ISSN 1392 – 1215 ELECTRONICS AND ELECTRICAL ENGINEERING
ELEKTRONIKA IR ELEKTROTECHNIKA 2006. Nr.3(67)

T 190 ELECTRICAL ENGINEERING
ELEKTROS INŽINERIJA

Simplified Numerical Simulation of Pulsed Magnets with a Finite Element Method

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Introduction

Recently the interest in pulsed magnet design has increased very much and investigations in solid state physics, biology, medicine, electrical engineering and technology were done [1]. The pulsed technology of magnetic field generation is commercially attractive because it does not require great investments comparing with traditional resistive magnets or superconductive magnets [2]. A relatively simple system included a capacitor bank, a pulsed switch and an inductor can be used for pulsed magnetic field generation up to 60-70 T [3]. But pulsed inductors operate under heavy electrical, mechanical and thermal conditions and induced overloads must be taken into consideration. After series of experiments inductors disintegrate due to pulsed overloads. Therefore it is necessary to control the total quantity of operation cycles to avoid non-expected failure. Actually the design of long life inductors and failure control are extremely important task for scientists and engineers [4].

The design of pulsed magnets involves the calculation of magnetic field distribution, pulse shape, the evaluation of mechanical stresses and the distribution of absolute deformations. For magnetic field intensity, magnetic flux density and absolute values of displacement calculation recently used a finite elements technique [5]. The commercially available powerful software package ANSYS, which includes electromagnetic field and structural analysis, is one of the most popular tools that have been used for coils optimization [6].

For numerical simulation and optimization of pulsed magnet electromagnetic field and structural analysis are coupled via electromagnetic force. Electromagnetic field analysis has a strong influence on the structural analysis. Therefore these are solved simultaneously by a so-called coupled field analysis. Usually 3-D modelling is applied. But for some tasks 3-D modelling can be reduced to 2-D modelling and relatively good results can be achieved [7].

In this paper simplified 2-D modelling is used for evaluation of magnetic field and deformations analysis of different construction of pulsed solenoids.

Electromagnetic field and structural analysis

The ideal conductor for pulsed coil ought to combine the high mechanical strength with high electrical conductivity. But in practice the high conductivity typically is combined with the low mechanical strength of material. At magnetic field of 50 T a load of the order of 1 GPa acts on the inductor construction and traditional materials are inapplicable without the special reinforcement. In present time composite materials combined the high electric and mechanical characteristics are applied in pulsed inductor design and non-destructive magnets can be developed [8].

After long term experimentation with various coil constructions it was found that the best prototype of long life inductor is the multilayer reinforced solenoid [9] as is shown in Fig. 1.

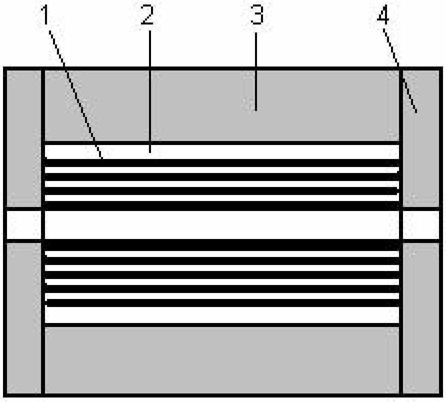

Fig. 1. Multilayer reinforced solenoid

Inductor winding 1 is divided into few layers and separated with interlayer reinforcement 2 and wet impregnated. To avoid the disintegration an assembled coil is put in steel container consisted of a cylinder 3 and heads 4. The analogical multilayer construction of metal matrix Cu-Nb micro composite wire wound Zylon-epoxy composite reinforced inductor is analyzed in further calculations. For the comparison the soft cooper wire wound inductor was made by the similar geometry and magnetic field characteristics.

Due to construction symmetry the 2-D structure is modelled. The PLANE 13 4-node (2-D coupled field solid) elements in ANSYS for numerical simulation of the pulsed magnets are used. The first solenoid consists of 108 Cu wire coils fixed in common epoxy structure with Zylon reinforcement and stainless steel shell. The second solenoid consists of 60 Cu-Nb composite wire coils fixed in common epoxy structure with Zylon reinforcement and stainless steel shell. The details of coils geometry, current density in adequate coils and materials properties are given in the Tables 1 – 3.

