# Eddy-Current Loss in a Conductive Material Inserted into a U-cored Electromagnet Device

Patrice Koffi Chetangny[1,2] , Sossou Houndedako[2], Antoine Vianou[3], and Christophe Espanet[2]

[1]Femto-ST Institute, ENERGY Department, UBFC, Belfort, France
[2]Department of Electrical Engineering, Polytechnic School of Abomey-Calavi University, Benin
chetangny@yahoo.com

*Abstract*— **This paper deals with the measurement and estimation of eddy-current losses in conductive plate (e.g. Permanent Magnet (PM) or Aluminum) involved in machine in general and in those with permanent magnets in particular e.g. Permanent Magnet Synchronous Machine (PMSM). The authors presented an experimental device for evaluating eddy current losses generated in the conductive plates and in order to derive an equivalent circuit diagram leading to analytical and experimental model of by eddy currents losses in a conductive material herein the aluminum. This model based on the electrical equivalent circuit (EEC) is determined from different tests such as no-load and short-circuit tests and has allowed us to quantify the various losses created in the conductive material by using the method of separation of losses when the electromagnet is with and without the conductive plate.**

***Keywords*— Eddy current losses in conductive material; electrical equivalent circuit; experimental measurement; semi-analytical model;**

## I. INTRODUCTION

### A. Context of this paper

In recent decades, electrical industry has undergone significant developments with improved magnetic materials manufacturing technology, thus allowing better use of energy. Thus, the combination and use of high-performance permanent magnets and soft magnetic materials results in structures with very good performance in terms of mass/power density with excellent performance. However, as they are electrically conductive, high spatial frequencies and temporal harmonics can lead to significant eddy current loss density. Although these losses do not significantly reduce the machine efficiency or performance, they may result in a temperature rise inside the magnets which can cause partial or total irreversible demagnetization [1][2][3]. To avoid these risks, losses in the magnets must be evaluated with precision during the design of the machine, which requires adequate models that can give accurate results.

In the literature the eddy currents losses in conductive materials (e.g. rare-earth permanent magnets, Aluminum ...) in electric machines, are difficult to determine; they represent in recent years, a significant part of the scientific research in electrical engineering. So many models both analytical and numerical exist but they are mostly in 2D and does not take into account the 3D distribution of eddy currents. To really predict what happens in terms of losses in these materials, it is imperative to have and use a 3D model and then compare them to an experimental test in a real time as possible. In order to make that comparison we propose to use the present experimental device. Before discussing the experimental model of effective validation of eddy currents losses, it is necessary to make a brief analysis of loss quantification devices in conductive materials (permanent magnet, Aluminium) proposed in the literature.

### B. Review of litterature

Among the reduced number of experimental model, we can cite that one used by K. Yamazaki et al [4] and Y. Aoyama et al, [5] for the study of eddy currents losses created in the Nd-Fe-B permanent magnets. Figure.1 shows the experimental device used by [5] to measurement eddy current losses induced in the segmented magnets. It quantifies the losses in magnets without using a magnetic circuit that canalize the magnetic flux. The disadvantage is that it is difficult to approach the operating conditions of a real machine. In the same way, S. Kanazawa et al. [6] has used an experimental device with a closed magnetic. It consists of two magnetics "U-shape" in series with the Nd-Fe-B magnet and a laminated magnetic core of the same length which close the circuit. The excitation circuit fed the coil at different frequencies (50Hz to 150Hz) with a variation of magnetic induction in the magnet from 0.01T to 0.1T. The device is used to extract the losses in the magnets under conditions which are closed to the operation point of a machine, but the absence of an air gap does not allow to vary the operating point of the magnet. In a similar purpose, R. Fratila et al [7] used an experimental system Fig.3.for demagnetization models validation of rare-earth permanent magnets and the calculations of the magnet losses. The model enables validation with operating conditions close to those of a real machine and also allows varying the operating point of the magnet studied. The Technical constraints of a loss validation model with operating conditions close to that of a real machine, and the possibility to vary the operating point of the magnet or the conductive material, guided our choice on an electromagnet device. In this paper, a dedicated test device , to measurement the eddy current losses is used and will focused on the conductive material made in aluminum; however it may be extended to other massive part (magnet, copper, etc.)

