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The Investigation of 3D Magnetic Field Distribution in Multilayer Coils

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Introduction

Nowadays high magnetic fields are widely used for various scientific applications and very high magnetic fields with flux density up to 100 T and higher have to be generated in laboratory conditions [1]. To unsure safe and long-life operation high magnetic fields facilities are under continuous improvements. But comparing with traditional resistive magnets or superconductive magnets pulsed technologies for high magnetic field generation is very attractive because do not require great investments [2].

A relatively simple system including a capacitor bank, a pulsed switch and a pulsed coil can be used for pulsed magnetic field generation up to 50 T [3].

The parameters of generated magnetic field are strongly related with the geometry of the coils. To create a pulsed coil for special applications with required field distribution and other parameters is enough complicated task because it is hard to predict magnetic field in such a coil especially if coil configuration is far from common use. For this purpose the simulation programs are used to forecast the properties of pulsed coil [4].

Within the limitation imposed by the mechanical strength, desired peak field, pulse duration, magnetic field homogeneity should be evaluated too. Magnetic field homogeneity depends on the coil geometry. It is obvious that the larger will be the pulsed coil the lower field distortions will be achieved in working area. But due to some limits of available energy sources this way is out of interest and a lot of calculations, numerical simulations and technological improvement should be done to attach desirable results [5]. Moreover there are technical details, such as connections of power supply with winding or no predicted displacement of winding in the coil, different thickness of interlayer insulation that finally have an influence on the magnetic field magnitude in the real coil.

Despite of the progress of computing simulation direct measurements of magnetic field distribution are welcome to confirm or give up computing results. For this purpose the experimental unit for magnetic field measurements was developed and the computing simulation and experimental results were compared for two coil configurations. The possibility to build 3D magnetic field mapping for coils with different geometries is demonstrated.

Subject description

The design of the coils involves many degrees of freedom. In most pulsed power applications multilayer coils are used and the inner, outer radiuses, length of winding, pulse duration, peak magnetic field are the basic parameters for further calculations. And a lot of parameters and steps of further optimization define the final configuration of the coil. For general case magnetic field can be performed using Biot - Savart law [6].

A current loop with radius R located in *x-y* plane, centred at the origin and carried a current I in cylindrical coordinate system create magnetic field H as

$$H = \begin{bmatrix} \frac{I}{2\pi}\frac{z}{r\sqrt{(R+r)^2+z^2}}(-K(k^2))+\frac{R^2+r^2+z^2}{(R-r)^2+z^2}E(k^2) \\ 0 \\ \frac{I}{2\pi}\frac{z}{r\sqrt{(R+r)^2+z^2}}(+K(k^2))+\frac{R^2-r^2-z^2}{(R-r)^2+z^2}E(k^2) \end{bmatrix}, \qquad (1)$$

here H – magnetic field strength; z, r – axial and radial distances between the centre of a loop and the point of measurements; $K(k^2), E(k^2)$ – complete elliptic integrals of the first and the second kind when $k^2 = \frac{4Rr}{(R+r)^2+z^2}$. Formulas can be transformed to Cartesian coordinate system with $r = \sqrt{x^2+y^2}$. Magnetic field components H_x, H_y, H_z can be measured experimentally using orthogonally oriented magnetic sensors and compared with calculating results given from

$$H = \begin{bmatrix} \frac{x}{r}\frac{I}{2\pi}\frac{z}{r\sqrt{(R+r)^2+z^2}}(-K(k^2))+\frac{R^2+r^2+z^2}{(R-r)^2+z^2}E(k^2) \\ \frac{y}{r}\frac{I}{2\pi}\frac{z}{r\sqrt{(R+r)^2+z^2}}(-K(k^2))+\frac{R^2+r^2+z^2}{(R-r)^2+z^2}E(k^2) \\ \frac{I}{2\pi}\frac{z}{r\sqrt{(R+r)^2+z^2}}(+K(k^2))+\frac{R^2-r^2-z^2}{(R-r)^2+z^2}E(k^2) \end{bmatrix}. \qquad (2)$$

In case of multilayer coil construction with n turns the magnitude of resulting magnetic field strength is defined as superposition of n magnetic fields

$$|H| = \sqrt{\left(\sum_{m=1}^{n} H_{m,x}\right)^2 + \left(\sum_{m=1}^{n} H_{m,y}\right)^2 + \left(\sum_{m=1}^{n} H_{m,z}\right)^2}. \quad (3)$$

Above presented equations do not include wire diameter, thickness of insulation, out of the tolerance of winding and other important parameters completely specified a construction of real coils.