Table 1. Basic parameters of analyzed coils

Parameters	Cu-Nb wire wound coil	Cu wire wound coil
Bore radius, mm	4	4
Layers	6	6
Turns/ layer	10	18
Ratio of outer and inner diameter α	2,7	3,4
Ratio of height to inner diameter β	2,45	3,0
Cross section of wire, mm	1.7x0.8	1,5
Thickness of stainless steel shell, mm	15	15

Table. 2. Data for magnetic analysis

Parameters	Cu-Nb wire wound coil	Cu wire wound coil
Current density in coils j x 10^{10}, A/m^2	1,10	0.561
Magnetic permeability of epoxy, coils, plastic and liquid nitrogen outside solenoid μ	1	1

The magnetic problem involves the static magnetic field analysis in a space around the coil and in the reinforced turns of the coil. Electromagnetic fields are governed by the Maxwell's equations [10]:

$$\nabla \times H = J_S \,, \tag{1}$$

$$\nabla \cdot B = 0 \,, \tag{2}$$

where H – is magnetic field intensity vector, B – is magnetic flux density vector, J_s – is applied source current density vector, while ∇ – is notation of the divergence operator of a vector.

Maxwell's equations (1-2) can be expressed by introducing potential field approach. Therefore magnetic field to be expressed as

$$B = \nabla \times A \,, \tag{3}$$

where A – is magnetic vector potential.

Total magnetic force acting on bodies contained in particular surface [11]:

$$F = \frac{1}{2} \oint \left(H(n \cdot B) + B(n \cdot H) - n(H \cdot B) \right) ds \,, \tag{4}$$

where H – is magnetic field intensity, B – is magnetic flux density, n – denotes the vector of the outward unit normal.

The structural problem involves the mechanical analysis of the coil structural parts. The accepted conditional characters and definitions for nonlinear structural analysis:

- used materials are isotropic plastic materials (BKIN – bilinear kinematic hardening model)

Table 3. Material properties for structural analysis

Material	Young's modulus E, GPa	Poisson's ratio, ν	Density, ρ, kg/m^3	Yield strength, $R_{0.2}$, MPa	Tensile strength, R_m, MPa
Cu-Nb wire	42	0.3	8900	850	1100
Cu wire	110	0.35	8900	250	320
Zylon	270	0.3	1560	3200	4500
Epoxy resin	3	0.3	1200	42	70
Plastic body	30	0.3	1300	115	168
Steel shell	196	0.3	7850	200	520

The general deformations at the each point of finite elements are expressed as the sum of elastic and plastic deformations [6]:

$$d\{\varepsilon\} = d\{\varepsilon^e\} + d\{\varepsilon^p\}, \tag{5}$$

where $\{\varepsilon^e\}$ – is elastic deformation, $\{\varepsilon^p\}$ – is plastic deformation.

For 2-D model the plastic behaviour of a material, characterized by nonrecoverable strain, begins when the stresses according to the following formula (6) exceed the material's yield point, i.e. correspond the von Mises yield criteria:

$$\begin{gathered} F(\{\sigma\},k) = \overline{\sigma} - \sigma_T(k) = \\ = \sqrt{\frac{1}{2}(\sigma_x - \sigma_y)^2 + \frac{1}{2}\sigma_x{}^2 + \frac{1}{2}\sigma_y{}^2 + 3\tau_{xy}{}^2} - \sigma_T(k) = 0, \end{gathered} \tag{6}$$

where $\sigma_T(k)$ – is yield strength limit, the value of which depends on the parameter of hardening, $\overline{\sigma}$ – is equivalent stress parameter, k – is plastic work.

The absolute value of displacement according to the following formula:

$$\delta = \sqrt{\delta_x{}^2 + \delta_y{}^2}\ , \tag{7}$$

where δ_x, δ_y – are two components of displacement vector δ in each point.

The results of numerical analysis of magnetic field distribution, magnetic force and displacement of Cu-Nb wire wound solenoid are shown in Fig. 2–4.

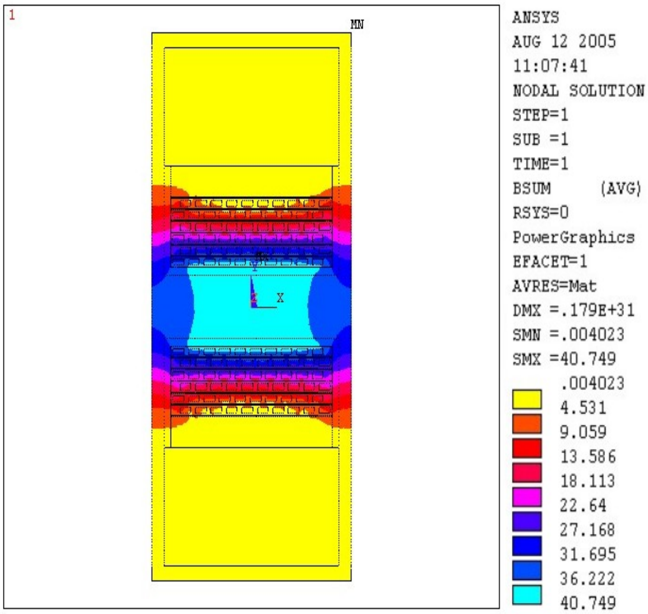

Fig. 2. The distribution of magnetic field density in the Cu-Nb composite wire wound coil (B, T)