The contributions of this work are based on modeling by electrical equivalent circuit including a representative eddy currents losses resistance and inductance.

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## II. MEASUREMENT SYSTEM AND ELECTRICAL EQUIVALENT CIRCUIT

In the literature, three possible geometric arrangements of electromagnet are available [8]: a U-shaped or E-shaped or a cylindrical core. With the U-shaped core we have four configuration depending on the principle: flat armature; valve armature; plunging armature and rotating armature. We opted here for flat armature presented in Fig.1 because we already have in the laboratory this type of electromagnet. However a task no less important is the characterization of this device.

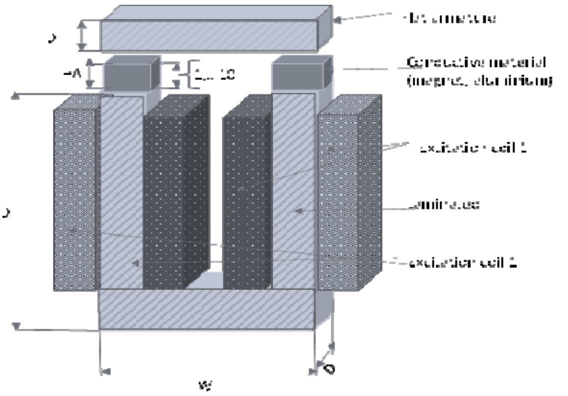

Fig. 1. Schematic representation of the experimental device

The test device is composed of a magnetic circuit made of high performance electrical steel of 0.5 mm thickness. The cross section is 43mm x43 mm and the weight is about 7.5 kg. The device is subject to an alternating field created by two identical excitation coils '(each with 500 turns) connected in parallel. The air-gap with, the supply frequency and the flux density can be varied. We can easily notice that our device is much simpler than a machine but it is important to notify that the quantification of losses is not straightforward and should be deducted from various measurements since the device is subject to total losses (1).

$$P_T = P_{cu} + P_{iron} + P_{Mat} \qquad (1)$$

$$P_{cu} = R_p I_p^2 \qquad (2)$$

TABLE I. MAIN DIMENSIONS OF TEST DEVICE

| Symbol | QUANTITY | Value |
|---|---|---|
| L | Length | 190 mm |
| W | width | 150mm |
| D | Deep | 43mm |
| HA | Material width | 1 to 10 mm |
| A | Cross section | 43x43 mm$^2$ |

Where $P_T$ is the total losses, $P_{cu}$ the copper losses of both excitation coils, $P_{iron}$ the laminated core losses and $P_{Mat}$ the eddy current losses in the conductive material according to (1). The copper losses can be deduced from direct measurement using (2). With Rp and Ip are respectively the measurementd parallel resistance of the coils and the the measurementd parallel current. The dissociation between $P_{iron}$ in the magnetic core and $P_{Mat}$ in the conductive material is not directly possible. One way to achieve this goal consists in quantifying accurately $P_{iron}$ in the device by another approach in order to be able to subtract them in Equation (1). One approach is FE calculation [7] using Bertotti approach [9] which is based on the decomposition of iron losses in three contribution:

$$P_{iron} = P_h + P_{cl} + P_{exc} = k_h f B_m^{\alpha} + k_{cl} f^2 B_m^2 + k_{exc} f^{1.5} B_m^{1.5} \qquad (3)$$

where $P_h$, $P_{cl}$ and $P_{exc}$ are, respectively, the quasi-static hysteresis, classic eddy currents and excess losses. The parameters $k_h$, $k_{cl}$, $k_{exc}$ and $\alpha$ are parameters obtained from data fitting with the experiment. In our case, these losses are obtained from analytical calculation based on the measurements and we use the separation method to deduct eddy current losses in the conductive material.

