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3D COUPLED ELECTROMAGNETIC-THERMAL ANALYSIS OF A HYBRID ELECTROMAGNETIC SYSTEM WITH MAGNETIC FLUX MODULATION

3D ELEKTROMAGNETNA IN TOPLOTNA ANALIZA HIBRIDNEGA ELEKTROMAGNETNEGA SISTEMA Z MODULACIJO MAGNETNEGA PRETOKA

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Abstract

This paper presents a study of the electromagnetic and thermal field of a new construction of a hybrid electromagnetic system with magnetic flux modulation. The numerical studies were realised using the finite element method. The coupled problem electromagnetic field-electric circuit-thermal field was solved. A computer model of the hybrid electromagnetic system was developed for the purpose of the study using the software programme COMSOL. Results for the distribution of the electromagnetic and thermal field in the hybrid electromagnetic system with magnetic modulation were obtained at different supply voltages.

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Povzetek

Prispevek predstavlja raziskavo elektromagnetnega in toplotnega polja nove konstrukcije hibridnega elektromagnetnega sistema z modulacijo magnetnega pretoka. Numerične raziskave so bile izvedene z metodo končnih elementov. Rešen je bil problem povezanega elektromagnega in toplotnega polja. Za namene raziskave je bil razviti računalniški model hibridnega elektromagnetnega sistema s programsko opremo COMSOL. Rezultati porazdelitve elektromagnetnega in toplotnega polja v hibridnem elektromagnetnem sistemu z magnetno modulacijo so bili pridobljeni pri različnih napajalnih napetostih.

1 INTRODUCTION

One of the main requirements when creating new devices is energy efficiency. In order to improve energy efficiency, new design solutions are being developed using new materials and technologies. In this regard, hybrid electromagnetic systems with magnetic flux modulation (HEMSMM) find wide application. HEMSMM have undergone a number of studies and patenting [1]-[6].

This paper describes the computer modelling of a new construction of HEMSMM developed and described in [7], [8], which was carried out by solving the coupled problem of electromagnetic field-electric circuit-thermal field in transient mode.

2 CONSTRUCTION OF THE STUDIED HEMSMM

The structure of the studied HEMSMM is shown in Fig. 1. It consists of a magnetic core, one input (control) coil, three output (signal) coils, two permanent magnets and an air gap. The magnetic core is made of ferrite with a cross-section of 20x10mm. The length of the air gap is 1mm. All the coils are made of a cylindrical copper conductor of diameter 0.56mm. The input coil 1 and the output coil 2 each have 200 turns. The other two output coils – 3 and 4 – each have 400 turns. The cross-section of the permanent magnets is 20x10mm, and their thickness is 2mm.

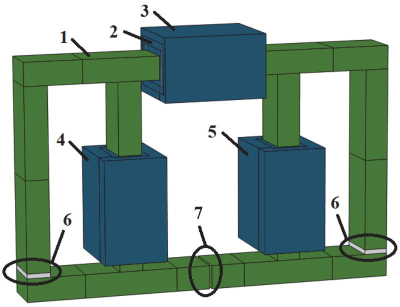


Figure 1: *Geometry of the studied construction of HEMSMM: 1 - ferromagnetic frame; 2 - input (control) coil 1; 3 - output (signal) coil 2; 4 - output (signal) coil 3; 5 - output (signal) coil 4; 6 - permanent magnets; 7 - air gap.*

3 MATHEMATICAL MODEL

To solve the coupled problem electromagnetic field-electric circuit-thermal field, the finite element method was used. The problem was solved in three steps. The equation of the electromagnetic field in steady state, created for permanent magnets, was solved in the first step. The permanent magnets were modelled with relative permeability μ_r = 1.05 and coercive force of 970 kA/m. The electric circuit was not involved in this step and the equation has the form:

$$\nabla \times (\mu^{-1} \nabla \times \boldsymbol{A} - \boldsymbol{M}) = 0, \tag{3.1}$$

where: $\boldsymbol{A}$ is the magnetic vector potential; $\boldsymbol{M}$ is the magnetisation; μ is the magnetic permeability.

The electromagnetic problem was solved by imposing the Dirichlet boundary condition on the boundary of the buffer zone.

The results of the static magnetic field were used as a starting condition for the second step. The coupled problem electromagnetic field-electric circuit in transient mode was solved in the second step. The equation for the electromagnetic field in transient mode is:

$$\sigma \frac{\partial \boldsymbol{A}}{\partial t} + \nabla \times (\mu^{-1} \nabla \times \boldsymbol{A} - \boldsymbol{M}) = N \frac{i(t)}{S}, \tag{3.2}$$

where: σ is the electrical conductivity of the material; N is number of turns of the coil; i is the current through the coil; S is the coil cross-section.

