THE USE OF SABER SIMULATOR FOR THREE-PHASE NON-LINEAR MAGNETIC DEVICES SIMULATION: STEADY-STATE ANALYSIS

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***Abstract* – This paper is focused on the subject of transformer models based on association of linear and non-linear reluctances. This approach is particularly suitable for use with the Saber Simulator computational packages. Some models of electromagnetic devices existent in Saber library are discussed, and the facility to connect them makes the implementation of transformer models very simple. Previous work has showed the necessity to implement a new template of electromagnetic hysteresis using Saber's Mast modeling language, where the model is represented in terms of linear or non-linear algebraic or integral-differential equations. The improved template, which uses the Jiles-Atherton proposal with more adequate parameters, has proved to provide a better hysteresis representation. The parameters for the non-linear model has been obtained by using an optimization algorithm based on combination of the Hooke-Reeves direct search method and the Simulated Annealing methodology in conjunction with the original Jiles-Atherton ferromagnetic hysteresis model. A three-phase core-type transformer is simulated and results show that exist a good agreement between the simulated and measured values for steady state waveforms.**

KEYWORDS

Transformer model, Saber, optimization algorithm, hysteresis Jiles-Atherton model, three-phase transformer.

I. INTRODUCTION

An accurate and adequate model for transformers is essential for investigating phenomena such as: inrush currents, ferroressonance and others transients. During the last few decades several approaches have been used to model transformers. They can generally be classified as models using: electrical equations, electrical and magnetic equations, and reluctances.

Regarding modelling using reluctances, the transformer model is derived from circuit theory based on association of linear and non-linear reluctances [1-3]. The single-phase representation is fully described in [4]. In this reference, a physically based modelling approach is used to develop transformer models. The method allow to model transformers with any number of windings and core type. The magnetic fluxes associated with the transformer can be subdivided into some categories and associated to linear and non-linear reluctances. In this case, the identification of model parameters requires only classical tests and a few geometrical data.

Simulations of steady state magnetization currents require an accurate description of magnetic material characteristic B versus H. The magnetizing inrush currents that occur during the switch on three-phase transformers and single-phase transformer needs that the B versus H curve be well represented in the saturation region too. Therefore, a good transformer model needs to include the non-linear magnetic characteristics. Many approaches have been proposed for modelling non-linear transformer cores. The representation of hysteresis effect can be generally classified as analytical models and curve fitting method.

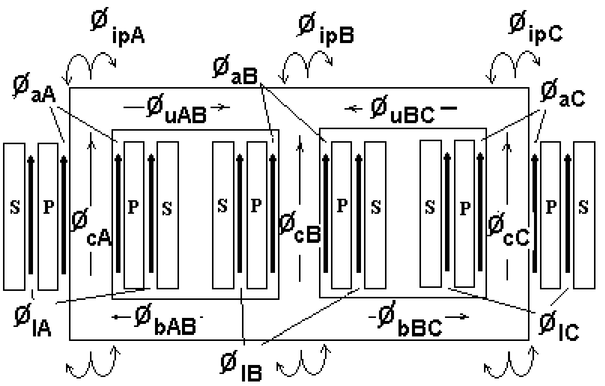
This work uses the Jiles-Atherton differential equations to model BxH hysteresis loop [5]. There is an equation for the differential irreversible susceptibility (dMirr/dH), an algebraic equation for reversible magnetization (Mrev) and an equation for the anhysteretic Magnetization (Man). The model exhibits all of the main features of hysteresis such as the initial magnetization curve, saturation of magnetization, coercivity, remanence and hysteresis loss.

The type of magnetic material used in power transformers is not available in the original Saber library. Thus, it must modeled using a new template using the Mast Language. This template provided a better hysteresis representation by supplying the parameters for the hysteresis physical model. These parameters are obtained of the BxH characteristic from laboratory measured.

