Damir SABIC, Helmut PFÜTZNER, Franz HOFBAUER, Georgi SHILYASHKI, Edin MULASALIHOVIC

Institute of Electrodynamics, Microwave and Circuit Engineering (EMCE), Vienna University of Technology

Dynamics effects on losses due to rotational magnetization

***Abstract**. As well known, rotational magnetization (RM) may cause high increases of power losses P in comparison to alternating magnetization (AM), in particular for highly grain oriented SiFe. So far, it had been assumed that the loss increase is a mere function of shape of the induction pattern **B**(t). However, closer investigations reveal that a further impact is given by the angular velocity of the vector **B**. Compared to low dynamics as being typical for simulations on RSSTs, high dynamics as being typical for T-joint regions of transformer cores yield further increases of losses. For elliptic RM, the increases are rather weak and tend to decrease with rising axis ratio a. On the other hand, distinctly increased P arises for rhombic RM as being typical for transformers. Further increases result for oblique rhombic RM as arising close to overlaps. On the other hand, lower P is given for the case of DC bias due to the fact that anomalous eddy current losses play a weaker role here.*

***Streszczenie.** Magnesowanie rotacyjne powoduje wzrost trat szczególnie w blachach anizotropowych SiFe. Szczegółowa analiza wykazała że straty te zależą od szybkości kątowej zmian indukcji. Szczególnie duży wzrost strat obserwuje się dla rombowej zmiany, typowej w rdzeniach transformatora. Z drugiej strony podmagnesowanie DC zmniejsza wzrost strat przez zmniejszenia strat dodatkowych powodowanych przez prądy wirowe. (**Efekty dynamiczne strat rotacyjnych**)*

Keywords: grain oriented silicon iron, rotational magnetization, magnetic losses, DC bias, magnetization dynamics.
Słowa kluczowe: blachy elektotechniczne zorientowane, straty, magnesowanie rotacyjne.

1. Introduction

As well known, rotational magnetization (RM) may cause high increases of power losses P in comparison to alternating magnetization (AM). Due to high effective anisotropy this is given especially for highly grain oriented (HGO) SiFe and even more for scribed highly grain oriented (SHGO) material. RM proves to be the number one impact factor on the building factor BF of transformer cores. For SHGO materials, T-joint regions show local values BF close to 2 corresponding to 100% loss increase. This means that industrial interest exists to attain a deeper understanding about those factors which have impact on losses due to RM.

So far, it had been assumed that the loss increase is a mere function of the *shape* of the induction pattern $\boldsymbol{B}(t)$. Experimental simulation of RM as performed by means of RSSTs (rotational single sheet testers) usually are performed for elliptic shape. This is the only one which can be mathematically defined in exact way. However, elliptic patterns actually do not occur in their pure form in power transformers. High effective anisotropy favours patterns of rhombic shape. Compared to elliptic patterns, they yield lower BF due to lower B_{HD} in hard direction (HD), but higher ones if being tilted [1]. Finally, tilted, oblique-rhombic magnetization is observable close to overlaps of T-joint regions [2]. As an effect of a high material anisotropy, it leads to considerably increased values of the field component H_{HD} and to distinctly increased losses.

The most important characteristic of such RM-patterns is given by the axis ratio $a = B_{TD}/B_{RD}$, with B_{TD} and B_{RD} the maximum induction in transverse direction (TD) and rolling direction (RD), respectively. As an upper limit, a = 0.5 tends to yield doubled losses P for SHGO material. However, it suggests itself that P should also rise with increasing dynamics of magnetization. That is, a further characteristic should be given by the angular velocity ω of the rotating induction vector $\boldsymbol{B}$. As a matter of fact, the literature considers this impact factor only to a certain extent. The aim of the present work was to clarify if practical relevance is given for the quantity ω.

2. Experimental

In a 1 m x 1 m model transformer core, typical local RM patterns $\boldsymbol{B}(t)$ were studied by means of the well known needle method, evaluating 512 instants of time per period. For that purpose, occurring patterns were captured and analyzed in terms of their shape, dynamics of the induction vector and the resulting core losses.