Numerical simulations based on finite element method (FEM) can introduce parameters of environment, test conditions, construction material and design features [7].

The efficiency of energy transformation in pulsed system strongly depends on coil damping factor. In variety of coil geometry coils named as Brooks coils has lowest damping factor and common used for different pulsed power applications [8]. Such multilayer coil has an inner radius $r_v = c$, outer radius $r_i = 2c$ and height c. In axial direction as well as in radial direction it has n layers. Total number of turns is $w = n^2$. The inductance and resistance of such coil can be calculated as

$$L = 2.5491 w^2 c,\ R = 3\pi \frac{w^2}{kc}. \quad (4)$$

Damping factor can be expressed as following

$$\delta = \frac{R}{L} = 3.6973 \frac{1}{kc^2}. \quad (5)$$

Here μ_0 is magnetic constant, k is coefficient depending on winding material. The design of Brooks coils is the optimal way to get the maximum inductance with the defined amount of wire. This construction also has advantages in front of other coils in mathematical simulations, because of its geometrical simplicity that can be easily defined in simulation programs.

Results of numerical simulation

One of common used configurations of multiplayer coils close to Brooks coil configuration has been chosen for numerical simulation and is shown in Fig. 1.

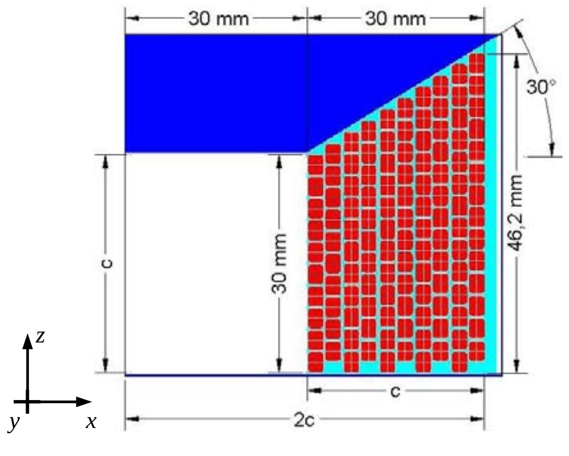

Fig. 1. Cross-section of multilayer coils for numerical simulation

In our experiments such construction of pulsed coil had 10 layers and 100 turns of copper wire in total. Components of magnetic field strength have been numerically simulated and are shown in Fig. 2.