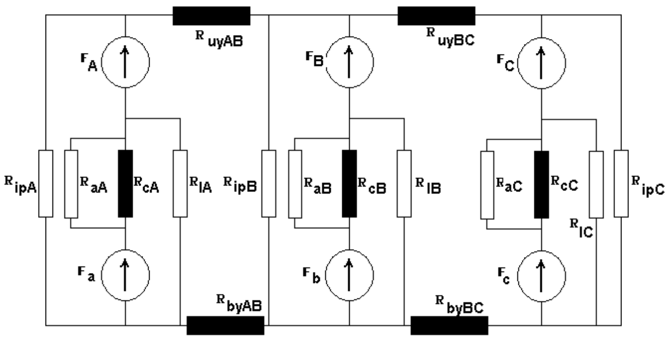
II. THE SABER SIMULATOR AND THE MAGNETIC MODEL

The software has some features that make it worthwhile for the simulation of electromagnetic devices. An electromagnetic device (such as an inductor or transformer) is special because it incorporates both types of circuits. This requires that the model include the magnetic and electrical interactions by combining two elements; a winding and a core, in a single device. However, electromagnetic behavior can occur in more elaborate configurations than an inductor, and there are different ways to construct a core. To satisfy these modeling requirements, the Saber model library has two separate templates named *wind* and *corenl* (*core* for linear device), and are referred to as building block templates. This approach allows a large flexibility in modeling the constituent parts of an electromagnetic device, such as reactors and transformers.

The model of a three-phase, core-type transformer, as shown in figure 1a, will be developed. The first step for modeling is the appropriate reduction of the original transformer structure into an equivalent magnetic circuit of lumped magnetic reluctances [6]. Figure 1b shows the equivalent magnetic circuit formed from magnetomotive forces and lumped reluctances in correspondence with the flux paths in the original transformer.



(a) – Transformer physical Model - Flux distribution.



(b) – Equivalent Magnetic Model

Figure 1 – Typical three-phase, core-type transformer.

Where:

R_{cA}, R_{cB} and R_{cC}	Non-linear reluctances for the left, central and right leg respectively;
R_{aA}, R_{aB} and R_{aC}	Linear reluctances of the air path flux between the core and internal winding;
R_{lA}, R_{lB} and R_{lC}	Leakage linear reluctances associated to leakage flux between internal and external windings;
R_{ipA}, R_{ipB} and R_{ipC}	Inter-phase linear reluctances from upper yoke to bottom yoke.
R_{uyAB} and R_{uyBC}	Non-linear reluctances associated with the flux in upper yoke;
R_{byAB} and R_{byBC}	Non-linear reluctances associated with the flux in bottom yoke.
F_a, F_b and F_c	Magnetomotive forces of the internal windings;
F_A, F_B and F_C	Magnetomotive forces of the external windings.

With reference to figure 1b, there are three types of elements in the equivalent magnetic circuit: magnetomotive forces, linear reluctances and non-linear reluctances. These elements will be associated to the models in the Saber simulator, named templates, which are supplied by the Saber library. The magnetomotive force is modeled using the template *wind.sin*, the linear reluctance is modeled using the template *core.sin* and the non-linear reluctance is modeled using a new template implemented through the Mast modeling language, which can represent a model in terms of any combination of linear and non-linear, algebraic or differential equations. The new template uses the same Jiles-Atherton hysteresis model, but with the parameters provided more adequately. For linear reluctances the necessary parameters are: area, magnetic path length and relative permeability of the air. For non-linear reluctances besides the parameters above, it is necessary other parameters for the hysteresis model. After to associate the equivalent magnetic model depicted in the figure 1b with the models belong to Saber, the complete electromagnetic transformer model is showed in Figure 2.

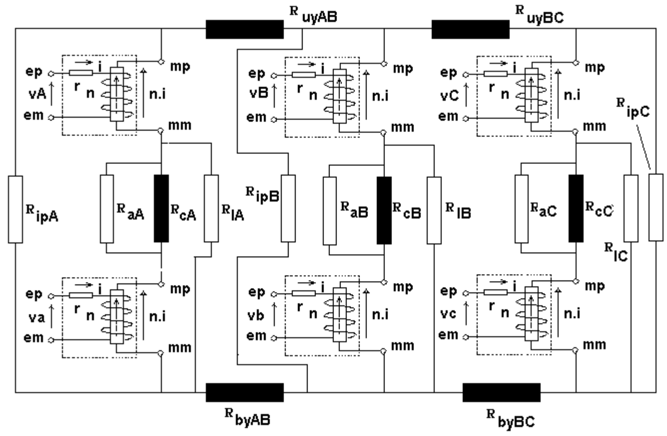


Figure 2 – Equivalent electromagnetic model for Saber.

