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Analytical modelling of a magnetization curve obtained by the measurements of magnetic materials' properties using evolutionary algorithms

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ABSTRACT

Magnetization curves are obtained with measurements and used for the description of magnetic material properties. In the case where the curve is rough problems can appear during the Finite Element Method (FEM) calculations. One of the solutions is the use of an analytically written curve, which fits the measured curve. In this paper different analytical expressions are tested on different measured magnetization curves and compared with each other. Different evolutionary methods are used and tested for the determination of the analytical expressions' parameters: The Genetic Algorithm, Differential Evolution with three different strategies, Teaching-Learning Based Optimization and Artificial Bee Colony. To obtain credible and optimal results, we made a statistic evaluation of the results using Cross-validation, CRS4EAs (Chess rating system for evolutionary algorithms), and the Holm test. Based on the test's results we improved the more appropriate evolutionary method, which was Artificial Bee Colony, using the Levenberg-Marquardt algorithm. As a result, two different methods: are presented and tested which combine Artificial Bee Colony and the Levenberg-Marquardt algorithm. An analytical expression is presented which can be used for a wide range of different materials' curves and also a stable and efficient method for the determination of the analytical expression's parameters. The presented solution is appropriate to be used together with, or as a part of, FEM calculation software. For preparation of magnetic material data the presented solution can be used as an independent programme for the transformation of the *H*-*B* table of values presenting not-smooth measured magnetic material curves (or measured with too few points) into the *H*-*B* table of values presenting smooth magnetic material curve which can be used as input data for any FEM software.

1. Introduction

Today, almost all electromagnetic devices, like electric motors, transformers, relays, switches, etc., are modelled numerically before the productions of prototypes and the final products are made after that. The calculated electromagnetic fields inside the parts of the electromagnetic devices help us to design a quality device with optimal use of the materials. Also, calculations of forces, torques, energies, losses, etc. are based on the correct electromagnetic field calculations. Different numerical methods are used for the modelling, of which the most common is the Finite Element Method (FEM) [1–11]. To obtain correct results using FEM magnetic properties of the materials, like iron, steel, transformers' sheet, etc. must be described correctly. One of the common ways of describing magnetic materials is usage of the magnetization curve. It gives us a correlation between the magnetic field strength $\boldsymbol{H}$ and magnetic flux density $\boldsymbol{B}$ [12–23].

The magnetization curve is nonlinear and more iterations of solving FEMs' linear equations' system must be done to obtain correct $\boldsymbol{B}$ due to the $\boldsymbol{H}$ produced by the excitation current in the coil of the device or by the permanent magnet which is part of the device. One of the common methods for nonlinear calculations is the Newton-Raphson method, where the derivative $d\nu/dB$ (ν is magnetic reluctivity, the reciprocal of magnetic permeability) is used to get a correct relation between $\boldsymbol{B}$ and $\boldsymbol{H}$, defined with the magnetization curve. The magnetization curve can be given by the material producer or it is measured using Epstein [24], Single sheet tester [25–27], etc. The measured curve is often rough due to the limited precisions of the measurements. If the measured curve is not smooth the derivative $d\nu/dB$ is also not smooth and causes a

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higher number of iterations to solve a nonlinear problem or the Newton Raphson procedure does not converge.

One of the approaches to obtaining an appropriate curve is smoothing. The calculation of the average value between neighbouring points for all points is common and this can be repeated more times. The biggest disadvantage of smoothing is that the smoothed curve does not coincide with the measured magnetization curve in the area for very low $\boldsymbol{H}$ (Rayleigh region) and it does not coincide with the measured curve in the knee area. For optimal usage of the material many devices work in the way that $\boldsymbol{B}$ inside the material is in the knee area and, due to the described, a smoothed curve is often not the best solution.

A possible approach for obtaining a smooth magnetization curve and, consequently, smooth $\mathrm{d}\nu/\mathrm{d}B$ also, is usage of the analytically written magnetization curve [15–23,28–32]. Some analytical expressions can be found in professional FEM software and in literature, but none of them cover well the wide range of different magnetization curves of different materials. An analytically written curve allows faster calculation. If the magnetization curve is written as a table of values (measured and also smoothed), the derivative $\mathrm{d}\nu/\mathrm{d}B$ for each finite element must be searched for within the table of values, which is not the case for an analytically written curve.

