The influence of pulsed magnet heating on maximal value of generated magnetic field

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Abstract. *The influence of pulsed magnet heating on maximal value of generated magnetic field is described. The operation of pulsed generator consisted of capacitor bank, thyristor switch and wire wound pulsed inductor is analyzed. The maximum value of generated magnetic field and pulse duration of pulsed magnet is limited by Joule heating and mechanical stresses. Using Matlab Simulink software the flexible model for simulation of thermodynamic processes in pulsed magnet is done. Calculated results of maximal value and distribution of magnetic field are verified experimentally and the acceptable compliance is achieved using calibrated array of four pick up inductive coils for measurements of axial magnetic field and a current shunt for pulsed current measurements.*

Keywords: pulsed magnetic field, wire wound magnet, Joule heating, pick up inductive coil

1. Introduction

Recently pulsed magnets are used in many scientific laboratories for fundamental and technological investigations. For this purpose the system consisting of capacitor bank, thyristor switch and wire wound coil is most acceptable due to the progress that has been done in generator design [1]. Compact non-expensive reliable energy storage banks with adjustable energy value by the manipulation of charged voltage can be constructed using modern capacitors. In spite of alternative methods of energy storage capacitor banks of 50-100 kJ with operation voltage 3-5 kV is the most attractive way to construct pulsed generators for daily experimentation. The same can be declared regarding thyristor switches applicable in pulsed generators. Modern thyristors are able to switch current in order of 50 kA in single mode operation, they are enough reliable, not noisy and assure good signal synchronization. Moreover they can be connected in series and parallel to increase values of operational voltage and current [2]. Most critical part of pulsed magnetic field generator is a pulsed inductor. Pulsed inductor operates under heavy conditions due to induced mechanical, thermal and electrical overloads. Pulsed inductors are made like a multilayer wire wound coil with internal and external reinforcement. Such construction ensures sufficient long life operation and magnetic field homogeneity that is acceptable for carrying out qualitative measurements. During operation huge current induces the Joule heat in a coil winding and operation temperature increases rapidly [3]. It influences the mechanical and electrical properties of applied materials. Pulsed coils have to be pre-cooled with liquid nitrogen to avoid critical thermal overloads which follow further coil disintegration. The design of non-destructive pulsed coils is a complicated technical problem and the complex analysis of construction should be done to ensure a long term coil operation [4].

In present article the analysis of thermodynamic processes using Matlab Simulink software was accomplished and coil heating influence on generated magnetic field was analyzed.

2. Subject and Methods

The simplified structure of pulsed magnetic field generator consists of capacitor bank, switch and pulsed coil. Self inductance, resistance of capacitor bank, thyristor switch and connectors are not taken into consideration and an equivalent circuit of wire wound coil is like an inductance and resistance connected in series. Therefore energy transformation equation looks as following:

$$CU^2/2 = LI^2/2 + I^2Rt \tag{1}$$

It means that the efficiency of the energy transformation strongly depends on active losses in the pulsed coil. It is evident that the best choice of a material for winding would be the best conductor. Unfortunately convenient winding materials with good conductivity like cooper, aluminium are not mechanically strong and are out of the application in magnetic fields exceed 25-30 T limit . Therefore some compromise should be done to find the optimal ratio between conductivity and mechanical strength. Last time micro-composite materials like Cu-Nb, Cu-Ag combined a good conductivity and mechanical strength were developed and applied in pulsed coil design. Such pulsed magnets were produced like a multilayer wire wound coil put in a steel or composite container. The operation cycle of a pulsed coil consists of 20-30 minutes of coil cooling with further rapid discharge during few milliseconds. Therefore coil heating is close to adiabatic process. The heating process of multilayer construction can be treated as heating of separate layers and estimated like

$$\begin{aligned} dQ_n &= I^2 \cdot R_{Cu} \cdot dt; \quad R_{Cu} = R_{Cu}(T); \\ dT_n &= \frac{dQ_n}{m_n \cdot c_{Cu}}; \quad c_{Cu} = c_{Cu}(T). \end{aligned} \tag{2}$$

Temperature distribution of six layer Cu-Nb wire wound coil insulated with glass fibre and enforced with Zylon is shown in Fig. 1.