By observing the figure 2 it is easy to see the flexibility and facility to connect templates. The electrical pins of the templates *wind.sin* in the equivalent electromagnetic model can be connected in various configurations. Reporting to three-phase transformers, there are several possible three-phase electrical connections. So, the primary and secondary windings can each be connected in star, star grounded or delta, and it is possible to change the phases sequence in the leg transformer. Additionally, zigzag and phase shifting transformers can be easily connected.

III – PERFORMANCE ANALYSIS OF THE MODEL USING SABER LIBRARY TEMPLATES

To validate the approach for modeling three-phase transformers and to use the ferromagnetic hysteresis model implemented, a three-phase, core-type transformer was tested in laboratory. Table I gives the geometrical and electrical characteristics for this transformer.

As the information about the magnetization and hysteresis curves of transformer cores is not readily available, the core hysteresis loop can be obtained indirectly by measuring current and voltage. However, for three-phase transformer, the three units (legs) are magnetically asymmetric. Therefore, to extract the core nonlinear characteristic it is necessary to use a different solution. In [7] is proposed a circuit for measuring the nonlinear magnetic characteristic of transformer limbs. The procedure consists in exciting two phases of the three-phase winding and let two legs have the same flux magnitude in opposite direction. There are at least two ways of measure the non-linear characteristic for each phase. To extract the phase (a) non-linear characteristic can excite the phases (a) and (b) or phases (a) and (c), anyway it measures the left winding current and the induced voltage on secondary left winding is integrated according to [8].

TABLE I
15 kVA, three-phase, core-type transformer.

Internal winding	127 V
External winding	127 V
Types of connections (primary or secondary)	Star or delta
Internal/external winding turns	66
External winding resistance	125 mΩ
Internal winding resistance	85 mΩ
External winding: External diameter Internal diameter	 $151x10^{-3}$ m $132x10^{-3}$ m
Internal winding: External diameter Internal diameter	 $106x10^{-3}$ m $87x10^{-3}$ m
Area: Leg Yoke	$49{,}996x10^{-4}$ m^2 $52{,}826x10^{-4}$ m^2
Stacking factor	0,95
Width: Leg Yoke	$80x10^{-3}$ m $66x10^{-3}$ m
Medium magnetic path length: Leg Yoke	0,26 m 0,163 m
Magnetic density flux: leg Yoke	1,55 T 1,44 T
Leakage impedance	3,47%
Frequency	60 Hz

The magnetic flux density *b(t)* is obtained by the integration of the induced voltage on secondary winding or external windings, *s* in figure 1a, using the equation:

$$b(t) = \frac{1}{N_{ind}.A}\int v_{ind}(t)dt \qquad (1)$$

Where $v_{ind}(t)$ is the induced voltage on the secondary winding or external winding with the N_{ind} turns, and A is the area of the core.

The magnetic field strength $h(t)$ is calculated by the equation:

$$h(t) = \frac{i_{en}(t).N_{en}}{l_m} \qquad (2)$$

Where $i_{en}(t)$ is the current on energized winding with N_{en} number of turns and l_m is the magnetic path length for the measured phase.

The digital oscilloscope is used to measure, digitize and storage the voltage and current, and after the data are transferred to the computer. All the further calculations are accomplished in the computer.

Figure 3 shows the magnetizing current and the magnetic flux density for the left leg, obtained for a 127 V voltage applied to the left and central leg in opposite direction.

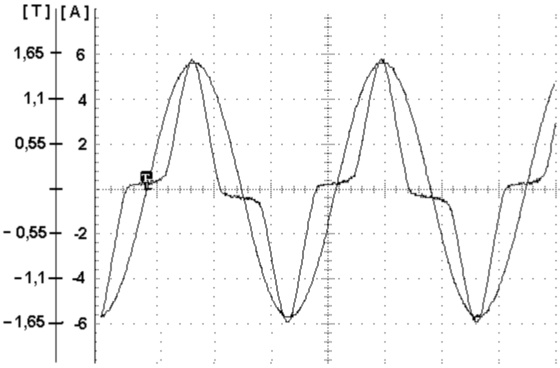


Figure 3 – Magnetizing current and magnetic flux density for the left leg.

Figure 4 shows the correspondent BH curve, as a result of the procedure formerly described.

