Numerical Determination of the Effective Magnetic Path Length of a Single Sheet Tester

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***Abstract*— We describe a numerical method for the correction of the magnetic field strength measured by a Single Sheet Tester (SST) based on the current method. This operation is performed by a reluctance network that considers the varying path length of the magnetic circuit by determining the parasitic magnetic voltage drops over the yoke, gaps and parts of the probe underneath the pole faces. In contrast to common magnetic circuit analysis, we enforce the magnetic flux and the magnetomotive force simultaneously and treat the magnetic resistance of the specimen as a degree of freedom. Hereby, we avoid errors due to uncertainties in the description of the B-H-behavior of the specimen and can correct arbitrary working points covering hysteretic and dynamic effects. The validity of this approach is demonstrated on a M330-35A sheet steel.**

***Index Terms*— circuit analysis computing, finite element methods, loss measurements, magnetic losses, magnetic circuits, magnetic field measurement, sheet materials**

I. Introduction

The Epstein frame was the established measurement system to gain the total magnetic power loss of electrical sheets but since the 1980s it has progressively been replaced by the so-called Single Sheet Tester (SST) [1]. Despite the description of both the Epstein frame and the SST by IEC standards [2], [3], the universal determination of the effective magnetic path length l_m on physical grounds is still unsolved. The focus of past studies lies in the comparison of these systems and in the calibration of the emerging SST so that its loss values match with the results of the established Epstein frame (e.g. [3], [4]). The magnetic path length was treated as a degree of freedom within the calibration process as the calculated field strength H^s on the surface of the probe and the total magnetic power loss $\overline{p}$ per period T directly depend on it. The number of turns and the current of the primary coil are described by w_1 and i_1, u_2 is the induced voltage in the secondary coil and c combines all geometric quantities:

$$H^\mathrm{s} = w_1 i_1 / l_\mathrm{m} \tag{1}$$

$$\overline{p} = \frac{c}{\mathrm{T}} \cdot \int_T u_2 H^s \, dt \tag{2}$$

This approach ensures the continuity of experimental results but introduces uncertainties of the Epstein method into the SST method along with a high sensitivity of the calibration quality on the magnetic material behavior of the specimen and the induction B. The IEC standard [3] defines the distance l_i between the inner sides of the yoke to be the magnetic path length to avoid the mentioned shortcomings of the calibration process. Nevertheless, a fixed value for l_m bears the risk of errors in the measured H^s and $\overline{p}$ due to the distinct nonlinearity of the underlying magnetic circuit [5].

The goal of this paper is to describe a physically sound method to numerically correct the value of H^s in respect of the actual magnetic path length considering the hysteretic and dynamic material behavior of the specimen. The effects of air gaps between the specimen surfaces and the pole faces as well as the insulation coating of the specimen are covered. Our approach consists of three steps: Firstly, a two-dimensional finite element (2d FE) model of the SST similar to [5] is built. Secondly, this model is used to evaluate a reluctance network describing the same magnetic circuit. The last step is the application of the reluctance network to calculate H_corr for each sampling point of a measured magnetizing period. The validity of this procedure is demonstrated on a M330-35A grade. The improved accuracy of the loss values may help to refine advanced loss models (e.g. [6]-[8]) that assume accurate measurements as basis for their fitting process.

II. Calculation of the Magnetic Field Strength

A. *2d FE Model of the SST*

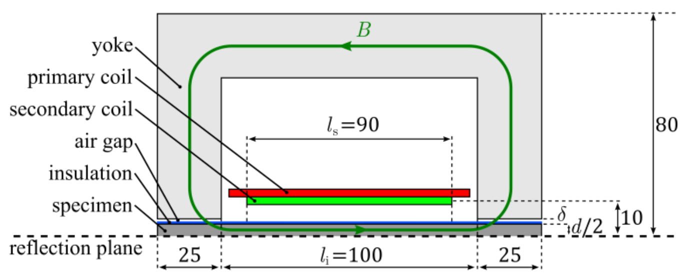

Fig. 1. Geometry (in mm) of the examined SST

The magnetic circuit of the SST was simulated by means of a static 2d FE model similar to [5]. We investigated the SST geometry shown in Fig. 1 with a specimen size of $150\,\mathrm{mm}\; x\; 150\,\mathrm{mm}$ and a wound yoke made of a grain oriented low loss M111-30P grade. The material behavior of the yoke and the specimen were described by the corresponding normal magnetization curves $B_n(H)$. For the sake of clarity we only present the results for a non-oriented M330-35A specimen with sheet thickness $d = 0.35$ mm and maximal relative permeability $\mu_{\mathrm{r,max}} = 17300$. The obtained magnetic path length is depicted in Fig. 2 as a function of the induction B for several values of the gap δ between the pole faces of the yoke and the steel surface of the specimen.