In a next step, attempts were made to simulate the "physiological" patterns and to investigate the correlation between the dynamics $\omega(t)$ and the losses P. All simulations were performed by means of a three-phase RSST (Fig.1). It uses a hexagonal sample of about 160 mm diameter, specifically designed for HGO material [3]. The RSST is fully software-controlled allowing for almost arbitrary patterns. For cases of exact simulation, $\boldsymbol{B}(t)$ was based on the 512 vector samples which are approximated with a mean square error of 0.2% for elliptic or rhombic patterns with B_{RD} up to 1.8 T and a up to 0.5. Considerably higher deviations occur for oblique rhombic patterns, which may involve very high values of exciting field H. Finally, the measured patterns were modified with systematic variations of B_{RD} and a.

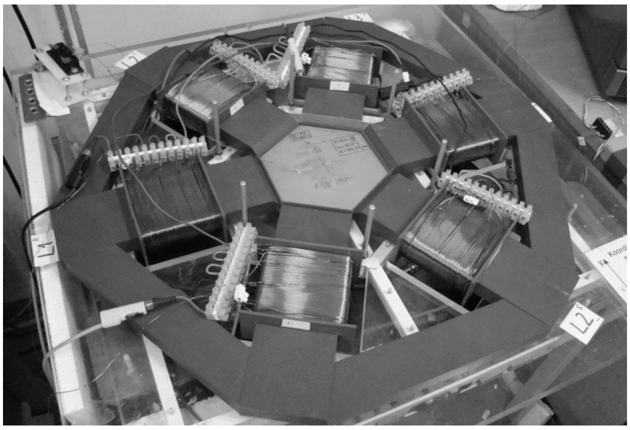

Fig.1. RSST as applied for the exact simulation of RM-patterns.

Special focus was put on time variations $\omega(t)$. The corresponding losses P were determined using a double field coil and a pair of search coils through holes of the sample. Because RM in clock-wise (CW) and anti-clock-wise (ACW) direction can yield considerably different loss values (e.g. [4]), all measurements were carried out under both constellations. Also, the orientation of the sample (up/down) was taken into account. Finally, an average was taken over the four measured loss values in order to calculate a result P.

Measurements at T-joints revealed a tendency of minimum angular velocity ω in instants of time when $\boldsymbol{B}$ passes through the RD. On the other hand, ***B*** tends to pass through the TD with a high maximal velocity $\omega_{\max}$. For a study of the practical relevance of $\omega_{\max}$, RM-patterns of different shape were simulated under varying dynamics on samples of laser scribed HGO SiFe and conventional GO (CGO) SiFe.

3. Elliptic RM

Considering that most experimental experience exists for elliptic RM, the present study was started with this shape of pattern apart from the fact that it is not typical for practice. For example, Fig.2a shows an elliptic pattern with B_{RD} = 1.7 T and a = 0.5 of rather low dynamics, $\omega_{\max}$ being close to 36°/ms according to Fig.2c. The pattern is characterized by almost constant spacing ΔB (as a scalar quantity) of the 40 indicated positions of ***B*** of 0.5 ms time distance. Fig.2b shows a pattern which is more physiological with respect to dynamics. $\omega_{\max}$ is close to 72°/ms, i.e. doubled dynamics are given, ***B*** remaining close to the RD for about 5 ms.

According to the figures on the right, the field pattern ***H***(t) shows a tendency of higher values for the HD in the case of increased dynamics. This can be interpreted by a more pronounced skin effect.