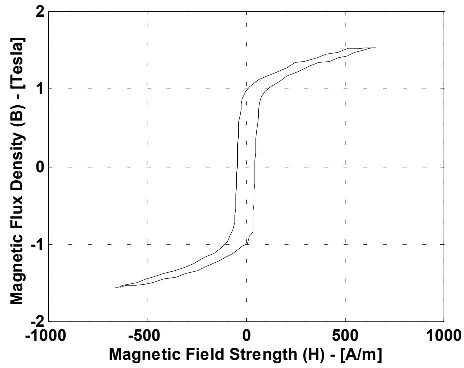


Figure 4 – Measured hysteresis loop.

Table II summarize the main parameters extracted from the hysteresis loop above.

Table II
Parameters extracted from figure 4

H_C (coercitive force)	46 [A/m]	B_R (residual flux density)	1.0 [T]
$H_{saturation}$	1500 [A/m]	$B_{saturation}$	1.8 [T]
H_{max}	5000 [A/m]	B_{max}	2.1 [T]
u_{hc} (relative permeability of the core at the coercitive coercitive level of H)	35000	u_i (relative permeability at the initial level of magnetization of the core)	4200

Figure 5 shows the results for the transformer magnetizing current, without residual flux, using the same conditions to obtain the magnetizing current and hysteresis curve in figures 3 and 4. It can be seen from the current waveforms, the measured and simulated currents are significantly differents.

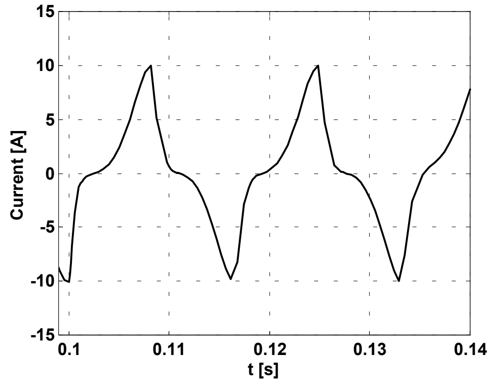


Figure 5 – Magnetizing current (simulation).

The BH loop given in figure 6 emphasizes the mentioned differences.

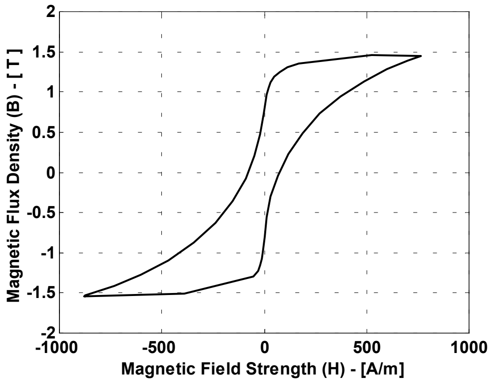


Figure 6 – Resultant BH curve, reproduced by the template *corenl.sin*.

The procedure implemented in *corenl.sin* template has some difficulties in extracting the correct set of model physical parameters from data of the measured hysteresis loop. So, a new procedure will be utilized to reproduce the non-linear curve.

IV – THE IMPROVED HYSTERESIS MODEL

The results showed the hysteresis cycle has significant influence on the transformer steady state magnetizing current wave shape. To overcome the drawback pointed out for the *corenl.sin* template, a new non-linear model was implemented using the Mast language [9]. This representation is based on the same Jiles-Atherton ferromagnetic hysteresis model. According to [5] it follows:

$$\frac{dMirr}{dH} = \delta_m \frac{Man - Mirr}{k\delta - \alpha(Man - Mirr)} \tag{3}$$

$$Man = Ms[\coth(\frac{H + \alpha M}{a}) - \frac{a}{H + \alpha M}] \tag{4}$$

$$Mrev = c(Man - Mirr) \tag{5}$$

$$M = Mrev + Mirr \tag{6}$$

Where:

- M Is the magnetization;
- Ms Is the saturation magnetization;
- α Is the factor that accounts for coupling between the domains;
- c Is the proportionality constant that accounts for reversible wall motion;
- k Coefficient accounting for the pinning energy;
- a Is the parameter modifying the curvature of the anhysteretic function;
- δ Is a directional parameter, +1 for increasing field (dH/dt >0), -1 for decreasing field (dH/dt<0);
- δ_m =0 if dH/dt < 0 and Man(H)-M(H)≥0 and if dH/dt > 0 and Man(H) – M(H)≤0, and
- δ_m =1 otherwise.

