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A generalized Jiles-Atherton hysteresis model

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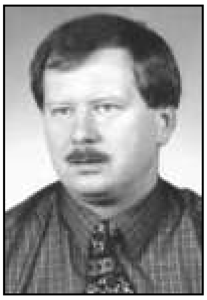

Abstract

The paper presents a generalization of the Jiles-Atherton (J-A) model. The main goal of this work is to take into account all phenomena, such as conducting media, which result in a change in the shape of the magnetic hysteresis with frequency. For this purpose a class of models of Chua is recalled. The authors pointed the model, named J-A-C able to reproduce any phenomena. The authors compared the model J-A-C with other extensions of the J-A model, obtaining the results more consistent with measurements than these models.

Keywords: Jiles Atherton model, magnetic hysteresis, eddy current losses.

Uogólniony model magnetycznej pętli histerezy Jilesa - Athertona

Streszczenie

W artykule przedstawiono uogólniony model pętli histerezy magnetycznej Jilesa-Athertona (J-A). Celem pracy było przygotowanie modelu fenomenologicznego obejmującego wszystkie zjawiska zachodzące w materiale, takie jak np. prądy wirowe, które prowadzą do zmiany kształtu pętli histerezy wraz ze zmianą częstotliwości. Aby osiągnąć ten cel odwołano się do koncepcji modelu zaproponowanego przez L.O. Chua. W istocie jest to cała klasa modeli ze zmienną szerokością pętli histerezy. Modele te są czysto fenomenologiczne i mogą być wykorzystane w celu opisania wszystkich zjawisk, bez konieczności odnoszenia się do ich fizycznych podstaw. Autorzy opracowali model nazwany J-A-C, który jest bardzo podobny do pewnego modelu z klasy modeli Chuy, dziedzicząc dzięki temu wszystkie jego właściwości. W szczególności model zawiera wszystkie parametry modelu J-A, ponadto może obejmować parametry opisujące zmiany kształtu histerezy. Stwierdzono, że parametry przygotowane dla modelu J-A, a wykorzystane w modelu J-A-C pozwalają na uzyskanie wyników równie dokładnych jak w przypadku modelu J-A. Autorzy artykułu porównali wyniki osiągnięte przy pomocy modelu J-A-C z innymi rozszerzeniami modelu J-A, które uwzględniają prądy wirowe w materiale magnetycznym. Model J-A-C lepiej oddaje wyniki pomiarów niż te modele. Niewątpliwą zaletą modelu J-A-C jest fakt, że rozszerza podstawowy model J-A pozwalając na odzwierciedlenie całej klasy zjawisk związanych z dyssypacją energii w materiale magnetycznym. Obecnie głównym przedmiotem badań jest uniwersalna metoda, która pozwoliłaby na wyznaczanie parametrów modelu niewystępujących w modelu J-A.

Słowa kluczowe: Model Jilesa Athertona, magnetyczna pętla histerezy, prądy wirowe.

1. Introduction

During the design of electrical components, such as transformers or inductors it is crucial to accurately estimate the losses that occur during the magnetization process inside the material. It was proved in the past that phenomenon that takes place during the magnetization process is highly nonlinear and very difficult to be predicted [1, 2]. In the past, some authors, in order to reproduce the behavior of a magnetic material in different frequency ranges, presented modifications of the known models of the hysteresis loop [3, 4, 5, 6] . As there is no model capable of reproducing the dynamic behavior of the magnetic material in a commercial software such as PSpice® [7], in many cases designers assume a linear increase in the power dissipation factor, instead of taking into account the real behavior of the magnetic material during the magnetization process.

The literature shows many modifications of the widely used Jiles-Atherton model. However, each of them describes a particular phenomenon which is not taken into account by the standard model [8, 9]. The most common phenomenon modeled by the authors are eddy current losses [10, 11, 12, 13]. The literature shows that the most common solutions are based on the modification of the existing models by extending them by equations describing a particular phenomenon [10, 11]. If we want to take into account one particular phenomenon it is still acceptable. In the case of a more complex behavior it might be very inconvenient to use many of such modifications at a time.