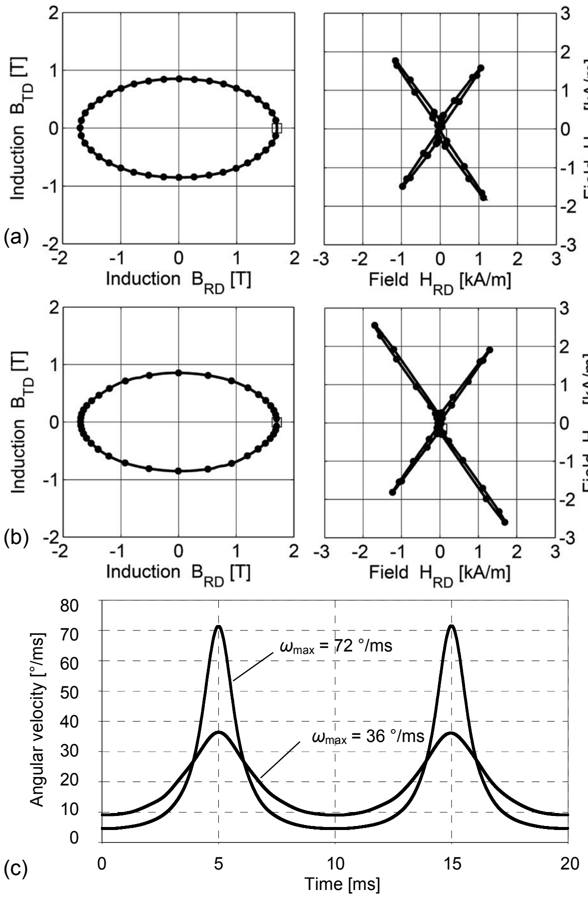

Fig.2. Examples for elliptic magnetization patterns with different dynamics of ***B***(t). 40 points indicate 40 instantaneous vectors ***B*** and ***H***, respectively, with 0.5 ms time distance. (a) Case of low $\omega_{\max}$. (b) Case of increased dynamics as being more typical for practice. (c) Corresponding time-domain diagram of angular velocities. Peak values occur for the instants when ***B*** passes through the TDs.

Fig.3 shows the corresponding losses P for the SHGO material for B_{RD} = 1.3 T up to 1.7 T and a up to 0.5. Increased dynamics prove to cause rising P in a general way. The impacts of increased dynamics tend to grow with increasing B_{RD} and with decreasing a. It should be noted that with reduced a, the angular velocity takes on even higher values, but the ratio between $\omega_{\max}$ in the case of low dynamics and $\omega_{\max}$ in the case of high dynamics remains constant regardless of the value of a.

Theoretically, the loss increases can be explained by increases of both classical eddy current (EC) losses and anomalous EC losses. As an interpretation of strong effects of dynamics, low values of a tend to involve ordered bar domain structures as a source of anomalous losses. They represent a source of anomalous losses due to the fact that the few corresponding main Bloch walls have to move with high velocity.

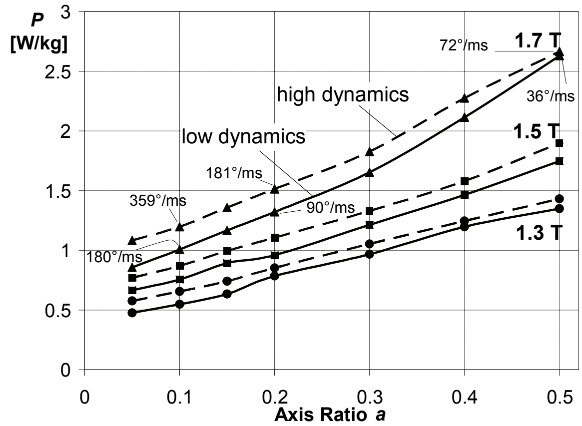

Fig.3. Losses of SHGO material under elliptic magnetization for three induction peak values B_{RD} and different $\omega_{\max}$.

4. Rhombic RM

Fig.4 shows simulated rhombic patterns for B_{RD} = 1.7 T and a = 0.5, for two levels of dynamics. As being typical, much lower field values H_{HD} (about 300 A/m instead of about 3000 A/m) lead to a general tendency of lower losses than the elliptic magnetization, especially for high values of B_{RD} and a (Fig.5). On the other hand, the impact of increased dynamics is more pronounced than in elliptic case. Contrary to the elliptic case, for rhombic magnetization considerable increases are given also for high a. As an interpretation, lower B_{HD} means that ordered bar domains remain to exist for increased values of a as a source of higher anomalous EC losses.