V – MODEL PARAMETERS ADJUSTMENT

To avoid the above magnetic/electric discrepancies, new model parameters, based on experimental hysteresis loop must be used. The approach selected for this work combines the direct search method of Hooke and Jeeves with the simulated annealing technique [10]. The optimization of the model parameters was then achieved by minimizing the least square error (LSE) by comparing the simulated results with the measured data.

The optimization procedure steps are:

- An initial parameter set is used to provide the first attempt to obtain the BH or MH curve;
- By knowing the measured magnetic field strength values (H), the 4th Range-Kutta method is used to solve equation (3). The Magnetization level (M) is also calculated through equations (5) and (6). The hysteresis cycle has been then obtained;
- The magnetization (M) levels are then compared to the corresponding measured values for the same (H);
- The quadratic error is used to compare calculated and measured values;
- Following, the hysteresis parameters are modified according to an established rate (Hooke-Jeeves method). A new hysteresis loop is then obtained and the quadratic error is recalculated and compared to the last error. If the actual error is less than the last one, the parameters are accepted. On the other hand, greater errors values may be permitted on the basis of a probability criterion (Simulated Annealing).
- The criterion to end the algorithm uses either a tolerable quadratic error or a small change in the quadratic error for recent iterations.

Figure 6 shows the square error evolution and control parameter versus the accepted parameter values during the optimization procedure execution. The final parameter values are: *Ms*=1.475e+6, *a*=166.0, *k*=100.0, α=33.0e-5 and *c*=0.556.

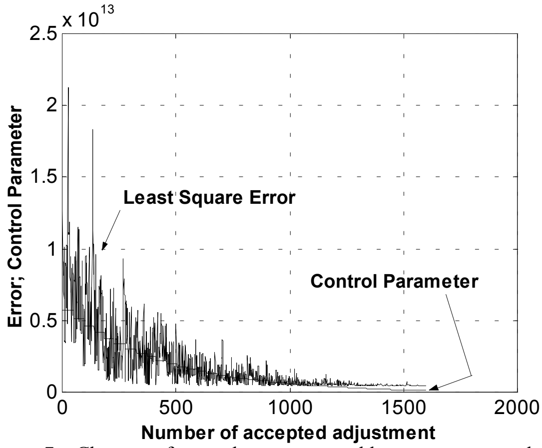


Figure 7 – Changes of control parameter and least square error during procedure of optimization.

Figure 8 compares the measured and computational hysteresis loop. The results show they are in good agreement.

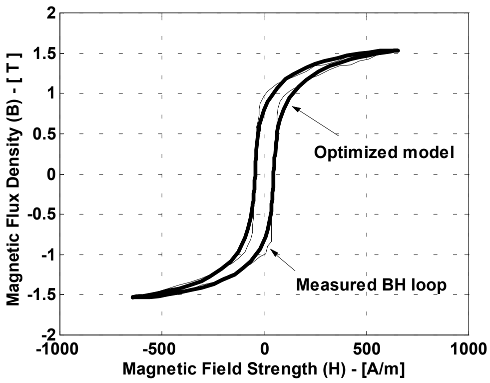
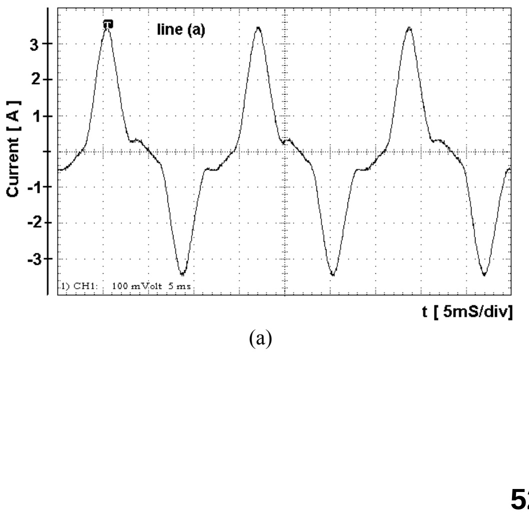


Figure 8 - Comparison between measured and optimized hysteresis loop.

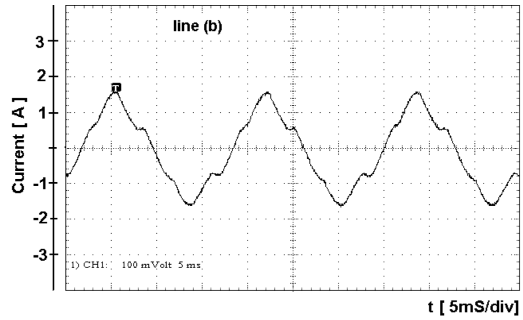
VI – THE IMPROVED HYSTERESIS MODEL PERFORMANCE

To validate the implemented template in conjunction with transformer model, a simulation using the specified three-phase transformer is discussed in the sequence.