The authors of this study propose a model of magnetization based on the commonly known Jiles-Atherton model (J-A), which allows the user to simulate the hysteresis loop not only during static but also dynamic conditions. It is realized by introducing an additional function dependent on the material. The authors of this study propose a phenomenological model that can be used to reproduce many phenomena without the knowledge of their physical nature. In the case of static simulation, the proposed model does not require recalculation of the parameters of the J-A model, if these already exist. Thus, the J-A-C model can be used with the J-A model's parameters to obtain as accurate results as a the J-A model gives. To take advantage of the dynamic properties of the J-A-C model, it is necessary to develop a function which is equivalent to the *signum* function in the J-A model for static simulation. The expanding of the J-A model in order to perform dynamic simulation does not require changes in the static parameters of the model. This means, that the existing database of the J-A parameters can be easily expanded without the need for re-processing it for the new model.

2. Short description of the Jiles Atherton model

The fundamental equation of the Jiles Atherton model is the equation describing the initial magnetization curve (1)

$$M_{an} = M_s(\coth\left(\frac{H_e}{a}\right) - \frac{a}{H_e}), \tag{1}$$

where: M_s is the saturation magnetization of the material; a is a parameter that describes the shape of the anhysteretic curve; $H_e = H + \alpha M$ and describes efficient field; α is the average parameter describing the coupling between domains.

Equation (2) describes the dependence between the induction of the magnetic field B and the magnetization M

$$B=\mu_0(H+M), \tag{2}$$

where: μ_0 is theelectrical permittivity of vacuum.

Equation (1) describes the state of thermodynamic equilibrium in the system. It shows only the statistical distribution of domains that correspond to the optimal energy of the system, without taking into account the structure of the material and its internal imperfections.

In a real material, the pinning of domain wall phenomenon occurs resulting from the obstruction of their movement caused, among others, by grain boundaries, grain inhomogeneities, dislocations, non-magnetic inclusions and regions of inhomogeneous strain [14]. This effect persists until the magnetic potential is not large enough to create another point of pinned walls. Movement of the walls can have reversible or irreversible nature. The irreversible movement is described by equation (3):

$$\frac{dM_{irr}}{dH}=\frac{M_{an}-M_{irr}}{\delta k-\alpha(M_{an}-M_{irr})}, \tag{3}$$

where: M_{irr} – irreversible part of magnetization; k – factor dependent on the energy needed to move a domain wall; $\delta=\operatorname{sign}\left(\frac{dH}{dt}\right)$ – positive sign means increase in the magnetic field and negative means decrease in the field.

In the case of domain wall deflection, the reversible magnetization $\mathrm{M_{rev}}$ is present, which is given by equation (4)

$$M_{rev}=c(M_{an}\text{-}M_{irr}), \tag{4}$$

where c is the parameter that should be chosen experimentally. Overall magnetization M is given by equation (5):

$$M=M_{rev}+M_{irr}, \tag{5}$$

$$\frac{dM}{dH}=\frac{1}{(1+c)}\frac{M_{an}-M}{\delta k-\propto(M_{an}-M)}+\frac{c}{(1+c)}\frac{dM_{an}}{dH}. \tag{6}$$

In order to solve the above equation in Simulink or in similar software, there is a need to introduce variables in the time domain. Therefore it is needed to multiply both sides of equation (6) by $\frac{dH}{dt}$. As a result we obtain equation (7):

$$\frac{dM}{dt}=\frac{1}{(1+c)}\frac{M_{an}-M}{\delta k-\propto(M_{an}-M)}\frac{dH}{dt}+\frac{c}{(1+c)}\frac{dM_{an}}{dt}. \tag{7}$$

3. The Jiles-Atherton-Chua model

In the early 70s L.O. Chua [6] introduced a whole class of functions that could be used to calculate the magnetization within the material exposed to the external magnetic field, thereby obtaining the dependence of the hysteresis loop by the frequency of the excitation signal.

The equation proposed by Chua has the general form:

$$\frac{dy}{dt}=w\left(\frac{dx}{dt}\right)\cdot h(y)\cdot g(x-f(y)). \tag{9}$$

Function (9) is presented as a derivative of x:

$$\frac{dy}{dx}=\frac{w(\dot{x})}{\dot{x}}\cdot h(y)\cdot g(x-f(y)), \tag{10}$$

where y represents magnetization M and x applied field H.