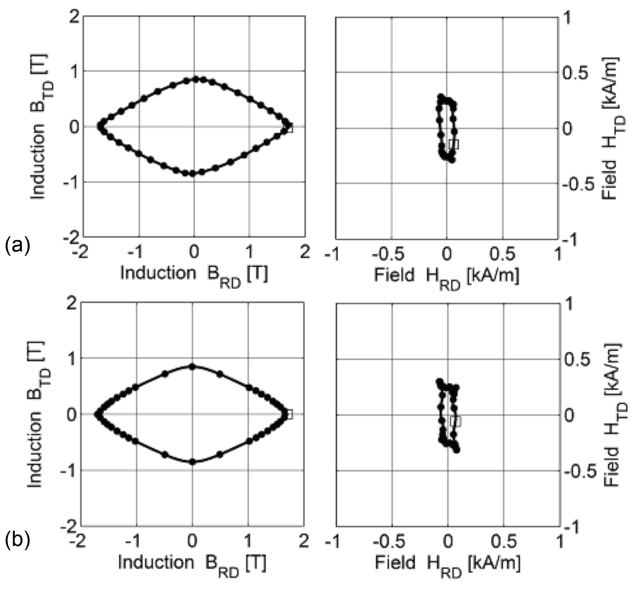

Fig.4. Examples of rhombic magnetization pattern with different dynamics of ***B***(t). (a) Case of lower $\omega_{\max}$. (b) Case of increased dynamics.

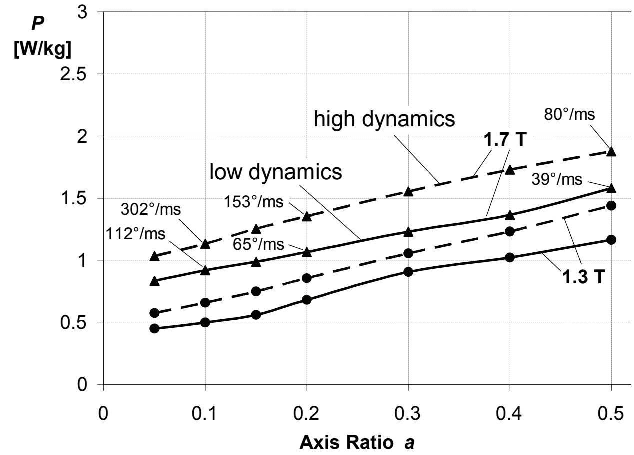

Fig.5. Losses of SHGO material under rhombic magnetization for two induction peak values B_{RD} and different ω_{max}.

5. Rhombic RM with DC bias

The case of rhombic RM was also investigated for additional DC magnetization impressed in RD. As well known, such bias may arise in practice due to several reasons. One is given by geo-magnetically induced currents (GICs), a second one by the general tendency to introduce DC in high-distance energy grids. A specific reason to study bias effects was the expectation to attain information on the role of domain configurations on dynamics effects.

