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# INTEGRATION OF MAGNETIC AMPLIFIER SWITCH MODEL INTO COMPUTER AIDED DESIGN FOR POWER CONVERTERS

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***Summary.*** *The designing of electrical power converters based on Magnetic Amplifier (MagAmp) switches is not fully automated. MagAmp is a magnetic component with nonlinear properties. Computer aided design (CAD) programmes are built to simulate electric circuits without electromagnetic field with distributed components. There is a problem of integration of a model of a component with magnetic hysteresis into the set of CAD models. In addition, estimation of the optimal parameters of such a component is rather complicated. The article proposes a new model of MagAmp switch which is based on a function that can be generated using digital technology. The digital generator of sinusoidal signals, consisting of discrete digital components for modeling the MagAmp switch, is investigated. Integration of the model into CAD programme and simulation of the electric circuit, which includes MagAmp switch, are obtained. Partial automation will reduce complexity, duration and cost of the design procedure, and will enhance the development of power converters.*

***Key words****: mathematical model, magnetic amplifier switch, CAD programme, magnetic hysteresis, computer simulation.*

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**Statement of the problem**. In electric circuits the semiconductor switching elements are commonly used for commutation. However, they cannot provide high quality of output characteristics in multi-output power converters and high output current applications. Here the magnetic amplifiers (MagAmps) are used as switching elements [1].

Computer simulation is an important stage in power converter design. Computer aided design programmes like Powersim, Multisim, MATLAB Simulink, PSpice, LabView, etc. facilitate engineer's work greatly. They can predict the simulated system's operation at certain conditions, reduce the calculations time and complexity, thus they reduce the cost of the design procedure.

When dealing with linear electrical circuits CAD simulation, their operation is modeled through currents and voltages relationships. However, CAD programmes are built to simulate electric circuits without electromagnetic field with distributed components. Since MagAmp is a magnetic component with nonlinear properties, the designing of power converters based on MagAmp switches is not fully automated. MagAmp switch is a coil wound on a core with a relatively square B-H characteristic [2, 3]. Its operation is described in detail in [2, 3]. The complexity of MagAmp switch modeling consists in characteristics of its dynamic operation and nonlinearity of core remagnetization processes.

Today CAD programmes (e. g. ELCUT, ANSYS Maxwell, MAFIA) work with magnetic field computation [4–8]. However, the mathematical models they use are rather complex to be integrated into a CAD programme for electric circuits' simulation. They provide the output in a form of data sets of values of magnetic potentials distributed within the investigated volume [4, 9]. For instance, the mathematical model used in ELCUT implies calculations of magnetic potential in each particular point of the magnetic field. Poisson

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equation, which concerns the vector magnetic potential $\overline{A} = A_z$ within a linear magnetic field, is presented in formula [4]:

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu'}\frac{\partial A_z}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu'}\frac{\partial A_z}{\partial y}\right)=-\mu_0 J_z \qquad (1)$$

where $\mu'$ is the magnetic permeability of the core,
$\mu_0$ – magnetic permeability of the vacuum,
$J_z$ – vector of the current density.

The complexity of the algorithm for solving second-order Poisson equation (1) equals to $N^2(4\log_2 N+1)$, as derived from [10], where $N$ is the order of the arithmetic operations.

Besides the complexity [4, 11, 12], integration of such a model into CAD software for electric circuits design would require essential preprocessing of its output data to be informative for electrical engineer.

Since magnetic hysteresis has complex physical nature, several empirical models have been developed. Jiles-Atherton [13] and John Chan [14] models of magnetic hysteresis have been integrated into pSpice and LTspice CAD programmes for electric circuits design respectfully. Yet, they do not allow modeling MagAmp operation in switching mode.

Thus, there remains a problem of integration of a model of a component with magnetic hysteresis into a set of CAD models.

**Analysis of the known research results**. The magnetization curves (hysteresis loops) of magnetic materials vary as a function of frequency and shape of an applied magnetic field signal [15]. Preisach [16–18], Jilles-Atherton [14] and John Chan [15, 19] mathematical models of magnetic hysteresis are empirical and require high-precision experimental data for their realization. These models are static, which means they do not take into account dependence of core remagnetization losses on switching frequency. They may be incorporated into a CAD programme. However, due to technical and numerical complexity of parameters extraction [20, 21], Preisach and Jilles-Atherton models of magnetic hysteresis are not convenient for an engineer, while John Chan hysteresis model gives a significant error in switch mode operation [2].