The inductance and the active resistance of the coils were obtained from the electromagnetic field interface and are directly employed in the electric circuit. Active loads are connected to the output coils. The equations of the four coils are:

$$u_1(t) = R_1 i_1(t) + \frac{\partial \psi_1}{\partial t}; \tag{3.3}$$

$$-\frac{\partial \psi_2}{\partial t} = R_2 i_2(t); \tag{3.4}$$

$$-\frac{\partial \psi_3}{\partial t} = R_3 i_3(t); \tag{3.5}$$

$$-\frac{\partial \psi_4}{\partial t} = R_4 i_4(t), \tag{3.6}$$

where: $u_1(t)$ is the voltage of coil 1; R_1 to R_4 are the active resistances of the coils; $i_1(t)$ to $i_4(t)$ are the currents through the coils; Ψ is the flux linkage.

The electric circuit used in the simulations is shown in Fig. 2.

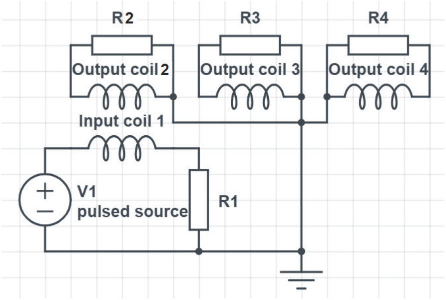


Figure 2: *Electric circuit used in the simulations*

The B-H curve of the magnetic core is shown in Fig. 3.

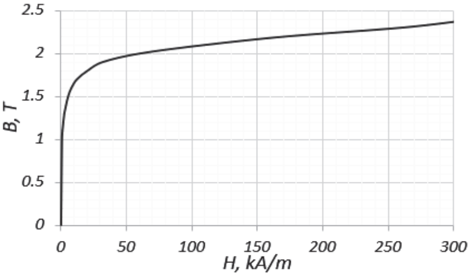


Figure 3: *B-H curve of the ferromagnetic material of the core*

From the solution to the electromagnetic problem, the volumetric loss density in the coils and the magnetic core are obtained. These losses are the sources of heat for the solution of the thermal problem, which is carried out in the third step. The thermal field is described by the equation of thermal conductivity in transient mode:

$$\rho c\left(\frac{\partial T}{\partial t}\right) = \nabla(\lambda \nabla T) + q, \tag{3.7}$$

where: T is the temperature; ρ is the density of the material; c is the specific heat; λ is the coefficient of thermal conductivity; q is the volumetric density of the heat sources.

The solution of the thermal problem is found under the following initial and boundary conditions:

- at time t=0 the ambient temperature is set to 20°C;

- heat transfer from the outer surfaces of the coils and the magnetic core to the environment through convection and radiation:

$$-\lambda\left(\frac{\partial T}{\partial n}\right) = h\left(T_s - T_{amb}\right); \tag{3.8}$$

$$\lambda\left(\frac{\partial T}{\partial n}\right) = \varepsilon k_B\left(T_s^4 - T_{amb}^4\right), \tag{3.9}$$

where: h is a coefficient of convection, defined by the criterion of Nuselt in the programme COMSOL; k_B=5.67x10^{-8} W/m^{2}K^{-4} is the constant of Stephan Boltzmann; ε is the emissivity; T_s is the temperature of the outer surface of the coils and the magnetic core; T_{amb} is the ambient temperature.

4 FINITE ELEMENT ANALYSIS

The numerical studies were conducted with the help of a 3D computer model in COMSOL [9]. The coupled problem electromagnetic field - electric circuit - thermal field in transient mode was solved. The finite element method was used to analyse the model and the resulting mesh is shown in Fig. 4.

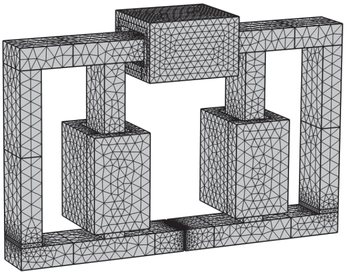


Figure 4: *Finite elements mesh*

5 NUMERICAL RESULTS

By using the developed 3D model of HEMSMM, the results for the electromagnetic and thermal fields were obtained at a frequency of 5kHz and different supply voltages of the input coil – 6V, 9V and 12V.

Fig. 5 and Fig. 6 illustrate the distribution of the magnetic field, while Fig. 7 and Fig. 8 show the input and output power at the 6V and 12V supply voltages respectively. Fig. 9 shows the thermal field distribution in HEMSMM at different supply voltages of the input coil and an operating time of 2h. Fig. 10 illustrates the transient mode of temperature rise in the coils and the magnetic core at different supply voltages of the input coil.