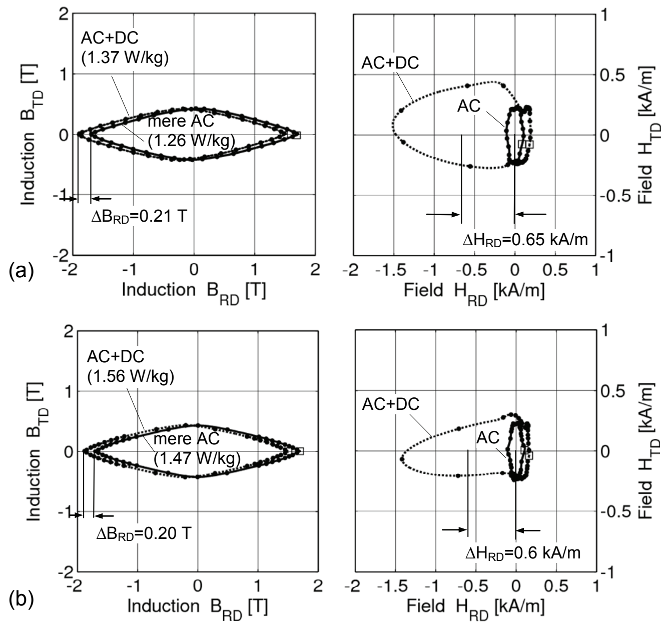

Fig.6. Rhombic magnetization under both mere AC-excitation and additionally superimposed DC-excitation. (a) Case of low dynamics. (b) Case of increased dynamics.

GICs may yield single-side saturation effects, which may even cause destructions of transformers. On the other hand side, bias through insufficient DC/AC transition by thyristor/transistor-sets can be assumed to yield very weak shifts ΔB_{RD} of the induction pattern $\boldsymbol{B}(t)$, as given in the examples of Fig.6 for a = 0.25. In the mere AC case, increased dynamics proved to yield loss increases of 17%, while a plus of 14% resulted for the case of bias (compare the loss values for the mere AC and AC+DC case, respectively in Fig.6). As a tendency, it proves to decrease with increasing a.

In fact, the differences due to the bias are small. But the behaviour is consistent with the following expectation: Due to approaching half-cycle saturation, bias tends to destroy ordered bar domain configurations. Hysteresis losses should be affected in a weak way. Classical EC losses should not change at all since being determined by the B-pattern, by its shape and by its dynamics. However, anomalous EC losses should sink, as being indicated by the results of measurement.

6. Oblique rhombic RM

As already mentioned in Chapter 1, oblique rhombic patterns tend to arise close to overlaps of T-joints. In fact, they have high practical relevance since representing spots of highest local building factor.

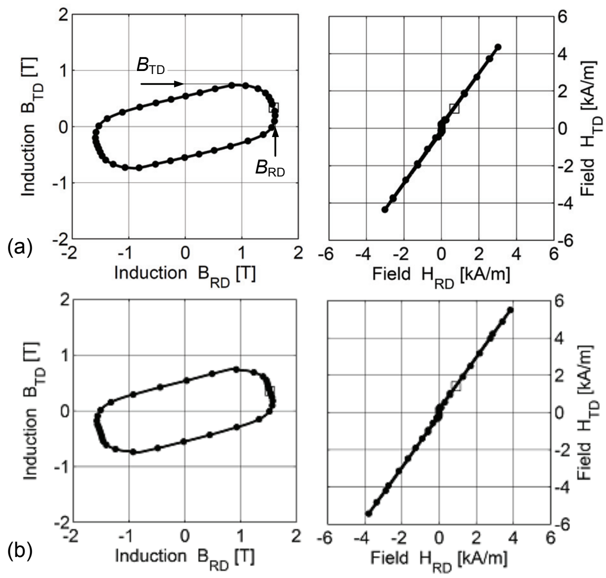

Fig.7. Examples of oblique rhombic magnetization pattern with different dynamics of $\boldsymbol{B}(t)$. (a) Case of low ω_{max}. (b) Case of increased dynamics.

Fig.7 compares two patterns for the considerably large axis ratio $a \approx 0.5$. This is linked with very high field values H_{HD} of an order of 5000 A/m, with about 10% increase from more pronounced dynamics. Corresponding results for losses are given in Fig.8 for B_{RD} = 1.5 T. Increases of P up to about 25% arise in the full range of a. An interpretation of the complex mechanisms involved will be subject of further work.

