Modern methods for iron loss computation

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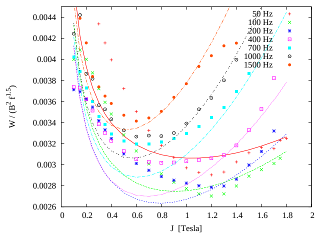
Introduction

- Accurate evaluation of **iron losses** in electrical machines is for many purposes of increasing importance (Automotive applications, etc. . .)
- Many approaches rely on very few measurement data (e.g. Iron losses at 50 Hz for B=1 T and B=1.5 T) and have therefore limited accuracy.
- In this paper, **extensive Epstein measurements** provided by ArcelorMittal over a large frequency range are analysed in detail and discussed.
- The aim is to provide an **accurate** and **widely applicable** model for iron losses.

Analysis of Measurements

- Induction range : $J \approx B \in$ [1 T, 1.8 T]
- Frequancy range : f_{min} =2 Hz, f_{max} = from 700 Hz to 10 kHz
- Plotting $W/(B^2 f^{1.5})$ is shown below :



ArcelorMittal

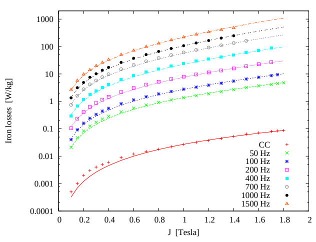
- grade : M250-50A (AM)
- Measurements = Points
- Identification = Lines

- A term $B^\alpha, \alpha < 2$ exists $\Rightarrow$ the **excess losses** of Bertotti ($\alpha = 1.5$).
- A term $B^\alpha, \alpha > 2$ exists, due to **saturation** which is not considered in Bertotti's approach.

Parameter Identification

Hence the **identification formula** (Bertotti's model + higher order term in B) :

$$W(B, f) = B^2 f (a_2 + a_1 f (1 + a_3 B^{a_4})) + a_5 (Bf)^{1.5}$$



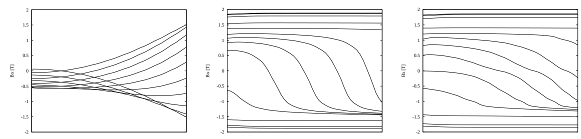
- grade : M250-50A (AM)
- a_1 : classical eddy current losses
- a_2 : hysteresis losses
- a_3, a_4 : higher order term in B
- a_5 : excess losses

- **5 parameters** $a_1, \ldots, a_5$ identified per material
- A large frequency range [CC=2 Hz, 1500 Hz] and the whole induction range $B \equiv B_{max} \in$ [0 T, 1.8 T] are covered.
- A **good match** over the whole B and f ranges is obtained.
- **BUT** : **Limited to unidimensional sinusoidal B fields.**
- How to go beyond interpolated measurements ? One needs for this a **theoretical ground** for extrapolation outside the measurement ranges, i.e. one needs a **physical material model** (See next box.)

Physical Material Model

A. Cross lamination eddy current FE model

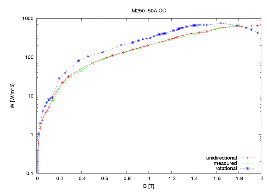
- The **1D approximation** is accurate in thin laminations. It can be used within an **homogenisation** process
- Typical results (one half period) are shown below at the same frequency (f =1000 Hz) and with a) the **linear** B-H characteristic, b) the **anhysteretic** characteristic and c) the **virgin** (first magnetisation) characteristic.
- One observes in c) that the virgin characteristic (used in most FE simulations assuming $\sigma = 0$) yields here unphysical eddy currents when the field B crosses 0 (presence of a Rayleigh zone in the virgin characteristic). The virgin curve should not be used when $\sigma \neq 0$, and replaced by the anhysteretic characteristic b), or even better, by a true coupling with the hysteresis model.
- Comparison of a) and b) clearly shows the effect of saturation on the distribution of eddy currents across laminations. **Skin effect dissappears** and a **saturation front** travels through the lamination. Losses computed in case b) are about 3 times larger as the ones computed by Bertotti's standard formula. This is the **justification for the higher order term in B.**



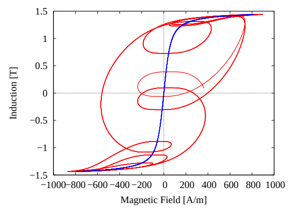
a) Linear b) Anhysteretic c) Virgin

B. Vector dynamic hysteresis model

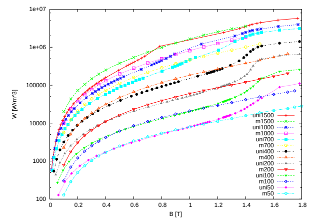
- Based on a **mechanical analogy** : hysteresis losses = dry friction force, eddy currents = viscous friction forces
- The model is able to represent **vector hysteresis** (3D) and **higher harmonics** (i.e. arbitrary input $\mathbf{H}(t)$ field) on basis of a sound theoretical background.



Match between modeled unidirectional hysteresis losses and measurements. **Rotational losses** are about 1.5 larger than unidirectional losses (as predicted by the theory) and decrease at high fields.



Unidimensional B-H loops computed with the dynamic hysteresis model in the presence of **higher harmonics**.



- Good match between the model and measurements over the whole frequency range. The discrepancy at higher fields is due to the fact that the physical material model works so far with a sinusoidal H field, whereas Epstein measurements where made with a sinusoidal B field (to be further investigated).

Conclusion

- A 5-parameter formula for **iron loss identification** has been proposed that allows a sufficient accuracy over large B and f ranges.
- This approach is however **limited to unidimensional sinusoidal B fields**.
- First results with different **physical material models for steel laminations** have been presented that allow going beyond this limitation.

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