The real experimental device is shown in Fig.2

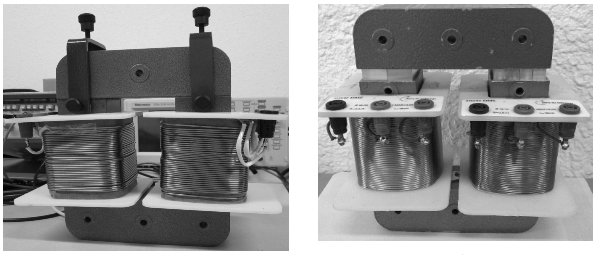
a.) b.)

Fig. 2. Real experimental device: a) without material; b.) with material

In the first time we use our device as a transformer. The equivalent circuit of a transformer is shown in Figure 6. In this circuit, Rs and Xs represent primary or secondary coil resistance and leakage reactance, respectively; Rμ is the resistance stands for core losses; Xμ represents magnetization reactance, m is the transformer turn ratio.

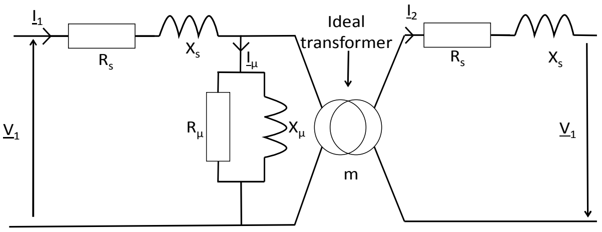

Fig. 3. Transformer model

We use the equivalent circuit to facilitate the computation of various operating quantities. The parameters of the equivalent circuit are obtained from the dc/ac, open-circuit and short circuit tests. When the three tests are performed, equivalent circuit parameters can simply be computed.

The primary and secondary resistance Rs are directly calculated from the dc test and the inductance in air $L_{sair}$ from ac test.. The open-circuit test gives the magnetizing resistance Rμ and reactance Xμ referred to primary side. The short-circuit test gives the leakage reactance $X_s$

## III. VOLTMETER-AMMETER METHOD (DC/AC TEST)

As voltmeter-ammeter method is the most common method used for transformer winding resistance measurement, we made our measurement using the previous described method with direct current, and simultaneous readings of current and voltage. The required resistance is calculated from the readings in accordance with Ohm's Law. The winding resistance determined from the dc test is an approximate value of the actual one since the skin effect and temperature effects are not taken into consideration. Note here that $L_{sair}$ is not the leakage inductance of the coil. It represents the inductance when the coil is in air without any magnetic core. The value of the inductance in air is find with differents test at different frequency. We found the inductance in air value obtained for example at low and high frequency by using a pulse @ 50 Hz and 12800 Hz .The resulting parameters are presented in Table II.

TABLE II. EQUIVALENT CIRCUIT PARAMETERS

| | **manufacturer** | **dc/ac(50hz) test** | **dc/ac(12800hz) test** |
|---|---|---|---|
| Ls | 18 mH | 11.3 mH | 18.7 mH |
| Rs | 2.8 Ω | 2.81 Ω | 2.81 Ω |

### A. *Short-circuit Test*

We use this test to calculate the coil leakage reactance which is one equivalent circuit parameters. In this experiment, the secondary terminals of the transformer are short-circuited, and the primary terminals are connected to a voltage source., as shown in Fig. 4.

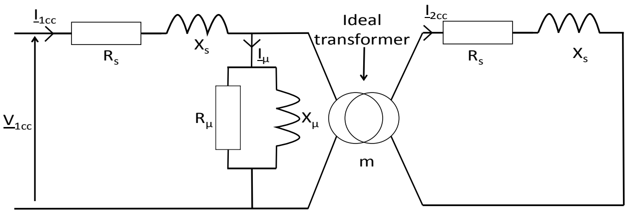

Fig. 4. . Short circuit model

The input voltage is adjusted until the current in the short-circuited winding is equal to its rated value. For each adjusted value of voltage, we measurementd current, active and reactive power. In our case, as the primary turn is the same as the secondary, the input voltage is not low during the short circuit test and we can't ignore the excitation current.