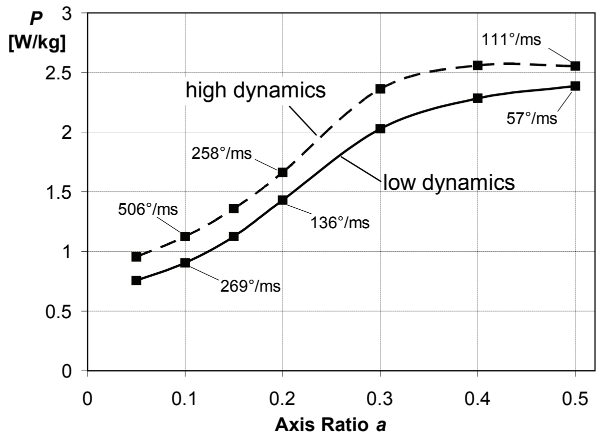

Fig.8. Losses of SHGO material under oblique rhombic magnetization for B_{RD} = 1.5 T and different ω_{max}.

Table 1. Losses for SHGO material.

elliptic RM	low dynamics	high dynamics
B_{RD} = 1.7 T a = 0.2 a = 0.5	1.32 W/kg 2.63 W/kg	1.51 W/kg (+14%) 2.66 W/kg (+1%)
rhombic RM		
B_{RD} = 1.7 T a = 0.2 a = 0.5	1.07 W/kg 1.58 W/kg	1.35 W/kg (+26%) 1.88 W/kg (+19%)
oblique rhombic RM		
B_{RD} = 1.5 T a = 0.1 a = 0.3	0.90 W/kg 2.03 W/kg	1.12 W/kg (+24%) 2.36 W/kg (+16%)

Table 2. Losses for CGO material.

elliptic RM	low dynamics	high dynamics
B_{RD} = 1.7 T a = 0.2 a = 0.5	1.46 W/kg 2.38 W/kg	1.68 W/kg (+15%) 2.46 W/kg (+3%)
rhombic RM		
B_{RD} = 1.7 T a = 0.2 a = 0.5	1.46 W/kg 1.79 W/kg	1.75 W/kg (+20%) 2.13 W/kg (+19%)
oblique rhombic RM		
B_{RD} = 1.5 T a = 0.1 a = 0.3	1.08 W/kg 1.90 W/kg	1.36 W/kg (+26%) 2.12 W/kg (+12%)

7. Conclusions

So far, most investigations of rotational magnetization patterns ***B***(t) for HGO SiFe have been performed with focus on the mere *shape* of a pattern. On the other hand, little attention has been put on the *dynamics* of rotation. The role of the latter can be assumed to be analogous to the role of distortion for alternating magnetization.

In the present study, a systematic comparison was performed between low dynamics – i.e. almost constant induction change ΔB per time – and increased dynamics – i.e. variable ΔB. The results yield the following main conclusions:

(1) Experimental investigation of T-joints and yokes of a model core reveal induction patterns ***B***(t) which are characterized by strong variations of the angular velocity ω of the B-vector during the period, corresponding to uneven ΔB.

(2) The angular velocity ω tends to be low when ***B*** passes through the RD, but much higher for the TD. This means that high dynamics are given in practice.

(3) B-patterns of different dynamics can be simulated by RSST modelling in very effective ways.

(4) Compared to low dynamics, high dynamics yield a general tendency of increased losses P, obviously due to more pronounced eddy currents.

(5) Elliptic RM shows increases of P which increase with rising B_{RD}. Distinct decreases arise with rising axis ratio a, probably due to less pronounced anomalous EC losses.

(6) Rhombic RM as being typical for practice shows a general increase of P.

(7) Rhombic RM with DC bias – as becoming frequent in mixed AC/DC grids – shows increases of P which decrease with rising a.

(8) Oblique rhombic RM as arising close to T-joint overlaps show general increases of P.

(9) According to Table 1 and Table 2, SHGO materials and CGO materials show similar orders of loss increases.

As a final conclusion, simulation of RM-patterns by means of RSSTs should not be performed with constant spacing ΔB per time. The latter case of low dynamics is not likely to arise in practice which means that losses are under-estimated. Rather, practical relevance is given for B-patterns of high dynamics, characterized by high values ΔB for those instants where ***B*** passes through hard directions.

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Authors: *All authors are with the Institute EMCE of Vienna University of Technology. Gusshausstr.27, A-1040 Vienna, Austria. E-mail: damir.sabic@tuwien.ac.at*