Cobalt-based soft magnetic saturable core was modeled using Jiles-Atherton and John Chan magnetic hysteresis models in PSpice and LTspice IV respectfully. Models' limitations proved to be significant, and they cannot be used to model the remagnetization processes of MagAmp switch accurately [2].

As the shape of magnetic hysteresis loop resembles a sigmoid function, numerous mathematical models are based upon it [22]. Alike Jilles-Atherton and John Chan models, other sigmoid-based models feature numerical complexity of their parameters extraction. As a rule, after the values of the coefficients (parameters) of such a model are calculated, they need to be readjusted to fit the particular hysteresis curve. This would make usage of their integration into a CAD programme extremely inconvenient for engineering applications.

Alternatively, the MagAmp equivalent circuit approach is used [23, 24]. It allows avoiding the integration of complex magnetic hysteresis models into CAD programmes. The MagAmp switch is modeled with discrete electric components. Their nominal values have to be readjusted each time any of the power converter's parameters changes, and that's a cumbersome time-consuming task.

**The objective of the work** is development of a new mathematical model which would allow MagAmp switch computer simulation in a CAD programme for electric circuits design without necessary further readjustment of the model's parameters.

Considering the principles of operation of DC power converter based on MagAmp [3], there are the following requirements for MagAmp mathematical model for its computer simulation:

- it should work in power-width modulation mode (PWM);
- in a frequency domain it should have the same transfer function as the real MagAmp, that is a non-inertial element with a delay for a half-period of the switching frequency;
- all real power relations between all functional elements should be maintained even when working under the influence of all distortion factors;
- operation modes of all circuit components shouldn’t be affected in any way.

It is important that the model parameters are specified in a datasheet.

**Statement of the task.** To develop a new model of MagAmp switch, which is based on a function that can be generated using digital technology. To investigate suitability of the digital generator of sine waveform, consisting of discrete digital components, for MagAmp switch modeling.

**The suggested mathematical model.** Every mathematical model is characterized by its structure and parameters. For instance, the structure of Jiles-Atherton and John Chan magnetic hysteresis models is based on a sigmoid function, which is a second-order system. Its coefficients are set as variables that depend on parameters characterizing the physical nature of remagnetization processes.

To solve a problem of integration of a model of a component with magnetic hysteresis into the CAD programme for electric circuits’ simulation, the article proposes a new model of MagAmp switch which is based on a function that can be generated using digital technology. Here, as a model structure, it is suggested to use one of the most widespread second-order systems. Such system is derived with difference second-order equation that in time domain is [25]:

$$b_2 g_{n-2} + b_1 g_{n-1} + g_n = y_n, \qquad (2)$$

where $n \triangleq nT_d$, $T_d$ – period of discretization, $n$=0,1,2,3,…. , $g_{n-1}$, $g_{n-2}$ – beginning conditions.

The resolution of equation (2) is represented by schema [25]:

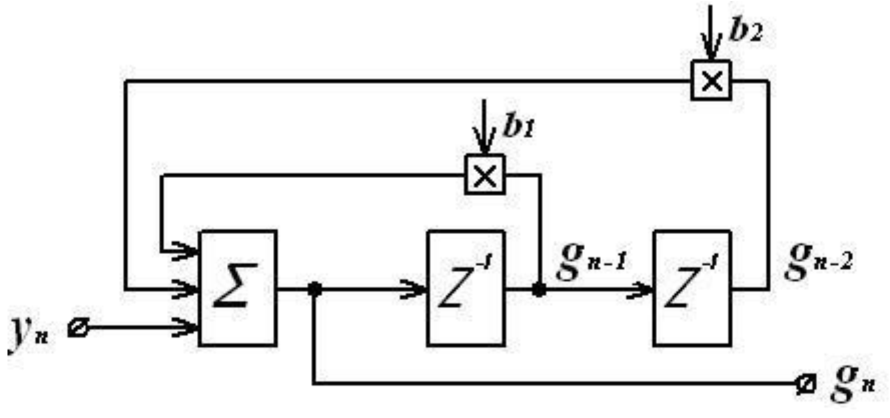


**Figure 1.** Scheme of the system is a second-order difference equation digital solver, where: $\Sigma$ – adder-accumulator; $Z^{-1}$ – delay of $n$-th sample at discretization period $T_d$ (in frequency domain $Z^{-1}$=$e^{-i2\pi\omega T_d}$); $b_2$=$-r^2$, $b_1$=$2r\cos(\omega T_d)$