According to Kirchhoff node law, $\underline{I}_{1cc} = m\underline{I}_{2cc} + \underline{I}_{\mu}$ .In our case $m = 1$ and $\underline{I}_{\mu} = 0.02 \times \underline{I}_{1cc}$ so that $\underline{I}_{1cc} \cong \underline{I}_{2cc}$ . As the magnetization current $\underline{I}_{\mu}$ flowing through magnetization branch is negligible, we can ignore it and the entire voltage drop in the transformer can be attributed to the series elements in the circuits as shown in Fig.5

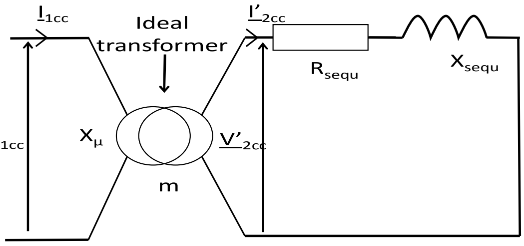

Fig. 5. Simplified Short circuit model

$$R_{sequ} = m^2 R_s + R_s \quad (3)$$

$$X_{sequ} = m^2 X_s + X_s \quad (4)$$

From the equivalent circuit in Fig.5 we can write the following equations:

$$\underline{V}_{2cc} = m\underline{V}_{1cc} \quad (5)$$

$$\underline{I}_{2cc} = \frac{1}{m}\underline{I}_{1cc} \quad (6)$$

$$X_{sequ} = \sqrt{Z_{sequ}^2 - R_{sequ}^2} \quad (7)$$

By combining Equations (7) (8) and (9) we found the leakage reactance of the coil which is:

$$X_{sequ} = \sqrt{\left(\frac{\underline{V}_{2cc}}{\underline{I}_{2cc}}\right)^2 - R_{sequ}^2} \quad (8)$$

The leakage inductance Ls is found from (9) and has a constant value of 65 mH which is independent of the voltage value.

$$L_s = \frac{\sqrt{\left(\frac{\underline{V}_{2cc}}{2\underline{I}_{2cc}}\right)^2 - R_s^2}}{2\pi f} \quad (9)$$

### B. *Open-circuit or no-load Test*

In an open-circuit test a transformer's secondary winding is open-circuited, and its primary winding is connected to ac voltage line. Here we connected the two coils in parallel with adding fluxes and without feeding any load. Under the conditions described, though the series elements Rs1 and Xs1 are too small, the input current flowing through the excitation branch is important and a significant voltage drop is caused. (10) give the resulting voltage Vμ across the magnetization branch:

$$\underline{V}_{\mu} = \underline{V}_{1v} - \frac{(R_s + jX_s)}{2}\underline{I}_{1v} \quad (10)$$

In the open-circuit test, where a one-phase 220V/50 Hz ac source is applied to the two coils connected in parallel, and the input voltage, input current, input active power and input reactive power to the transformer are measurementd. From this information, it is possible to determine the copper losses $P_{cu}$ of the two coils from (12).

$$P_{cu} = R_p \underline{I}_{1v}^2 \qquad (11)$$

where $R_p = \frac{R_S}{2}$ is the measurementd parallel resistance of the coils and $I_{1v}$ the measurementd parallel current of no-load test. (12) and (13) give the input active total power and the input reactive power.

$$P_{Tv} = P_{cu} + P_{iron} \qquad (12)$$

$$Q_{Tv} = Q_{coil} + Q_{iron} \qquad (13)$$

With $P_{iron}$ and $Q_{iron}$ we calculate the value of the core-loss resistor $R_\mu$ and the value of the magnetizing reactance $X_\mu$. Considering that $P_{iron}$ is proportional to the voltage squared leads to:

$$G_\mu = \frac{1}{R_\mu} = \frac{P_{iron}}{\underline{V}_\mu^2} \qquad (14)$$

Fig.6 shows the conductance of the core-loss according to the squared of voltage.