In the Chua model only $w(\dot{x})$ function affects the width of the hysteresis loop under dynamic conditions. In particular, if someone choose $w(\dot{x})=|\dot{x}|$, then the independence of frequency hysteresis curve will be obtained. The authors of this publication have defined Jiles Atherton model by a function that is similar to the class of functions proposed by Chua. The proposed model allows simulating the dynamic hysteresis loop still preserving properties of the J-A model and Chua model. In order to present the J-A models as a subset of the Chua class of models, it is necessary to perform normalization process [15] introducing new unitless parameters.

The anhysteretic function Man using unitless variables will be expressed as:

$$\frac{M_{an}}{M_s}=\mathrm{L}\left(\frac{\frac{H}{\alpha M_S}+\frac{M}{M_S}}{\frac{A}{\alpha M_S}}\right), \tag{11}$$

where $L(x)=\coth(x)-\frac{1}{x}$.

To equation (6) we will introduce unitless variables $\frac{M}{M_s},\frac{H}{\propto M_s}$. Therefore $\frac{dM}{dH}$ is expressed as:

$$\frac{dM}{dH}=\frac{M_s d\frac{M}{M_S}}{\propto M_s d\frac{H}{\propto M_S}}=\frac{d\frac{M}{M_S}}{\propto d\frac{H}{\propto M_S}}=\frac{dz}{dx}\frac{1}{\propto}. \tag{12}$$

To Eq. (12) we will introduce the previously calculated $\frac{M_{an}}{M_s}$, therefore:

$$\frac{dz}{dx}\frac{1}{\propto}=\frac{1}{(1+c)}\frac{\frac{M_{an}}{M_S}-\frac{M}{M_S}}{\delta\frac{k}{M_S}-\propto\left(\frac{M_{an}}{M_S}-\frac{M}{M_S}\right)}+\frac{c}{(1+c)}\frac{d\frac{M_{an}}{M_S}}{d\frac{H}{\propto M_S}}\frac{1}{\propto}. \tag{13}$$

Using unitless variables[15]: $y=\frac{M_{an}}{M_s}$, $x=\frac{H}{H_0}$, $z=\frac{M}{M_s}$, $a=\frac{A}{H_0}$, $H_0=\alpha M_s$ and $\kappa=\frac{K}{H_0}$, we can present the Jiles-Atheron model (6) by the following equation:

$$\frac{dz}{dx}=\frac{\delta}{(1+c)}\frac{y-z}{[\kappa-\delta(y-z)]}+\frac{c}{(1+c)}\frac{dy}{dx}, \tag{14}$$

where $y=\mathrm{L}\left(\frac{x+z}{a}\right)$ and $L(x)=\coth(x)-\frac{1}{x}$.

When the normalized J-A model is obtained, it is necessary to introduce a series of transformations in order to be able to classify this model as a part of Chua`s class of functions.

Let us introduce a new variable v:

$$v=z-\frac{c\cdot y}{1+c}. \tag{15}$$

Next from equation (15) we calculate $\frac{dz}{dx}$:

$$\frac{dv}{dx}+\frac{c}{1+c}\frac{dy}{dx}=\frac{dz}{dx}. \tag{16}$$

The obtained Eq. (16) should be compared with that previously obtained (14)

$$\frac{dv}{dx}+\frac{c}{1+c}\frac{dy}{dx}=\frac{dz}{dx}=\frac{\delta}{(1+c)}\frac{y-z}{[\kappa-\delta(y-z)]}+\frac{c}{(1+c)}\frac{dy}{dx}. \tag{17}$$

Eq. (17) can be reduced by $\frac{c}{(1+c)}\frac{dy}{dx}$ and $\frac{dv}{dx}$ can further be calculated:

$$\frac{dv}{dx}=\frac{\delta}{(1+c)}\frac{y-z}{[\kappa-\delta(y-z)]}. \tag{18}$$

In order to be able to solve Eq. (18), we need to relate the right side of Eq. (18) from variable v rather than z.