When $0<b_1<1$ and $1<b_2<2$, it is the second order (pass-band) filter. For a sine function, when $b_2$ equals to 1, $y_n$=0 the system becomes a generator of frequency ω/2π. The digital generator of sine waveform, consisting of discrete digital components, suggested for modeling the MagAmp switch, is described in [26]. It is a prototype of the structure of the proposed model. Although the primary purpose of such structure is sine waveform generation, here it is suggested to use it as a digital computational model for MagAmp voltage and current. With certain values of $b_1$ and $b_2$ coefficients, it can model MagAmp switch nonlinear properties:

$$g_{n+1} > g_n : \begin{cases} H_n = \overline{H_{\min}, H_{\min} + 2H_c}, B_n = B_{\min}, \\ H_n = \overline{H_{\min} + 2H_c, H_{\max}}, B_n = k\sin(2\pi f n T_d + \varphi_1), \end{cases} \tag{3}$$

$$g_{n+1} < g_n : \begin{cases} H_n = \overline{H_{\max}, H_{\max} - 2H_c}, B_n = B_{\max}, \\ H_n = \overline{H_{\max} - 2H_c, H_{\min}}, B_n = k\sin(2\pi f n T_d + \varphi_2), \end{cases} \tag{4}$$

where $n = \overline{1, N}$ – index of digital codes of electromagnetic variables, another denotations are digital codes of appropriate (corresponding) constants. $H_{min}$, $H_{max}$ are minimum and maximum values of strength of magnetic field respectfully. $H_c$ is a coercive force. $B_{min}$, $B_{max}$ are minimum and maximum values of magnetic induction respectfully. For more simplicity, the current model suggests that saturation magnetic induction $B_s = B_{max}$, while in real physical systems $B_{max}$ usually is magnetic induction value at $H=5H_c$ [15].

Since the filter is realized with discrete digital components, it can be easily modeled in any CAD system for electric circuits design with no additional integrations required. Moreover, digital nature of the model eliminates difficulties with modeling of high-frequency magnetic fields. Actual MagAmp switches often work with high currents (even over 10A). Although no real digital component is able to operate at such current, the digital filter CAD model parameters can be easily scaled to represent real-life values.

**Analysis of experimental results**. To record an experimental MagAmp hysteresis loop the evaluation board with the electric circuit shown in Fig. 3 was used:

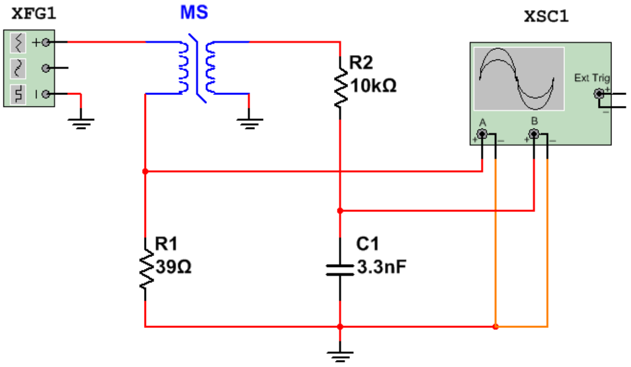


**Figure 2.** Scheme of the electric circuit used for magnetic induction $B$ and strength of magnetic field $H$ measurement

It consists of: a) a generator G3-109 (XFG$_1$, load resistance $r_{out}$ =5Ω, 50Ω, 600Ω or 5kΩ; here f=50 kHz) of sinusoidal voltage V$_g$, MagAmp switch MS (whose magnetic core is made of amorphous Co-based soft magnetic material), resistor R$_1$; b) the R$_2$C$_1$ integrator (which allows to measure the signals at higher frequencies without additional filters or signal processing algorithms) [27]. ATTEN 100 MHz oscilloscope (XSC1) has been used for measurements.