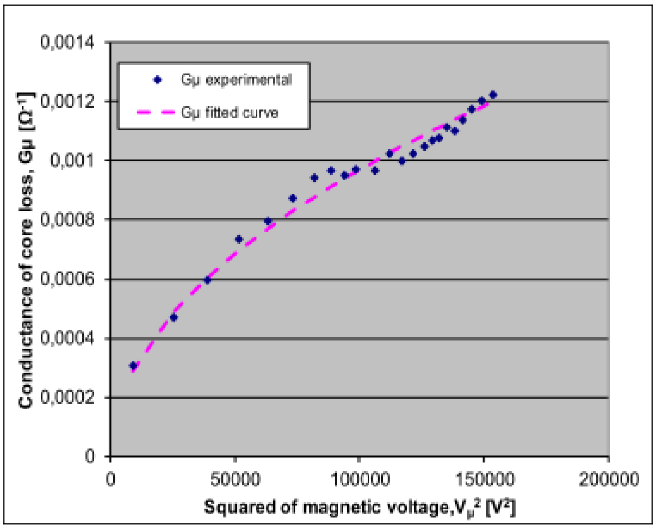

Fig. 6. Conductance of core-loss Vs squared magnetic voltage

In the same way, it is possible to determine the susceptance of the magnetizing reactance from (15).

$$B_\mu = \frac{1}{X_\mu} = \frac{Q_{iron}}{\underline{V}_\mu^2} \qquad (15)$$

$$Q_{iron} = Q_{Tv} - Q_{coil} \qquad (16)$$

$$Q_{coil} = \frac{X_S}{2} \underline{I}_{1v}^2 \qquad (17)$$

Fig. 7 shows the susceptance of the magnetizing reactance

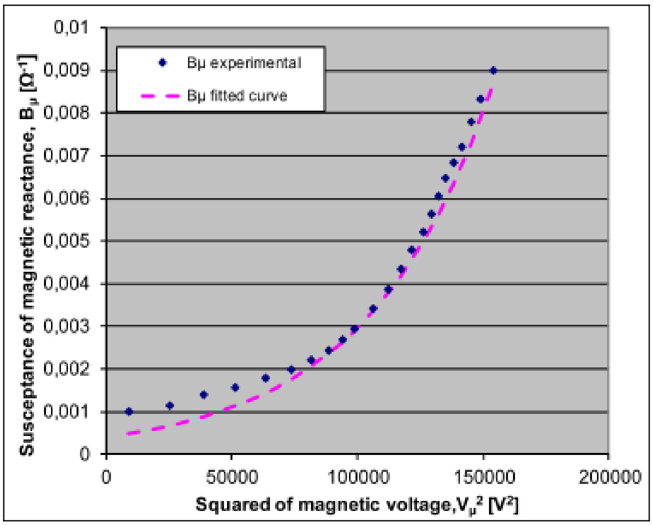

Fig. 7. .Susceptance of magnetizing reactance Vs squared magnetic voltage

In order to separate eddy current losses created in the conductive material, it is important to know precisely $P_{iron}$ and $Q_{iron}$.In the range of the measurement we found a trend which can be approximate by a polynomial function of degree 6 and 7. Equations (18) and (19) show the evolution of both the conductance of –core-loss and the susceptance of magnetizing reactance according to the squared of the voltage. These polynomial function are used to find the exact active or reactive core loss when we insert the conductive material into the device

$$G_\mu = f(\underline{V}_\mu^2) = \sum_{i=0}^{6} k_i \underline{V}_\mu^{2i} \qquad (18)$$

$$B_\mu = f(\underline{V}_\mu^2) = \sum_{j=0}^{7} k_j \underline{V}_\mu^{2j} \qquad (19)$$