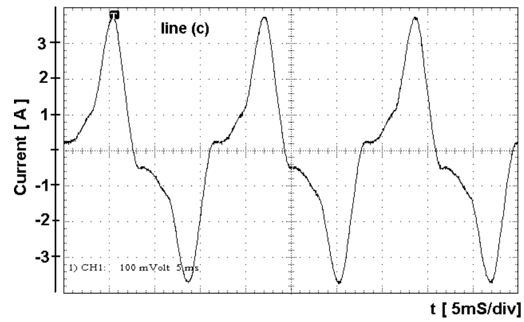
Figure 9 shows the transformer no-load line currents. The currents were measured in steady-state conditions at rated voltage. The primary windings were connected in star grounded and the secondary windings were open.



(a)



(b)



(c)

Figure 9 – Measured magnetizing current – lines (a), (b) and (c).

Figure10 presents the computational results for the same transformer steady-state magnetizing current. These were achieved by using the new hysteresis model for non-linear core, after adjusting the parameters in accordance with the previous procedure.

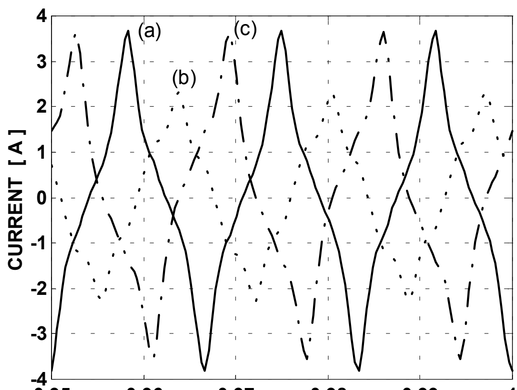


Figure 10 - Simulated magnetizing current for lines (a), (b) and (c).

Figure 11 shows the computational BH curve. By comparing the computational e experimental results it is possible to conclude they are in quite good agreement. The waveforms, the peak and RMS values, and other characteristics for both the no-load current and hysteresis loop emphasizes the proposed approach are suitable to investigate the non-linear behavior of devices such as transformers.

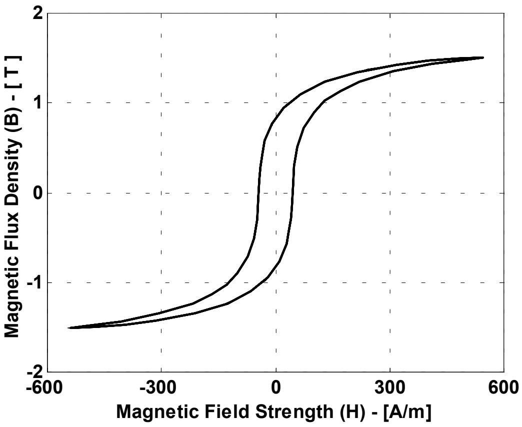


Figure 11 – Hysteresis loop valid for phase (a).

VII – CONCLUSIONS

Transformer modeling using reluctances as provides by Saber simulator has showed to be a very flexible strategy to represent non-linear equipment behavior. This strategy can be easily extended to study different types of magnetic cores and windings. Some difficulties have been found concerning the accuracy when the original non-linear core model was used. According to the investigations, the errors were not caused by the Jiles-Atherton method itself but the way the magnetic parameters provided by real measurements are converted into model coefficients for the original template. The parameters required by the template are based on intrinsic characteristics related to magnetic material and, the way it has been given, this methodology has shown to be inappropriate to reproduce the non-linear BxH curve. Due to the differences found during the computational studies, a new template was implemented based on the same Jiles-Atherton model. The main changes consist in using an optimization algorithm searching for more accurate parameters and their impact on the representation. The proposed approach to adjust the parameters is based on the combination of the Hooke-Jeeves direct searching and simulated annealing probabilistic method. An example of application using a three-phase transformer has been given to illustrate the original deficiencies and the improvements achieved with the new strategy.

The results are quite encouraging in the sense they result in expressive improvements to the non-linearity representation.

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