Equation (15) yields that:

$$z=v+\frac{c\cdot y}{1+c}. \tag{19}$$

Now the expression $y-z$ has to be calculated by substituting variable z from the previously calculated Eq. (19)

$$y - z = y - \left(v + \frac{c\cdot y}{1+c}\right) = \frac{y}{1+c} - v. \tag{20}$$

Now if we name expression $\frac{y}{1+c}$ as y_c, the solution of expression $y - z$ will be as follows:

$$y - z = y_c - v. \tag{21}$$

Finally obtaining equation (18) with variable v

$$\frac{dv}{dx} = \delta \frac{1}{(1+c)} \frac{y_c - v}{[\kappa - \delta(y_c - v)]}. \tag{22}$$

Because on the main magnetic hysteresis loop the equality holds $\operatorname{sign}\delta = \operatorname{sign}(y_c - v)$, equation (22) can be approximated in the following way:

$$\frac{dy}{dx} = \frac{w(\dot{x})}{\dot{x}} \cdot h(y) \cdot g_\kappa(f(x,y) - y), \tag{23}$$

where $w(\dot{x}) = |\dot{x}|$, $h(y) = 1$ and

$$g_\kappa(x) = \begin{cases} \frac{x}{\kappa + x} & \text{when} \quad x < 0, \\ \frac{x}{\kappa - x} & \text{when} \quad x > 0. \end{cases} \tag{24}$$

In fact equation (23) is equivalent to (6) and can be implemented in Simulink, moreover Chua proved that the function described by equation (23) can be modeled by standard electrical components, therefore, it is apparent that this function can be solved in an electrical circuits simulator like PSpice®. In order to implement the final model in Simulink environment, the authors divided it into two parts: the core model and Chua part. The core model is a part of the model which is responsible for solving the variable v, while the second one is responsible for the solution of anhysteretic function y_c. In the implementation, the input of the model is a magnetic field strength expressed in A/m and then converted to a dimensionless variable x. To obtain the static simulation, function $w(\dot{x})/\dot{x}$ is expressed by just a *signum* function - $\operatorname{sign}\left(\frac{dx}{dt}\right)$. To obtain frequency dependence, a specific function was implemented.

4. Simulation results

In order to perform simulation, the authors used Matlab Simulink environment. The simulations were performed using only one set of parameters a, α, κ, M_s, C. As a database the authors took the measurements and simulations data from the publications of Szczygłowski [11] and D.C. Jiles [10]. All measurement data presented in Figs.1 - 4 and Figs. 6 - 9 were directly taken from the graphs presented in the publications of Szczygłowski and D.C. Jiles. In Figs. 1 - 10 the authors showed that the appropriate selection of the function $w(\dot{x})/\dot{x}$ allowed the accurate representation of the phenomena occurring in the material during the magnetization process. The authors assumed that $w(\dot{x})/\dot{x}$ was an odd function and consisted of several steps. The height and location of steps were chosen so as to best match the results of the measurements – see Figs. 5 and 10. It should be emphasized that there is no need to develop any physical phenomena that takes place inside the material to use the proposed model. The presented model is based on the existing Jiles-Atherton and Chua models, which allows us to determine the magnetic hysteresis loops under both static and dynamic conditions. The main advantage while using the proposed model for static simulation is that there is no need to introduce additional parameters which interfere with the existing ones. Consequently, while implementing the proposed model, final users can use all of their sets of the existing J-A model parameters and obtain similar results. In order to take advantage of the possibility of simulating the dynamic hysteresis loops, a function describing the material properties should be introduced e.g. by extending a *signum* function. Introduction of this function does not imply the need of change of any parameters that describe static properties of the material. This means that the existing database needs to be updated only with a set of functions $w(\dot{x})/\dot{x}$ without the need to re-process other parameters: $M_s, a, \propto, C, K$.

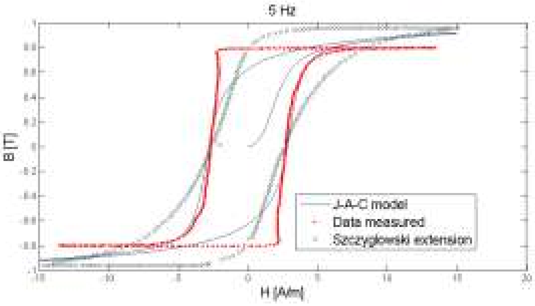

Fig. 1. Comparison of B-H curves for the J-A-C model, Szczyglowski extension and measured data for 5 Hz

Rys. 1. Porównanie krzywych B-H dla modelu J-A-C, rozwinięcie Szczygłowskiego oraz zmierzonych danych dla częstotliwości 5 Hz

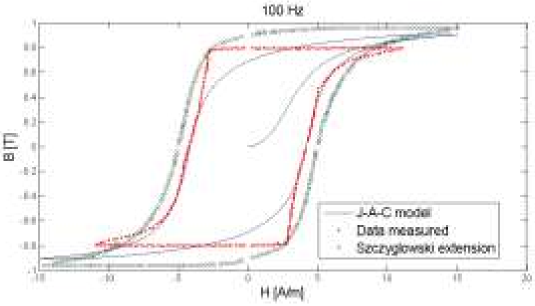

Fig. 2. Comparison of B-H curves for the J-A-C model, Szczyglowski extension and measured data for 100 Hz.