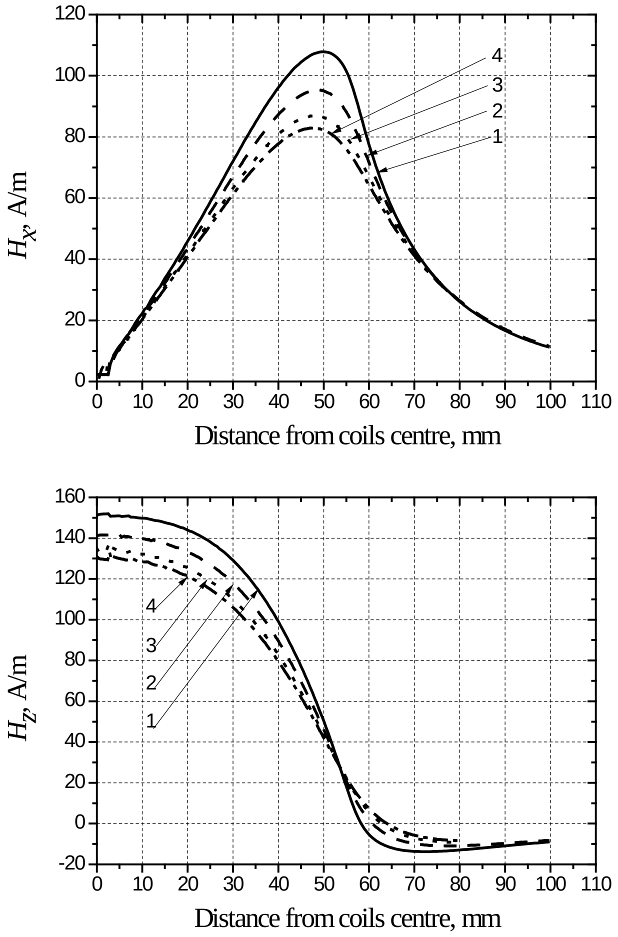

Fig. 2. Results of numerical simulation of H_x, H_z components: 1 – results of basic FEM model, 2 – influence of non-rectangle wire cross-section, 3 – influence of real geometrical parameters of wire, 4 – influence of thickness of interlayer insulation

As was expected the significant differences take place when additional parameters characterizing coil construction as wire cross-section, thickness of interlayer insulation were introduced into coil numerical model. Therefore every time starting the numerical simulation it is necessary to specify an acceptable tolerance of expected results because addition parameters complicate calculations and the model finally will loose flexibility.

Experimental results

The experimental equipment for investigations of magnetic field distribution was built up. Such equipment allows to map a magnetic field at any point, over any surface moving a 3-axis magnetic probe through a three dimensional volume while measuring the three orthogonal components of magnetic field at designated points and magnetic field profile can be plotted. Measurements of the Cartesian components of magnetic field strength can be executed by the application of three orthogonal arranged magnetic field sensors witch being capable of incremental three-axis motion by virtue of linear actuators on each axis. A PC controls the whole experimental setup. The control algorithm for automatic measurements was developed using programming package *LabView*®. The structure of such experimental equipment is shown in Fig. 3.

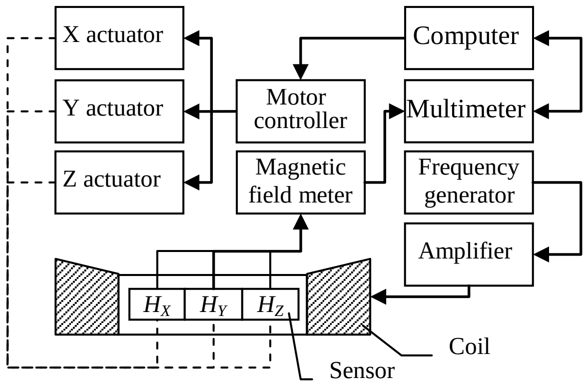

Fig. 3. The structure of experimental equipment for investigation of magnetic field distribution

A frequency generator and an amplifier are used as a power supply to feed a pulsed coil instead of pulsed generator. Such method is enough advantageous. Magnetic field measurements that are lasting only a few milliseconds make it really difficult to insure the same conditions for long time repetitive experiments. In our case sinusoidal current generates stable 1 kHz magnetic flux in the coil. For general case frequency of the generator can be adjusted and it is chosen close to expected transient processes of pulsed coil feeding from capacitor bank.

Applied magnetic field probe consists of three Wheatstone bridges made from 12 magneto-resistive sensors and is shown in Fig. 4.