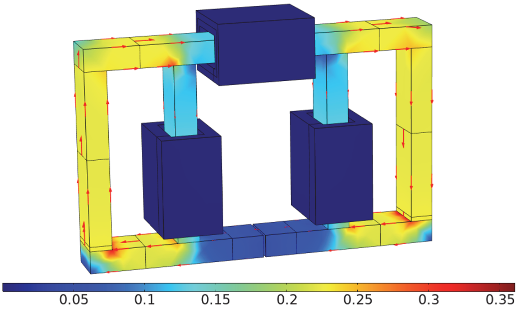
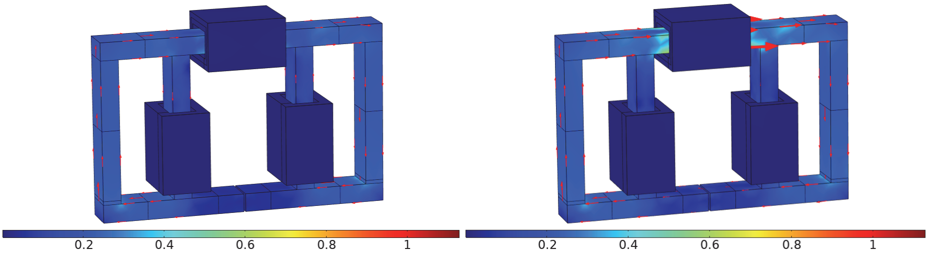
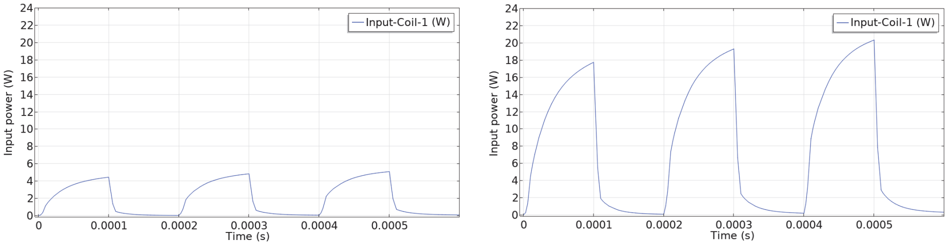


Figure 5: *Distribution of the magnetic flux density (T) in HEMSMM, when the input coils are not energised*



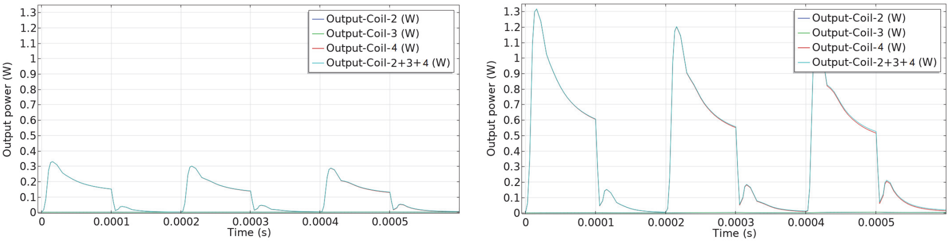
a) *b)*

Figure 6: *Distribution of the magnetic flux density (T) in HEMSMM, when the input coil is supplied with the following voltages: a) 6V; b) 12V*