TABLE III. POLYNOMIAL CONSTANT

| **$K_i$ coefficient for Gμ, [A/V$^{(2i+1)}$]** | | **$K_j$ coefficient for Bμ, [A/V$^{(2j+1)}$]** | |
|---|---|---|---|
| i | $k_i$ | j | $k_j$ |
| 0 | $6.11.10^{-4}$ | 0 | $-43.10^{-4}$ |
| 1 | $-6.048.10^{-8}$ | 1 | $1.183.10^{-6}$ |
| 2 | $4.421.10^{-12}$ | 2 | $-8.966.10^{-15}$ |
| 3 | $-1.24.10^{-16}$ | 3 | $3.269.10^{-20}$ |
| 4 | $1.741.10^{-21}$ | 4 | $-6.38.10^{-20}$ |
| 5 | $-1.020.10^{-26}$ | 5 | $6.842.10^{-25}$ |
| 6 | $3.24.10^{-32}$ | 6 | $-3.803.10^{-30}$ |
| 7 | | 7 | $8.573.10^{-36}$ |

## III) EDDY CURRENT LOSSES IN THE CONDUCTIVE MATERIAL

Once the iron loss model is validated for the experimental device without the conductive material, the calculation of eddy current losses in the material can be extracted from the following power balance:

$$P_{Mat} = P_T - P_{cu} - P_{iron\_Trend} \qquad (20)$$

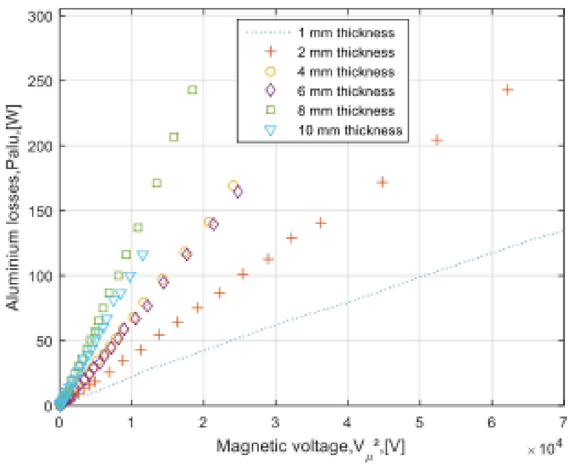

Fig. 9. Aluminum joule losses

Here we introduce different thickness of aluminum in the device. All the materials have a cross section of 43mm x43mm and they thickness are respectively 1, 2, 4, 6, 8, and 10 mm.To draw the equivalent circuit and the position of the branch representing the eddy current losses resistance, we made several assumptions. We compared the evolution of these losses according either to the current that should pass through the branch if the resistance were in series or to the voltage across its terminals if it were in parallel.

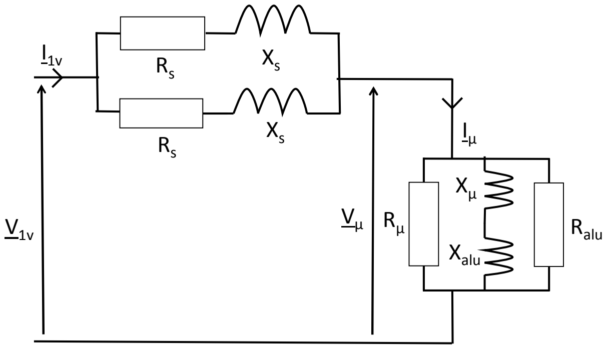

Fig. 8. Electrical equivalent model

The total input reactive losses can be divided into four components according to (21)

$$Q_{Tv} = Q_{coil} + Q_{iron\_Trend} + Q_{Mat} \quad (21)$$

We plot the total reactive losses $Q_{mag}$ define in (22) according to the current and the voltage as shown in Fig. 8

$$Q_{mag} = Q_{iron\_Trend} + Q_{Mat} \quad (22)$$

Once the copper losses $P_{cu}$ are extracted from the experiment, the iron losses $P_{iron\_Trend}$ obtained from (18) are used in the power balance given by (20) to deduce the eddy current losses $P_{Mat}$ in the conductive material. Fig.9 and Fig. 10 show the result for Aluminum at 50 Hz and for each thickness

From Fig.9 and Fig.10, a linear function (23)-(26), depending on the thickness and the voltage was found, in order to estimate the exact conductance of eddy current losses and the susceptance of the eddy current reactance.