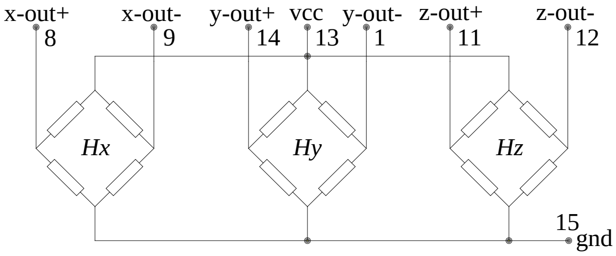

Fig. 4. The structure of 3D magnetic field probe

Such magnetic field probe is enough sensitive and can measure magnetic flux density up to 8,5 mT and it usually is used to measure the distribution of magnetic field on Earth surface. Therefore designed experimental equipment is able to detect very low magnetic fields and allows investigating the influence of power supply connections, winding configuration, wire cross-section, thickness of interlayer insulation and other design parameters on magnetic field in pulsed coils. For each step of measurements a distance from the coil centre to magnetic field probe was enlarged by 5,0 mm discretely and components of magnetic field strength H_x, H_y, H_z were measured experimentally.

In Fig. 5 results of magnetic field strength measurements are shown.

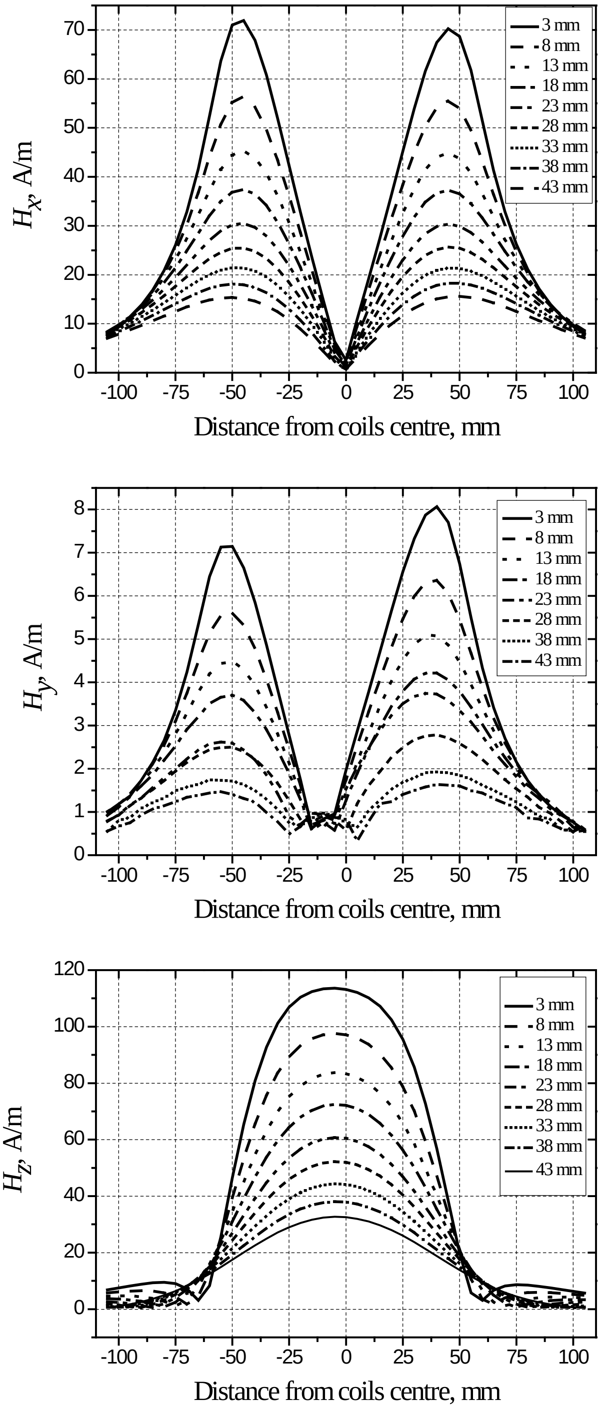

Fig. 5 Experimental results of H_x, H_y, H_z measurements using 3D magnetic field meter

Magnetic field strength H_x is maximal in the windings and close to zero in the centre of the coil. The current in opposite parts of winding flows in different direction and magnetic field in opposite parts of winding contrary as shown should be opposite too. It takes place because output signal of applied magnetic field meter always is positive independently of field direction.