Rys. 2. Porównanie krzywych B-H dla modelu J-A-C, rozwinięcie Szczygłowskiego oraz zmierzonych danych dla częstotliwości 100 Hz

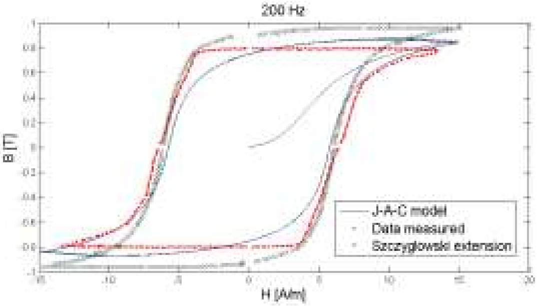

Fig. 3. Comparison of B-H curves for the J-A-C model, Szczyglowski extension and measured data for 200 Hz

Rys. 3. Porównanie krzywych B-H dla modelu J-A-C, rozwinięcie Szczygłowskiego oraz zmierzonych danych dla częstotliwości 200 Hz

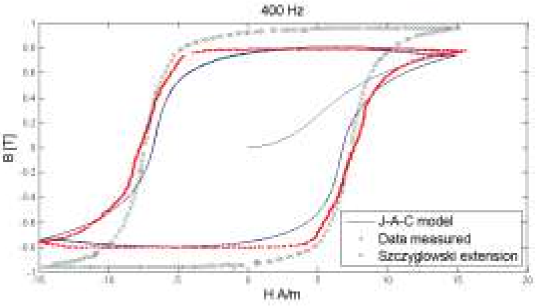

Fig. 4. Comparison of B-H curves for the J-A-C model, Szczyglowski extension and measured data for 400 Hz

Rys. 4. Porównanie krzywych B-H dla modelu J-A-C, rozwinięcie Szczygłowskiego oraz zmierzonych danych dla częstotliwości 400 Hz

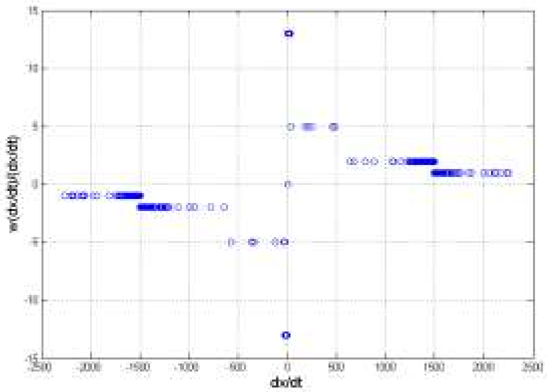

Fig. 5. $\frac{w(\dot{x})}{\dot{x}}$ function used to reflect eddy currents in a material during the magnetization proccess

Rys. 5. Funkcja $\frac{w(\dot{x})}{\dot{x}}$ wykorzystana do odzwierciedlenia występujących prądów wirowych w materiale podczas procesu magnetyzacji

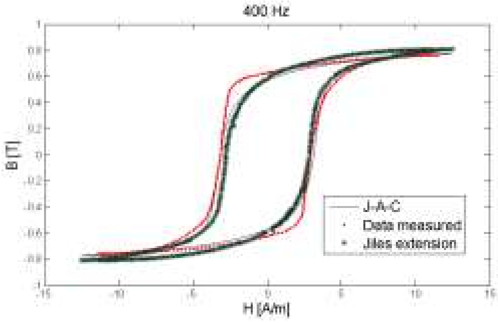

Fig. 6. Comparison of B-H curves for the J-A-C model, Jiles extension and measured data for 400 Hz

Rys. 6. Porównanie krzywych B-H dla modelu J-A-C, rozwinięcie Jiles'a oraz zmierzonych danych dla częstotliwości 400 Hz