According to the total current law [14]

$$I = \frac{Hl}{N}, \tag{5}$$

where $H$ is the strength of the magnetic field, $N$ is the number of MagAmp winding turns (here the number of turns of primary and secondary MagAmp windings is equal: $N_1 = N_2 = N$ ), $l$ is the length of magnetic path, calculated as

$$l = 2\pi \cdot \left( r_{out} - \frac{(r_{out} - r_{in})}{2} \right). \tag{6}$$

$r_{out}$ and $r_{in}$ are the outer and inner radii of the MagAmp core.

Using (5) and (6), we can derive strength of magnetic field $H$ :

$$H = \frac{V_{chA} \cdot N}{R \cdot l}. \tag{7}$$

The voltage $V_{ch.B}$ of oscilloscope is related to the voltage across MagAmp switch $V$ [27]:

$$V_{ch.B} = \frac{1}{RC} \int_0^t V(t)dt. \tag{8}$$

According to Faraday’s law [27]

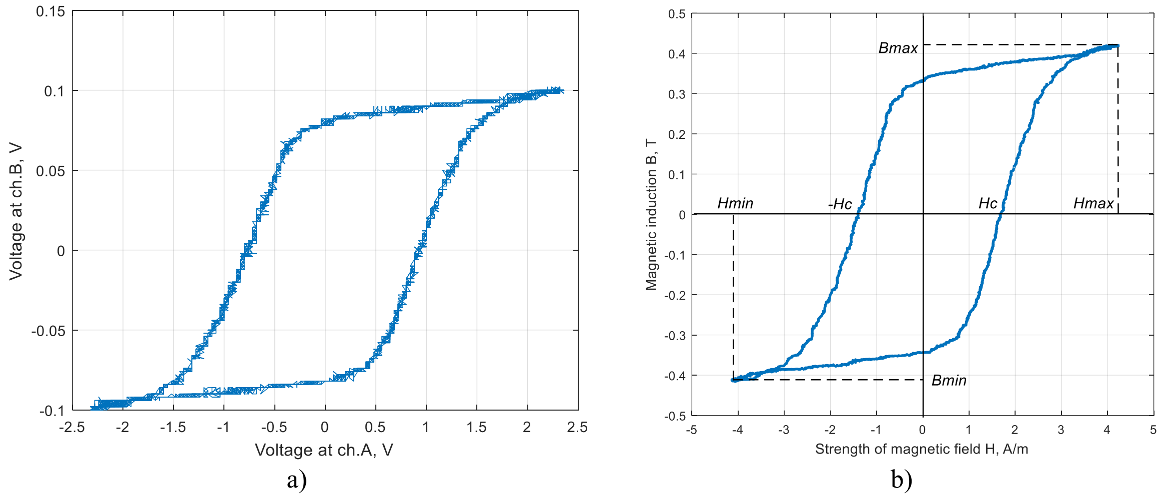
$$V = \frac{d\Phi}{dt} \cdot N_2 = \frac{dB}{dt} SN_2 \tag{9}$$

where $B$ is magnetic induction, $S$ is the cross section area of MagAmp saturable core.

Since digital oscilloscope gives us a discrete signal, which is a sequence of voltage values at certain moments of time (a set of data points), we can derive magnetic induction value at each moment of time from equations (8) and (9)

$$B = \frac{V_{ch.B} \cdot RC}{SN_2} \tag{10}$$

Fig. 3 (a) shows the experimental data – MagAmp current (5) versus integrator voltage (9) which were used to derive MagAmp characteristic B (H), (7, 10), Fig. 3 (b).



a) b)

**Figure 3.** Hysteresis loop measurement: a) raw data measured with oscilloscope (assemble with 10 loops); b) the estimation of mathematical expectation of B (H) loop

**Analysis of simulation results**. The suggested MagAmp switch model (3, 4) has been integrated into Matlab CAD environment (Fig. 4). The *H*, *B* axes values on Fig. 4 are given in conditional units (c. u.), which are obtained by scaling the results of formulas (2, 3, 4) to the result (Fig. 3, b) of the experiment. Magnetic field strength *H* and induction *B* values which are presented on Fig. 4, depend on the oscilloscope ($XSC_1$, Fig. 2) period of discretization $T_d$, frequency of the generator ($XFG_1$, Fig. 2), and, of course, parameters in expressions (7, 10). Ratio of the oscilloscope and generator frequencies will give us the number of data points recorded during one period (represented along H axes). Conditional units of magnetic induction *B* correspond directly to its value measured in teslas (T).