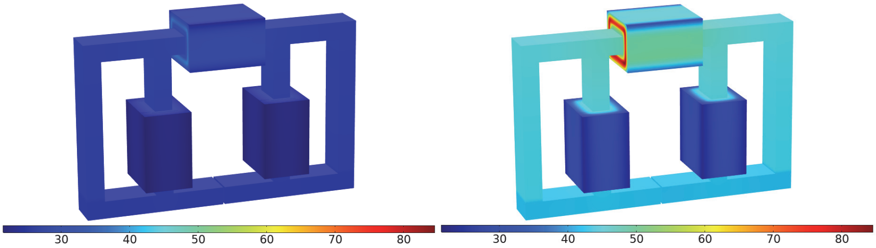
a) *b)*

Figure 7: *Input power at supply voltage of: a) 6V; b) 12V*



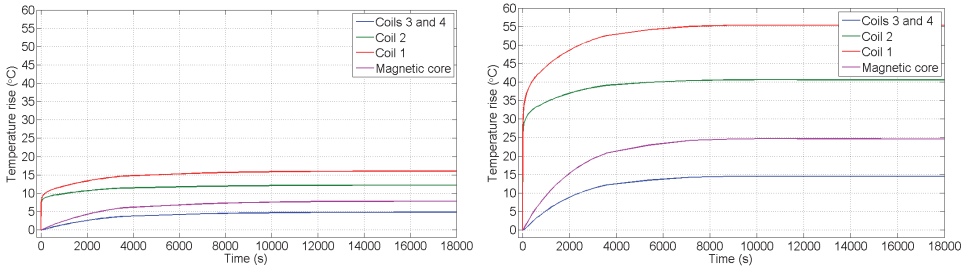
a) *b)*

Figure 8: *Output power at supply voltage of the input coil: a) 6V b) 12V*



a) *b)*

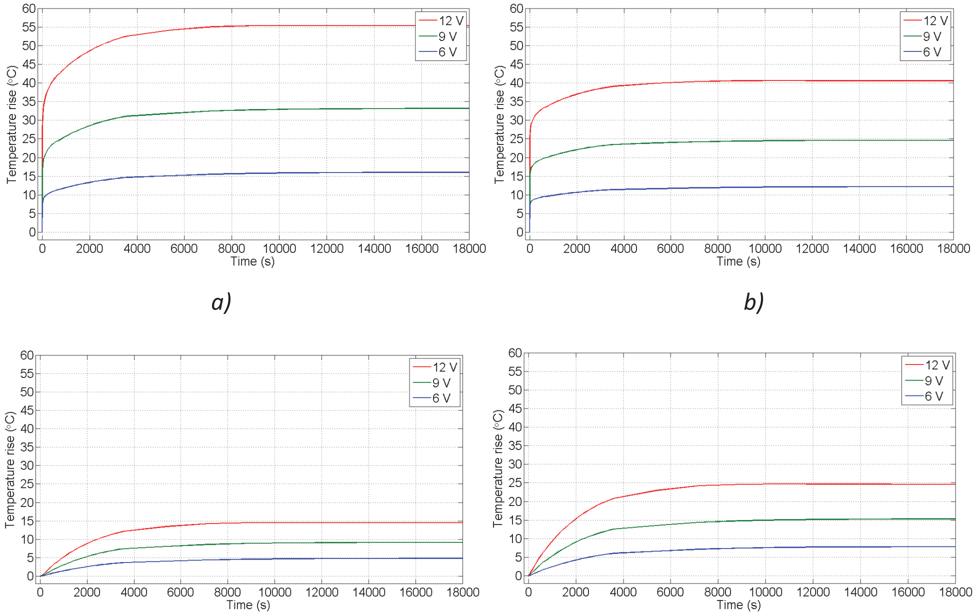
Figure 9: *Thermal field distribution (°C) in HEMSMM at operating time 2h and supply voltages: a) 6V; b) 12V*



a) *b)*

Figure 10: *Transient mode of temperature rise in the coils and the magnetic core of HEMSMM at supply voltages: a) 6V; b) 12V*

Fig. 11 illustrates the results obtained for the temperature rise in the coils and the magnetic core in transient mode at different supply voltages and a frequency of 5kHz.



a) *b)*

c) *d)*

Figure 11: *Transient mode of temperature rise in: a) the input coil 1; b) the output coil 2; c) the output coils 3 and 4; d) the magnetic core*

6 CONCLUSION

Numerical studies of a new HEMSMM design were conducted at different supply voltages and results were obtained for the distribution of the magnetic and thermal fields.

As the value of the supply voltage increases, the input power, output power and the magnetic flux density in HEMSMM increase.

Due to the losses in the coils and the magnetic core, the HEMSMM temperature rise also increases with the increasing value of the supply voltage. When the supply voltage is doubled (from 6V to 12V), the temperature rise of the coils and the magnetic core increases about three-fold.

The greatest temperature rise occurs on the input coil 1, and the least on the two output coils 3 and 4. HEMSMM reaches a thermal steady-state after about 2 hours of operation.

The developed computer model can be used for optimisation of HEMSMM.

Acknowledgement

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Nomenclature

(Symbols)	(Symbol meaning)
A	magnetic vector potential
M	Magnetisation
μ	magnetic permeability
σ	electrical conductivity
N	number of turns in the coil
i	current through the coil
S	coil cross section
$u_1(t)$	voltage of coil 1
R_1	active resistances of the coil 1
R_2	active resistances of the coil 2
R_3	active resistances of the coil 3
R_4	active resistances of the coil 4
$i_1(t)$	current through the coil 1
$i_2(t)$	current through the coil 2
$i_3(t)$	current through the coil 3
$i_4(t)$	current through the coil 4
Ψ	flux linkage
T	temperature
ρ	density of the material
c	specific heat
λ	coefficient of thermal conductivity
q	volumetric density of the heat sources
h	coefficient of convection
k_B	constant of Stephan Boltzmann
ε	emissivity
T_s	temperature of the outer surface of the coils and the magnetic core
T_{amb}	ambient temperature