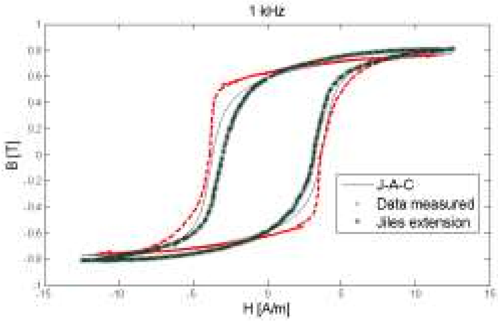

Fig. 7. Comparison of B-H curves for the J-A-C model, Jiles extension and measured data for 1000 Hz

Rys. 7. Porównanie krzywych B-H dla modelu J-A-C, rozwinięcie Jiles'a oraz zmierzonych danych dla częstotliwości 1000 Hz

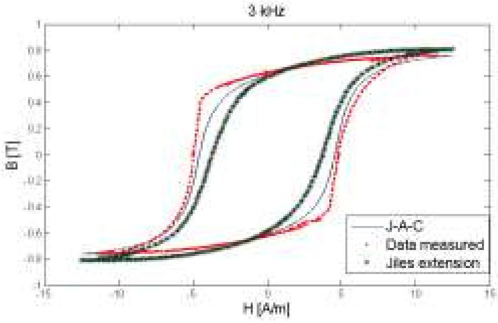

Fig. 8. Comparison of B-H curves for the J-A-C model, Jiles extension and measured data for 3000 Hz

Rys. 8. Porównanie krzywych B-H dla modelu J-A-C, rozwinięcie Jiles'a oraz zmierzonych danych dla częstotliwości 3000 Hz

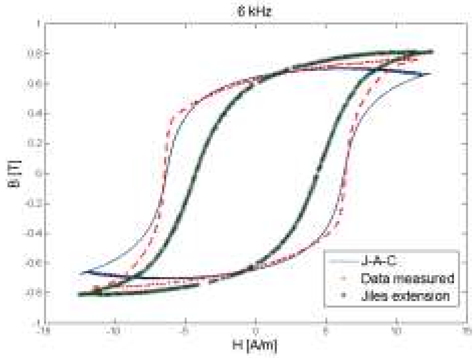

Fig. 9. Comparison of B-H curves for the J-A-C model, Jiles extension and measured data for 6000 Hz

Rys. 9. Porównanie krzywych B-H dla modelu J-A-C, rozwinięcie Jiles'a oraz zmierzonych danych dla częstotliwości 6000 Hz

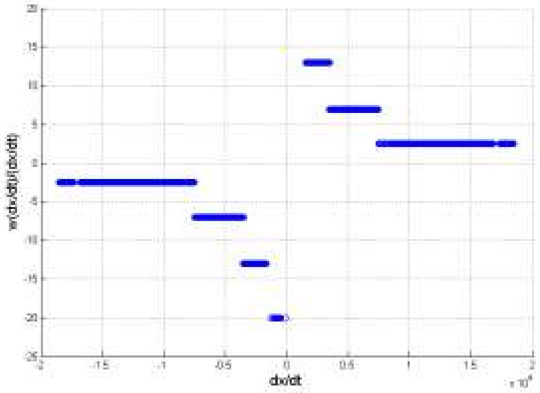

Fig. 10. $\frac{w(\dot{x})}{\dot{x}}$ function used to reflect eddy currents in a material during the magnetization proccess

Rys. 10. Funkcja $\frac{w(\dot{x})}{\dot{x}}$ wykorzystana do odzwierciedlenia występujących prądów wirowych w materiale podczas procesu magnetyzacji

5. Conclusions

In this paper the authors have presented a mathematical model which can be used to simulate frequency dependent hysteresis loops of different materials.

The proposed model is an efficient tool for engineers to simulate the dynamic hysteresis loop. The authors realize how important source of knowledge the database of J-A model parameters created over several years is. Their intention is not to create a competitive model, but only to propose the extension of the existing and well documented one.

At the moment extensive tests of the J-A-C model are being performed in simulations of real behavior of chokes in DC/DC LED driver designs in Magneti Marelli Poland (R&D rear lamps division).

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otrzymano / received: 03.03.2014
przyjęto do druku / accepted: 02.05.2014 *artykuł recenzowany / revised paper*

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