The aim of our work was to find an analytical expression which can be used for a wide range of different curves of magnetic materials and also for defining an appropriate method for determining parameters. The best of the tested methods was modified further to obtain even better results. We tested different analytical expressions and we also tested different evolutionary algorithms [33,34] for determination of an analytical curve's parameters. As a result of the work, we suggested an analytical expression which can be used for a broad range of different materials' curves, and we suggested a modified evolutionary method that is more appropriate for determining analytical curve parameters. Within a broader scope our work can be related to the fitting curve problem [35] or parameter estimation problem [36–39], which has been solved successfully in the past using evolutionary algorithms. For example, in [35] a parameter estimation of Sovova's mass transfer mode to describe the extraction kinetics curve with evolutionary algorithms was presented by Liu et al. (2013). In [40] N. Chernov et al. studied the problem of fitting parameterized curves to noisy data. H. Park et al. in [41] described a B-spline curve fitting to a set of ordered points. In [42] A. Galvez et al. used a GA-PSO approach for curve fitting in manufacturing. According to [42], fitting data points to curves (usually referred to as curve reconstruction) is a major issue in computer-aided design/manufacturing (CAD/CAM). M. Barukčić et al. explained in [43] a method for estimating the I–V curves of a photovoltaic panel by analytical expression using an evolutionary strategy in order to estimate PV panel parameters. In the real world applications, analytical expressions are used in professional FEM software, such as Cedrat FLUX [44], for one of the possible descriptions of magnetic material characteristics. As a separate programme, it can be used for the transformation of the H-B table of values presenting a not-smooth measured magnetic material curve into the H-B table of values presenting a smooth magnetic material curve which can be used in any FEM software.

This paper consists of six Sections. In the second Section six tested measured curves are presented and five used analytical expressions are shown, together with their backgrounds. The third Section is the longest. We have attempted to solve our problem using standard optimization methods. Solutions and problems are described that appear with the use of such methods. After that, evolutionary methods are described used for solving the problem and the used parameters. The calculation results for all measured curves using all five analytical expressions and all six evolutionary methods are written in the Tables. The presented results were confirmed using cross-validation. Also, correction of the more appropriate evolutionary method using standard optimization together with results is shown in the third Section. The fourth Section contains a graphical presentation of the calculated analytical, together with the measured curves and the analytical curve's parameters are also written. In the fifth Section the calculated analytical magnetization curve is used in the finite element software and results presented. In the last, sixth Section, conclusions considering the analytical expressions and used evolutionary methods are given.

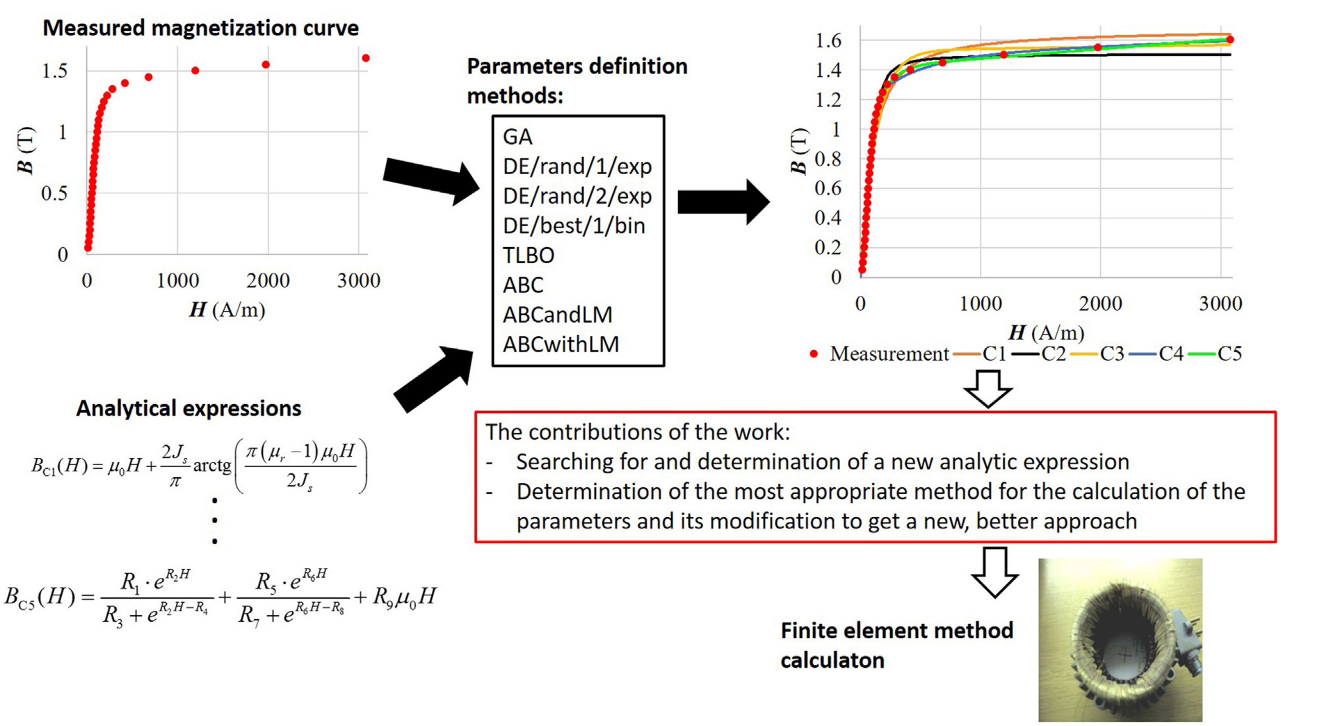

Fig. 1. Overview and contributions of the paper.

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