An electrical method for measuring the complex magnetic permeability of steel wires

Karl-Ludwig **ABKEN**, Prysmian Group, (Germany), karl-ludwig.abken@prysmiangroup.com
Luigi **COLLA**, Prysmian Group, (Italy), luigi.colla@prysmiangroup.com
Josef **TIMMERBERG**, Jade-Hochschule, University of Applied Science, (Germany), jt@jade-hs.de

ABSTRACT

In this paper, a method for measurement of the complex valued relative magnetic permeability of steel wires is described. The principle is based on skin effect and its influence on resistance and reactance of a loop formed by the steel wire sample to be investigated. The method is based on purely electrical measurement. Fundamental conditions of the set-up, the configuration of the electromagnetic field as well as the applicability of the results for loss calculations within steel wire cable armouring are discussed.

KEYWORDS

Complex valued magnetic permeability; armour losses; hysteresis; steel wire; magnetic losses;

INTRODUCTION

For determining the losses within the steel wire armouring of subsea power cables, knowledge of the magnetic properties are essential in order to include losses caused by eddy currents, cyclic magnetization and hysteresis. One possibility of taking magnetic material properties into account is using a complex relative permeability

$$\mu_r = \mu_{r,real} - j \cdot \mu_{r,imaginary} \qquad [1]$$

For many purposes, this method has been found to be accurate enough to include the magnetic properties of the steel wires, while avoiding complicated and time consuming evaluation of the complete hysteresis curve, e.g. within a Finite Element Analysis.

A "magnetic" method for measurement of the complex permeability has been described by Ivanenko and Nordebo ([1]).

In the following, a different method for determining the complex relative permeability μ_r of round wires is described, which is based on electrical impedance measurement.

PRINCIPLE OF MEASUREMENT

Using the commonly known formula for the skin effect in a round wire as a basis (e.g. provided in [2]) and after some re-arrangement of the variables, the internal impedance per length Z' of a straight cylindrical wire can be written as:

$$Z' = (1-j) \cdot \sqrt{\frac{\mu_0 \cdot \mu_r \cdot f \cdot R'_{DC}}{4}} \cdot \frac{J_0\left\{(1-j) \cdot \sqrt{\frac{\mu_0 \cdot \mu_r \cdot f}{R'_{DC}}}\right\}}{J_1\left\{(1-j) \cdot \sqrt{\frac{\mu_0 \cdot \mu_r \cdot f}{R'_{DC}}}\right\}} \qquad [2]$$

On the other hand,

$$Z' = \frac{U'}{I_0} = R' + j \cdot 2\pi f \cdot L'$$

This means, that for determination of the relative complex magnetic permeability μ_r at a certain frequency f, the DC resistance per length R'_{DC}, the voltage per length U' and the current I_0 (absolute value and phase angle in relation to U') need to measured. The influence of the external magnetic field of the wire, which is not covered by formula [2], can be derived theoretically and be taken into account if a known and preferably simple set-up is used. The evaluation of the measurement is straightforward and can be easily implemented in off-the-shelf software and leads directly to a numerical complex value of μ_r. In formula [2] and [3], R' is the AC resistance per length, μ_0 is the magnetic field constant and J_0 and J_1 are the Bessel functions of the first kind, zero and first order, respectively.

ELECTROMAGNETIC FIELD INSIDE THE WIRE

If an alternating electrical current is fed into a cylindrical wire, the current flow is – as a matter of course - in longitudinal direction (z). If there is considerable influence of skin effect, depending on frequency and magnetic properties of the material, the current density near the surface of the wire is higher than the current density in the centre of the wire. If it is assumed that the internal field is not distorted by external influence, e.g. by the loop shape of the sample, the magnetic field strength $\overleftarrow{H}$ can be calculated according to

$$\oint \cdot \overleftarrow{H} \cdot \overleftarrow{ds} = \iint \overleftarrow{J} \cdot \overleftarrow{dA} \qquad [3]$$

In formula [3], $\overleftarrow{ds}$ is a length element, $\overleftarrow{J}$ is the current density and $\overleftarrow{dA}$ is a surface element. Taking into account current flow in longitudinal direction and the symmetry of the problem, leading to an azimuthal component H_φ of $\overleftarrow{H}$ only, formula [3] can be written as

$$H_\varphi(r) = \frac{1}{2\pi r} \cdot \iint J_z(\rho) \cdot dA = \frac{1}{r} \cdot \int_0^r J_z(\rho) \cdot \rho \cdot d\rho \qquad [4]$$

Formula [4] describes the fact that the azimuthal magnetic field strength is not constant with radius, but is zero at the centre and highest close to the surface of the wire. If a longitudinal current I_0 is flowing, the maximum magnetic field strength directly at the surface of the wire is

$$H_{\varphi,max} = H_\varphi(r_0) = \frac{I_0}{2\pi r_0} \qquad [5]$$

Due to the skin effect, the concentration of the magnetic field close to the wire surface is even more relevant for higher frequencies and higher permeability.

Thus, the magnetic properties (and hence the complex μ_r) of the material to be investigated are relevant close to the surface of the wire only (figure 1).