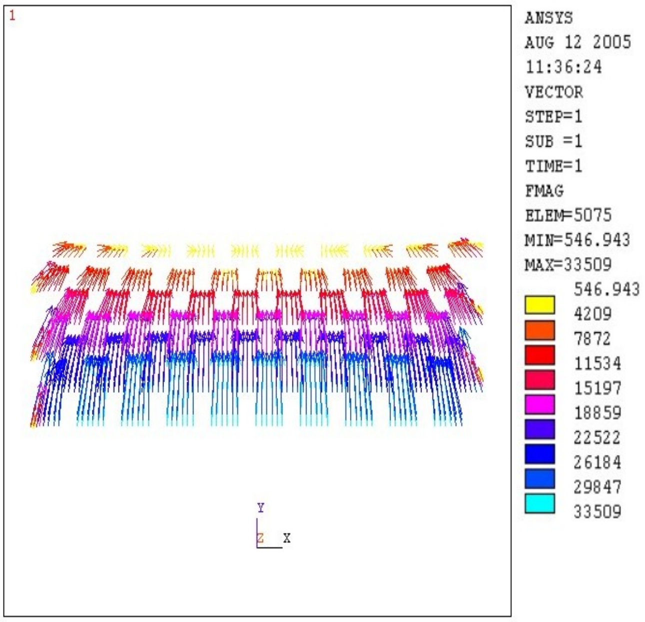

Fig. 3. The vectorial distribution of Lorenz force density in the Cu-Nb composite wire wound coil. Half of model (F, N/m)

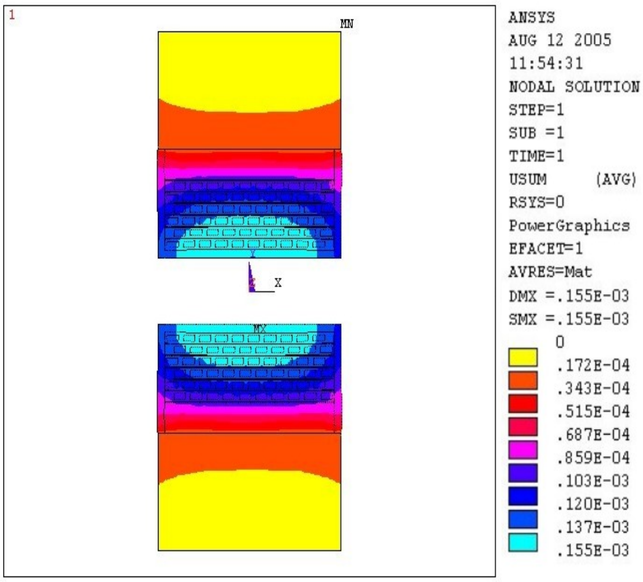

Fig. 4 The total displacements of Cu-Nb composite wire wound coil (δ, m)

Results of numerical analysis of Cu wire wound solenoid are not shown. But both solenoids generate the equivalent magnetic field in 40 T range with similar field distribution. Taking into account that turn quantity of Cu-Nb wire wound solenoid, which was approximately two times less then for Cu wire wound inductor, the equivalent current for Cu-Nb wire wound solenoid should be two times higher. This circumstance has resulted two times higher mechanical overloads in solenoid construction due to induced Lorenz force proportional to magnetic flux density and current values. But contrary as can be expected by first glance the displacement of winding for higher currents was two times less then for low current case. Cu-Nb wire wound coil can sustain the more then 2 times largest value of magnetic forces. Moreover the coils have different deformations and rigidity. The axial displacement for Cu-Nb wire wound solenoid was 0,032 mm, radial – 0,155 mm. For the comparison Cu wire wound solenoid had the axial displacement 0,07mm and radial – 0,27 mm. The mechanical stability of Cu-Nb wire wound solenoid can be explained taking into consideration that Cu-Nb tensile strength limit is three times higher (1,10 GPa) then Cu wire (0,32 GPa).