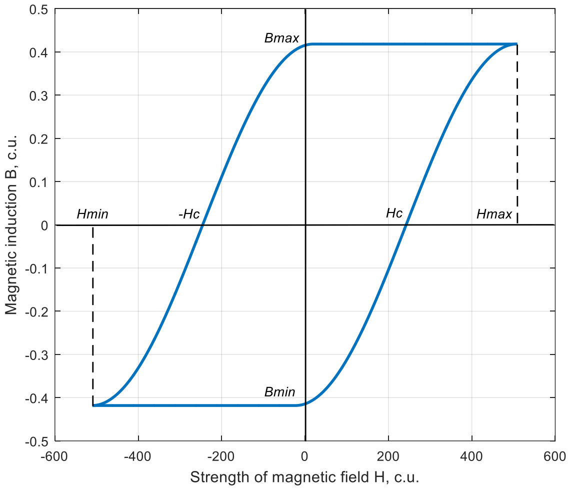


**Figure 4.** The digital model (3, 4) of MagAmp hysteresis loop

The absolute error ($\varepsilon \leq 0.144$ T) and mean squared deviation between modeled and experimental data ($\sigma=0.0706$ T) have been calculated. Comparison of obtained simulation results and mean experimental results over one period of switching frequency is represented with Fig. 5–7. Similarly to the figures above, the magnetic induction and time axes are measured in conditional units (c. u.). Time c. u. depend directly on the oscilloscope discretization frequency, and generator frequency. Ratio of these frequencies will give us the number of data points recorded during one period (represented along Time axes). Conditional units of magnetic induction *B* correspond directly to its value measured in teslas (T).

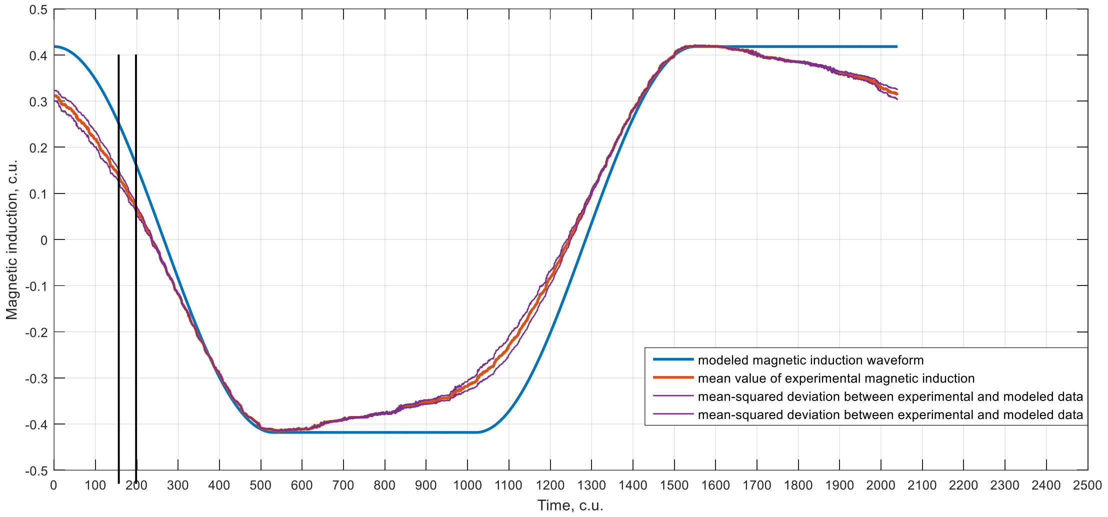


**Figure 5.** Modeled magnetic induction waveform, mean experimental magnetic induction B, and mean-squared deviation σ between experimental and modeled data