Magnetic field strength H_z is maximal in the middle point of the coil and exponentially decreasing outside of the coil. Experimentally magnetic field strength H_y was given too. But a significant mismatch of obtained results took place in experiments and to be analyzed later. Probably coils winding was far from ideal and various technological limits did not allow making turns with expected configuration especially in places when feeding cables are connected. Moreover power cables generating proper magnetic field can significantly distort initial field distribution in the coil. Therefore described factors should be taken into consideration in further model improvements and experiments.

Conclusions

The experimental equipment for investigations of magnetic field distribution was build up and investigation of magnetic field distribution in multiplayer coils has been performed. Finite elements method was used for numerical simulation of orthogonal components of magnetic field strength and significant difference took place when additional physical parameters as wire shape, winding cross-section and thickness of interlayer insulation were introduced into the numerical model. The experimental equipment is able to map a magnetic field at any point over any surface moving a three-axis magnetic probe through a three dimensional volume while measuring the three orthogonal components of magnetic field strength at designated points and magnetic field profiles can be plotted. Numerical model was verified experimentally and acceptable compliance (error less than 20 %) of experimental and simulated results was achieved. Obtained results have been applied for further coils design.

Acknowledgments

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The investigation of magnetic field distribution via *x-y-*z directions of multilayer coils has been carried out. Finite elements method was used for numerical simulation of magnetic field components. The model was verified experimentally using experimental PC controlled equipment. The control algorithm for automatic measurements was developed using *LabView*® programming package. It allows to map a magnetic field at any point over any surface moving a 3-axis magnetic probe through a three dimensional volume while measuring the three orthogonal components of magnetic field strength at designated points and magnetic field distribution profiles can be plotted. The experimental and simulation results were compared and acceptable compliance has been achieved. The results provide a possibility to forecast parameters of multilayer coils avoiding expensive and long lasting experiments. Ill. 5, bibl. 8 (in English; abstracts in English, Russian and Lithuanian).

А. Грайнис, Ю. Новицкий. Исследование 3D распределения магнитного поля в многослойных катушках // Электроника и электротехника. – Каунас: Технология, 2010. – № 7(103). – С. 9–12.

Представлены результаты исследования распределения магнитного поля многослойной катушки в ортогональной *x-y-z* системе координат. Компоненты напряженности магнитного поля были найдены путем численного моделирования, используя метод конечных элементов. Для проверки результатов моделирования создана автоматизированная, управляемая компьютером установка. Алгоритм управления написан, используя программный пакет *LabView*®. Установка путем перемещения системы из трех ортогональных датчиков поля, позволяет в заданном пространстве экспериментально установить распределение напряженности магнитного поля. Результаты численного эксперимента сравнивались с результатами физического эксперимента и достигнуто приемлемое соответствие результатов, что позволяет использовать предложенную методику при проектировании конструкции многослойных катушек. Ил. 5, библ. 8 (на английском языке; рефераты на английском, русском и литовском яз.).

A. Grainys, J. Novickij. Daugiasluoksnių ričių 3D magnetinio lauko pasiskirstymo tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 7(103). – P. 9–12.

Pateikta daugiasluoksnės ritės magnetinio lauko pasiskirstymo *x-y-z* koordinačių sistemoje analizė. Taikant baigtinių elementų metodą buvo atlikta skaitinė imitacija magnetinio lauko pasiskirstymui nustatyti. Rezultatams patvirtinti buvo sukurtas kompiuterio valdomas eksperimentinis stendas. Stendo valdymo algoritmas parašytas *LabView*® programinio paketo aplinkoje. Matavimo stendas su erdvėje judančiu x-y-z magnetinio lauko jutikliu įgalina išmatuoti magnetinio lauko pasiskirstymą tam tikroje erdvėje. Eksperimentiniai rezultatai buvo lyginami su skaitmeniniais ir pasiektas pakankamas rezultatų tikslumas. Pasiūlyta modelį bei gautus rezultatus taikyti daugiasluoksnių ričių konstrukcijos analizei ir projektavimui. Il. 5, bibl. 8 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).

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