{(t_1)}$ for the current time step t_1, solve the non-linear system equations of (4) based on Newton-Raphson method;
2. Linearize all non-linear materials by freezing the permeability at each element;
3. Solve the frozen linearized system equation of (4) based on the updated $\mathbf{H}_{p_{(k)}}^{(t_1)}$ at the right hand side;

4. Compute **B** from the solution of the above step 3 and further re-update $\mathbf{H}_{p(k)}^{(t_1)}$ based on (10), (12) and (14);
5. If the error between $\mathbf{H}_{p(k)}^{(t_1)}$ and $\mathbf{H}_{p(k-1)}^{(t_1)}$ is acceptable, go to the next time step; otherwise, go back to step 3.

This iterative procedure works for most cases. However, it is found that for some applications with very strong classical eddy current loss component, the solution becomes hard to converge, even leads to divergence.

III. New Algorithm to Allow Strong Eddy-Current Loss Component

Let us assume the flux density **B** at the last time step is $\mathbf{B}^{(t_0)}$. From (5), after time discretization, the equivalent additional field component $\mathbf{H}_{pc}$ due to eddy-current loss at time t can be expressed as

$$\mathbf{H}_{pc} = \frac{k_c}{2\pi^2}\frac{\mathbf{B}-\mathbf{B}^{(t_0)}}{\Delta t}. \tag{8}$$

From (2), (3) and (8), we have

$$\begin{aligned}\mathbf{H} &= \frac{1}{\mu}\mathbf{B} + \left(\frac{k_c}{2\pi^2}\frac{\mathbf{B}-\mathbf{B}^{(t_0)}}{\Delta t} + \mathbf{H}_{ph} + \mathbf{H}_{pe}\right) \\ &= \left(\frac{1}{\mu} + \frac{k_c}{2\pi^2\Delta t}\right)\mathbf{B} + (\mathbf{H}_{pc0} + \mathbf{H}_{ph} + \mathbf{H}_{pe}) = \left(\frac{1}{\mu/k_\mu}\right)\mathbf{B} + \mathbf{H}'_p\end{aligned} \tag{9}$$

where

$$k_\mu = 1 + \frac{k_c\,\mu}{2\pi^2\Delta t} \tag{10}$$

$$\mathbf{H}_{pc0} = -\frac{k_c}{2\pi^2\Delta t}\mathbf{B}^{(t_0)} \tag{11}$$

$$\mathbf{H}'_p = \mathbf{H}_{pc0} + \mathbf{H}_{ph} + \mathbf{H}_{pe} \tag{12}$$

With the introduction of the equivalent permeability

$$\mu_{eq} = \mu/k_\mu, \tag{13}$$

and the replacement of $\mathbf{H}_p$ by $\mathbf{H}'_p$, Eq (4) becomes

$$\begin{aligned}&\nabla\times\left(\frac{1}{\sigma}\nabla\times\mathbf{T}\right) + \frac{\partial}{\partial t}\mu_{eq}(\mathbf{T}+\nabla\Omega) = -\frac{\partial}{\partial t}\mu_{eq}(\mathbf{H}_s - \mathbf{H}'_p) \\ &\nabla\cdot\mu_{eq}(\mathbf{T}+\nabla\Omega) = -\nabla\cdot\mu_{eq}(\mathbf{H}_s - \mathbf{H}'_p)\end{aligned} \tag{14}$$

After (14) has been solved, **H** and **B** can be further obtained by

$$\begin{aligned}\mathbf{H} &= \mathbf{H}_s + \mathbf{T} + \nabla\Omega \\ \mathbf{B} &= \mu_{eq}(\mathbf{H} - \mathbf{H}'_p)\end{aligned} \tag{15}$$

The similar iterative procedure described in the previous section can be applied to consider the feedback of other two components: hysteresis loss component by $\mathbf{H}_{ph}$ and the excess loss component by $\mathbf{H}_{pe}$. However, the feedback from the eddy current loss component has been directly incorporated into original field equations without involving an iteration process based on equivalent permeability μ_{eq} and $\mathbf{H}_{pc0}$ which are known and constant during the iteration process. Therefore, this new algorithm is much more stable and efficient with less iteration.