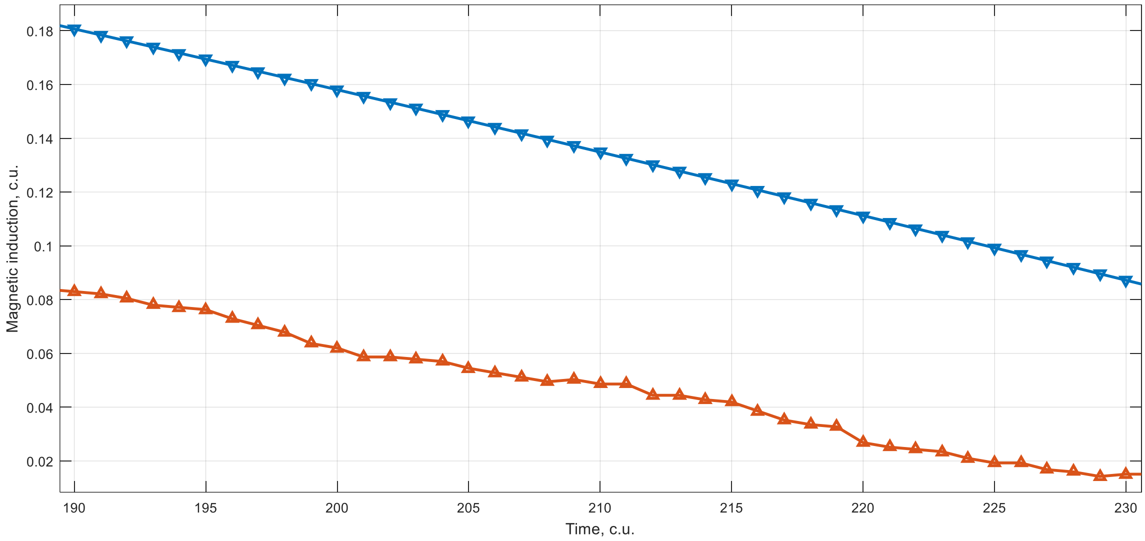


**Figure 6.** Modeled magnetic induction waveform versus mean experimental MagAmp magnetic induction

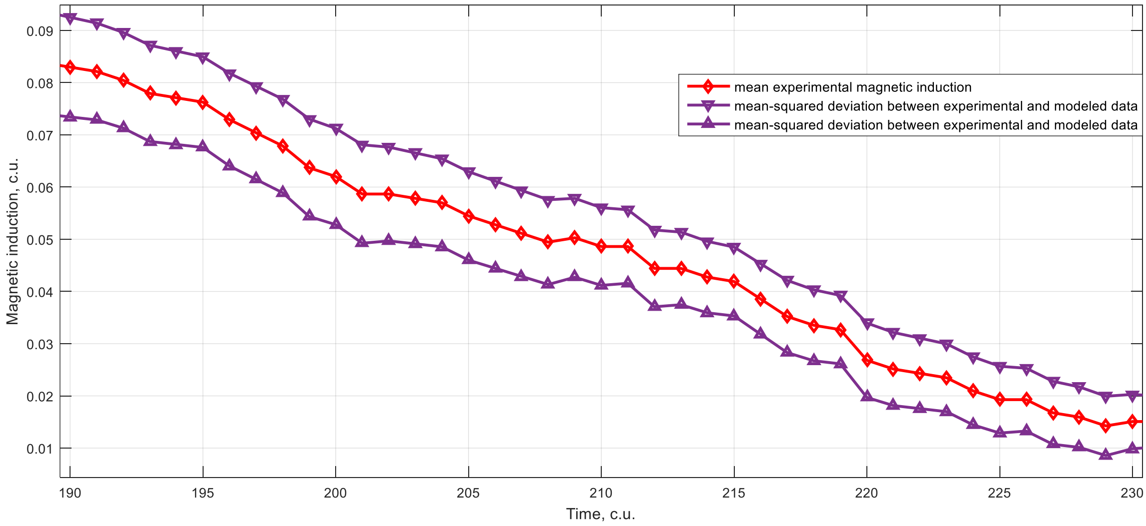


**Figure 7.** Mean experimental MagAmp magnetic induction B and mean-squared deviation σ between it and modeled data

**Conclusions.** New MagAmp switch model (3, 4) has been integrated into CAD environment for electric circuits. Since the model is based on a function that can be generated using digital technology, the model's structure has been realized with discrete digital components. This has allowed modeling the electric circuit with MagAmp switch in a single CAD system for electric circuits with no additional integrations required, instead of using separate CAD environments for electric and magnetic components modeling. Complexity of the MagAmp switch model algorithm in CAD for electric circuits was decreased from $N^2(4\log_2 N+1)$ for the elliptical second-order polynomial Poisson equation (1) used in ELCUT to $\tau N$ for a system of linear first-order polynomial equations (3, 4). Due to the integration of the model and its decreased complexity, the complete machine time of MagAmp switch computer aided design has been decreased significantly.

The other advantages of the suggested model are the following:

a) its parameters ($H_c$ and $B_{max}$) can be found in MagAmp core's datasheet;

b) model processes MagAmp input voltage and current signals, working as a digital filter, thus model parameters do not require readjustment when parameters of the electric circuit where the model is used change;

c) digital nature of the model eliminates difficulties with modeling of high-frequency magnetic fields;

d) the output of the model provides electrical engineer with MagAmp switch current and voltage waveforms and its B(H) characteristic (when the output of model (1) is a set of magnetic potentials that needs to be preprocessed to be informative for electrical engineer).

The experimental electric circuit with MagAmp switch was built and tested. The absolute error ε and mean squared deviation σ between modeled and experimental data can be significantly decreased by taking into account the slope of magnetic induction waveform, where it was assumed that $B_n = B_{\min}$ (3) and $B_n = B_{\max}$ (4). To improve the modeling accuracy we can use $B_n = kx$ function, where *k* is proportional to $(B_{\max} - B_r)$. $B_r$ is remnant magnetic induction.