A profound dependence of l_m on B can be observed which eliminates the chance of precisely calculating H^s by (1) with a fixed value for l_m. The gap size plays a significant role which makes it necessary to properly consider the roughness and planarity defects of the pole faces as well as the thickness of the insulation coating of the specimen, adding up to δ.

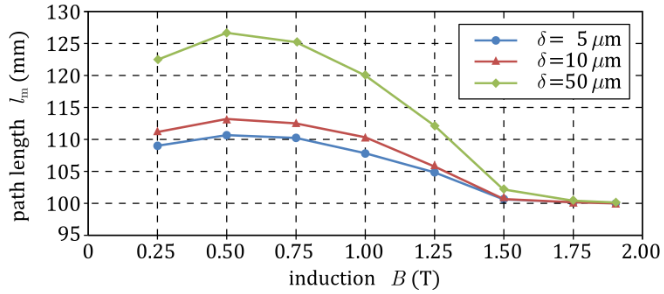

Fig. 2. Magnetic path length as function of the induction in the specimen and gap size – 2d FE simulation with single-valued $B_n(H)$

B. Reluctance Network of the SST

The 2d FE model was used to validate a reluctance network describing the same magnetic circuit of the SST. Fig. 3 depicts the topology of the network with the universal source enforcing the magnetic flux $\Phi = dB$ and the magnetomotive force $\Theta = w_1 i_1$. The equation system is not over-determined as the magnetic resistance R_s corresponding to the part of the specimen enclosed by the secondary winding with length l_s is a degree of freedom. Hereby, the material behavior of the probe is not considered for the solution what makes it immune to uncertainties of the material description and enables the calculation of any working point including hysteretic and dynamic effects. The 2d FE model does not offer these features and needs more computing time.

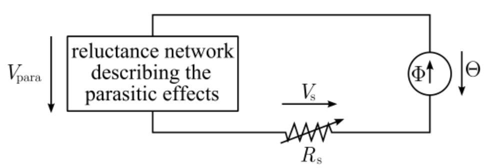

Fig. 3. Reluctance network describing the magnetic circuit of the SST

The reluctance network reduces Θ for the parasitic magnetic voltage drops V_{para} over the yoke, the gaps and the remaining parts of the specimen under the pole faces resulting in the corrected magnetic field strength:

$$H_{corr} = V_s/l_s = \left(\Theta - V_{para}\right)/l_s \tag{3}$$

C. Application of the Reluctance Network

The reluctance network is applied to each sampling point n of a loss measurement with corresponding $B(n)$ and i_1(n). The insulation coating of the M330-35A grade was removed to reduce the gap to the roughness of the pole faces and their planarity defects. The effective gap for the standard measuring procedure sums up to $\delta \approx 25$ µm mainly due to a surprisingly high planarity defect of the used SST. Fig. 4 compares the measured dynamic hysteresis loop (standard) for $\hat{B} = 1.0$ T and $f = 50$ Hz (fixed $l_m = 100$ mm) with the corrected BH-loop which encloses a significant different area compared to its measured counterpart revealing a loss error of 8 %.

The validity of the numerical correction was checked by widening the gap with one and two layers of sticky tape between the surface of the specimen and the pole faces. Hereby, the gap adds up to 75 µm and 125 µm respectively corrupting the measurements shown in Fig. 4. By means of the reluctance network we determined the corrected BH-loops which sufficiently match with the corrected loop linked with $\delta = 25$ µm. The observed deviations can be explained by slightly different values of $\hat{B}$ and a varying pre-magnetization.

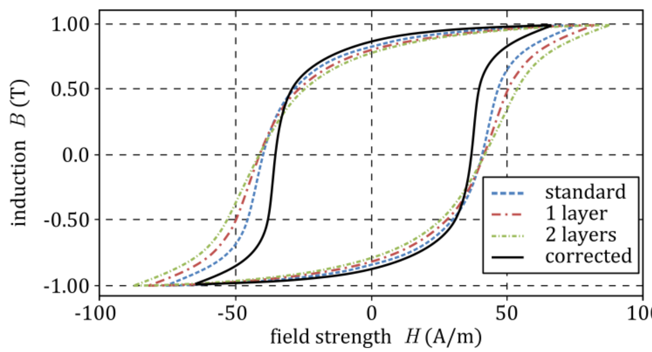

Fig. 4. BH curves for $\hat{B}$ = 1.0 T and = 50 Hz : measured (standard / gap due to 1 layer and 2 layers of sticky tape) and numerically corrected

III. Conclusion

The results depicted in Fig. 2 demonstrate that the magnetic field strength cannot be precisely determined with one single value for l_m. By means of the developed reluctance network the measured H^s can be corrected at any working point also improving the accuracy of the loss value. Future studies have to clarify the impact of planar eddy currents underneath the pole faces on the magnetic path length.

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