IV. Numerical Validation

The proposed approach can be validated by the power-balance testing method, that is, the input power increase between with and without considering core-loss effects should equal the total core loss. The validation example is a 500W, 4-pole adjustable-speed synchronous motor (ASSM). According to the periodic condition, only one pole is required as shown in Fig. 1. Due to its strong eddy-current loss component (k_c=3.12), the iterative approach used in [3] failed to converge. But the new approach works without any problem as expected. At no-load operation without considering core loss effects, the developed torque has only the cogging torque component. When core loss effects are taken into account, there exists an additional torque component due to the impact of core losses. Fig.2 shows this additional torque component derived by subtracting the torque waveform without considering core loss effects from that with core loss effects, where negative value means that the additional torque component is in the opposite direction of the speed. The resultant (mechanical) input power increase (the rotor speed multiplied by the additional torque component) matches well with the core loss as shown in Fig. 3.

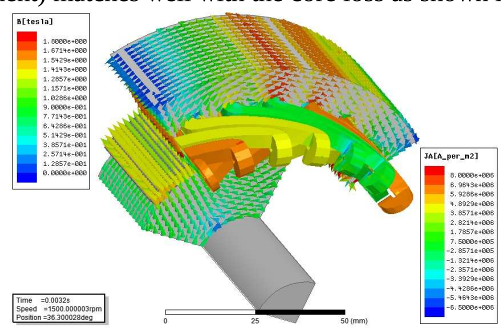

Fig. 1 500 W, 4-pole ASSM motor (k_h=160.1, k_c=3.12, k_e=2.54)

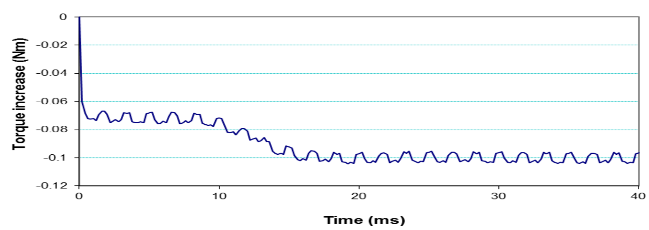

Fig. 2 Torque increase due to core loss effects at no-load and 1500 rpm

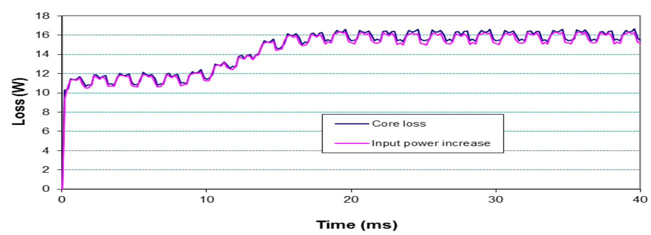

Fig. 3 Mechanical input power increase due to considering core loss effects

References

[1] G. Bertotti, “General properties of power losses in soft ferromagnetic materials,” *IEEE Trans. Magn.*, vol. 24, no. 1, pp. 621-630, 1988.

[2] D. Lin, P. Zhou, W. N. Fu, Z. Badics, and Z. J. Cendes, “A dynamic core loss model for soft ferromagnetic and power ferrite materials in transient finite element analysis,” *IEEE Trans. Magn.*, vol. 40, no. 2, pp. 1318-1321, March 2004.

[3] D. Lin, P. Zhou, Q. M. Chen, N. Lambert, and Z. J. Cendes, “The effects of steel lamination core losses on 3D transient magnetic fields,” *IEEE Transactions on Magnetics*, vol. 46, no. 8, pp. 3539-3542, Aug. 2010

[4] P. Zhou, D. Lin, B. He, S. Kher and Z.J. Cendes, "Strategies for accelerating non-linear convergence for T- Ω Formulation,” IEEE Transactions on Magnetics, Vol. 46, p. 3129-3132, Aug. 2010.