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# ІНТЕГРАЦІЯ МОДЕЛІ СИЛОВОГО КЛЮЧА НА ОСНОВІ МАГНІТНОГО ПІДСИЛЮВАЧА В СИСТЕМУ АВТОМАТИЗОВАНОГО ПРОЕКТУВАННЯ ПЕРЕТВОРЮВАЧІВ ЕЛЕКТРОЕНЕРГІЇ

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***Резюме.*** *Зазвичай у джерелах вторинного електроживлення (ДВЕЖ) комутаційну та регулюючу функції виконують напівпровідникові компоненти. Однак вони не можуть забезпечити високу якість вихідних характеристик у багатоканальних джерелах живлення та в ДВЕЖ із високим рівнем струму навантаження. В таких випадках як силові ключі використовують високочастотні магнітні підсилювачі (ВМП) на основі аморфних магнітом'яких сплавів з прямокутною петлею гістерезису. Розроблення перетворювачів електроенергії на основі ВМП не є повністю автоматизованим. ВМП є магнітним компонентом з нелінійними властивостями. Системи автоматизованого проектування (САПР) для комп'ютерного імітаційного моделювання електричних кіл не призначені для розрахунків магнітних полів та працюють з дискретними електричними компонентами. Існує проблема інтеграції моделі компонента з магнітним гістерезисом у бібліотеку моделей САПР. Крім того, досить складно оцінити оптимальні параметри такого компонента. У статті запропоновано нову математичну модель силового ключа на основі ВМП, що ґрунтується на функції, яку можна генерувати з допомогою цифрових технологій. Досліджено цифровий генератор синуса, що складається з цифрових дискретних компнентів для моделювання силового ключа на основі ВМП. Запропоновану математичну модель силового ключа на основі ВМП інтегровано у САПР. Проведено комп'ютерне імітаційне моделювання електричного кола, що містить ВМП. Розраховано абсолютну похибку та середньоквадратичне відхилення моделі процесів перемагнічення ВМП у порівнянні з експериментально отриманими даними. Така часткова автоматизація процесу розроблення високочастотних перетворювачів електроенергії на основі ВМП суттєво зменшить його складність, тривалість і вартість, а також сприятиме розвиткові нових схемотехнічних рішень.*

***Ключові слова:*** *математична модель, ключ на основі магнітного підсилювача, САПР, магнітний гістерезис, комп'ютерне імітаційне моделювання.*

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