Conclusions

Numerical analysis of magnetic field distribution, magnetic forces distribution, deformations analysis of pulsed solenoids was done. Due to geometric symmetry of simulated object 3-D finite element modelling was simplified to 2-D numerical modelling and relatively good results are achieved. Numerical 2-D modelling was done for multilayer Cu-Nb and Cu wire wound coils. It was found that mechanical strength of winding materials is most limited factor to insure mechanical strength of pulsed solenoid. Applied results of numerical simulation should be taken into account for further steps of construction improvement and will be checked experimentally soon.

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Presented for publication 2006 02 01

N. Višniakov, J. Novickij, S. Bartkevičius. Simplified Numerical Simulation of Pulsed Magnets with a Finite Element Method // Electronics and Electrical Engineering. – Kaunas: Technologija, 2006. – No. 3(67). – P. 47 – 50.

The numerical simulation of magnetic field and mechanical deformation in pulsed magnets is described. ANSYS software was applied for numerical simulation. Due to construction symmetry the 3-D structure is simplified to 2-D structure and the numerical model of pulsed magnet was realized using the finite element method. The numerical model was done for two variants of multilayer reinforced pulsed magnet construction. The first one was wound with copper-niobium micro-composite wire, another - with traditional copper wire. Both magnets had similar pulsed magnetic field distribution and maximal value of magnetic flux density. Analyzing magnetic forces distribution and wire displacement it was found, that in spite of twice higher mechanical overloads took place in copper-niobium winding this magnet had the evidently better mechanical stability. Therefore numerical simulation results should be taken into account in further magnet optimization steps. Ill.4, bibl. 11 (in English; summaries in English, Russian and Lithuanian).

Н. Вишняков, Ю. Новицкий, С. Барткевичюс. Упрощенное числовое моделирование импульсных магнитов методом конечных элементов // Электроника и электротехника. – Каунас: Технология, 2006. – № 3(67). – P. 47 – 50.

Описано численное моделирование распределения магнитного поля, механических нагрузок и деформаций импульсных соленоидов. Численное моделирование выполнено методом конечных элементов, используя программный пакет ANSYS. Учитывая симметричность задачи, трехмерная модель упрощена до двухмерной модели. Численное моделирование выполнено для двух вариантов многосекционной армированной обмотки импульсного соленоида. В одном случае обмотка намотана микрокомпозитным медно-ниобиевым проводом, в другом случае – медным проводом. Оба импульсных магнита имели примерно идентичное значение амплитуды и распределение магнитного поля. Что касается механических нагрузок, то несмотря на значительно большие их значения, обмотка с медно-ниобиевым проводом имела явно большую механическую прочность. Таким образом делается вывод, что, несмотря на дополнительные внутреннее и внешнее армирование, механическая прочность импульсного магнита определяется в основном прочностью провода, что будет учтено в последующих экспериментах. Ил. 4, библ. 11 (на английском языке; рефераты на английском, русском и литовском, яз.).

N. Višniakov, J. Novickij, S. Bartkevičius. Impulsinių magnetų supaprastintas modeliavimas baigtinių elementų metodu // Elektrotechnika ir elektronika. – Kaunas: Technologija, 2006. – Nr. 3(67). – P. 47 – 50.

Pateikta impulsinių magnetų magnetinio lauko pasiskirstymo, mechaninių perkrovų ir deformacijų skaitinė analizė. Skaitinis modeliavimas atliktas baigtinių elementų metodu, panaudojant ANSYS programų paketą. Daugiasluoksnė kelių sekcijų impulsinio magneto armuota konstrukcija analizuojama, supaprastinant 3-D modelį iki 2-D modelio dėl užduoties simetriškumo. Palyginami dviejų impulsinio magneto konstrukcijų skaitinio modeliavimo rezultatai. Nustatyta, kad iš vario ir niobio mikrokompozicinės vielos suvyniotos magneto apvijos mechaniškai yra gerokai stabilesnės nei analogiškos armuotos apvijos, suvyniotos iš vario vielos, mechaninė apkrova, veikianti apvijas magnetinio impulso metu, yra du kartus didesnė. Daroma išvada, kad impulsinio magneto mechaniniam stabilumui, neskaitant tarpsluoksnio bei išorinio armavimo, didžiausia įtaką daro vielos mechaninės charakteristikos. Gauti rezultatai bus panaudoti magneto konstrukcijai toliau optimizuoti Il. 4, bibl. 11 (anglų kalba; santraukos anglų, rusų ir lietuvių, k.)