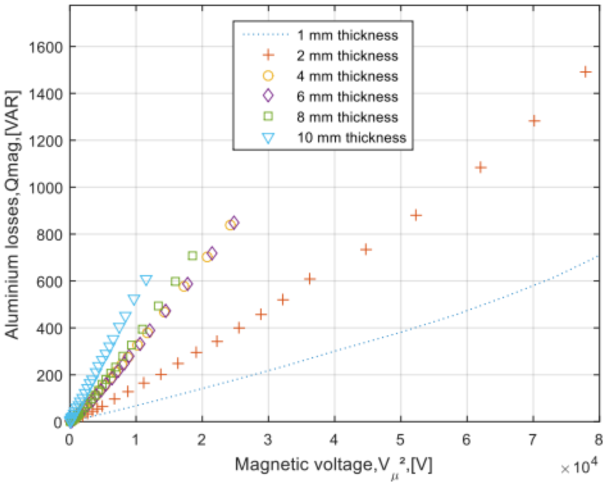

Fig. 10. Aluminum reactive losses

$$\frac{1}{R_{alu}} = f_r\left(\underline{V}_\mu^2, E_p\right) \quad (23)$$

$$\frac{1}{X_{alu}} = f_x\left(\underline{V}_\mu^2, E_p\right) \quad (24)$$

$$f_r\left(\underline{V}_\mu^2, E_p\right) = K_{Ep_r}.Ep.\underline{V}_\mu^2 \quad (25)$$

$$f_x\left(\underline{V}_\mu^2, E_p\right) = K_{Ep_x}.Ep.\underline{V}_\mu^2 \quad (26)$$

with $K_{Ep_r} = 0.001613$ and $K_{Ep_x} = 0.005352$

Fig.11 shows the evolution of Kep according to the thickness for both the conductance and the susceptance.

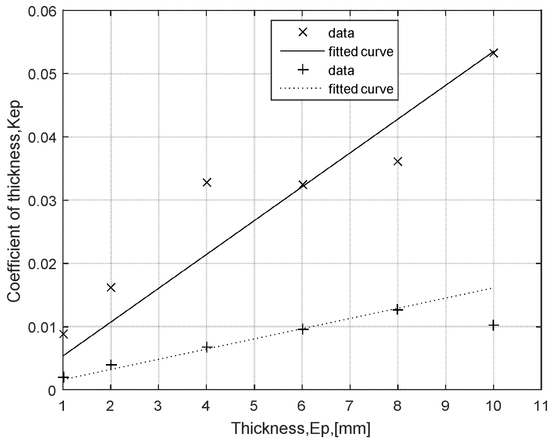

Fig. 11. Coefficient of thickness

## IV. CONCLUSION

In this study an open-circuit experimental device is used to measurement the eddy current losses in conductive materials. A loss balance technique combining experimental and semi-analytical result was proposed in order to quantify eddy current losses in the materials. This allows us to find an equivalent electrical circuit which will be used in the future paper taking into account the frequency and the segmentation. The precision of the results is not depending on the quantity of material which have been used. The tests performed helped us to determine parameters of the equivalent circuit of the device and eddy current equivalent losses resistance. In this paper only experimental test at 50 Hz with only aluminum were performed. The same tests have been done at different frequencies including the high frequencies and will be presented later. The eddy current losses estimated with this method will be compared to those obtained directly by the 3D FEM analysis in the next paper.

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