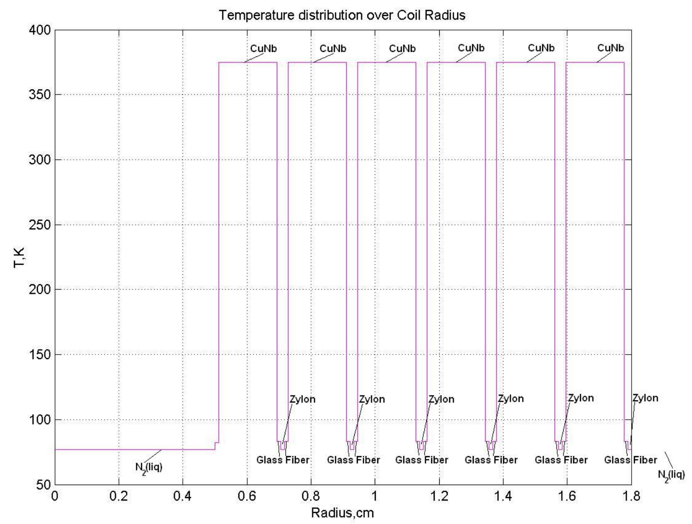


Fig.1. Temperature distribution over coil radius (I = 12,8 kA, t = 3 ms)

Pulsed coil resistance strongly depends on temperature. Therefore calculating the current values this fact has to be taken into consideration. Generated magnetic field B in central area can be calculated by the formula

$$B = \mu_0 \frac{NI}{a_1}\left[\frac{F(\alpha,\beta)}{2\beta(\alpha-1)}\right]. \qquad (3)$$

where μ_0 is the magnetic constant, N is the quantity of turns, I is the current, a_1, a_2, $2b$ are internal, external radius and length of the solenoid respectively, $\alpha = a_1/a_2$, $\beta = b/a_1$ are relative sizes and $F(\alpha,\beta) = \beta \ln\frac{\alpha+\sqrt{\alpha^2+\beta^2}}{1+\sqrt{1+\beta^2}}$ is a form factor of the solenoid. The maximal value of pulsed current can be found from differential equation $L\frac{d^2 I}{dt^2} + R(T)\frac{dI}{dt} + \frac{1}{C}I = 0$ for every time moment like $I = \frac{U}{\omega L}\exp(-\gamma t)\sin(\omega t)$.

There $\gamma = \frac{R}{2L}$ is damping factor of the circuit, $\omega = \sqrt{\omega_0 - \gamma_2}$ describes circuit's oscillation frequency with losses, $\omega_0 = \frac{1}{\sqrt{LC}}$ is oscillation frequency in lossless circuit. During discharge the pulsed coil is heated and the resistance R has a non-linear dependability on temperature. Using Matlab Simulink software the simulation of maximal value pulsed current was done and is shown in Fig.2

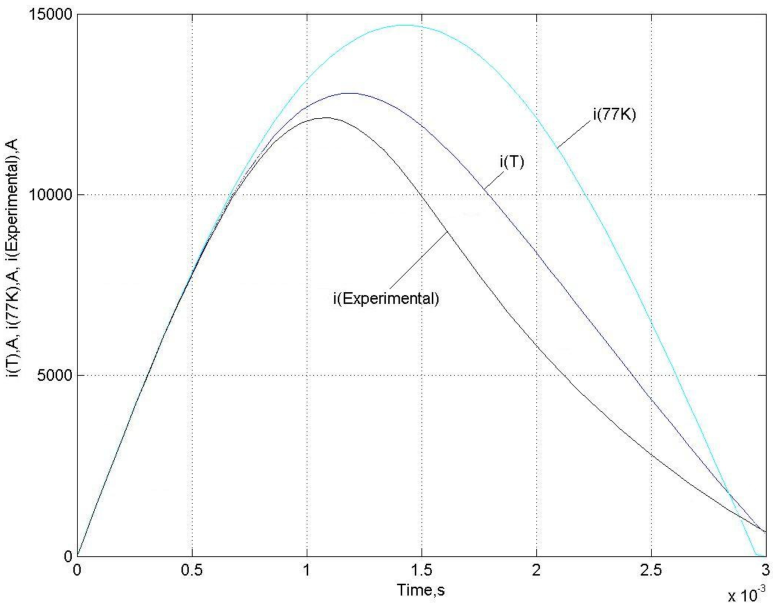
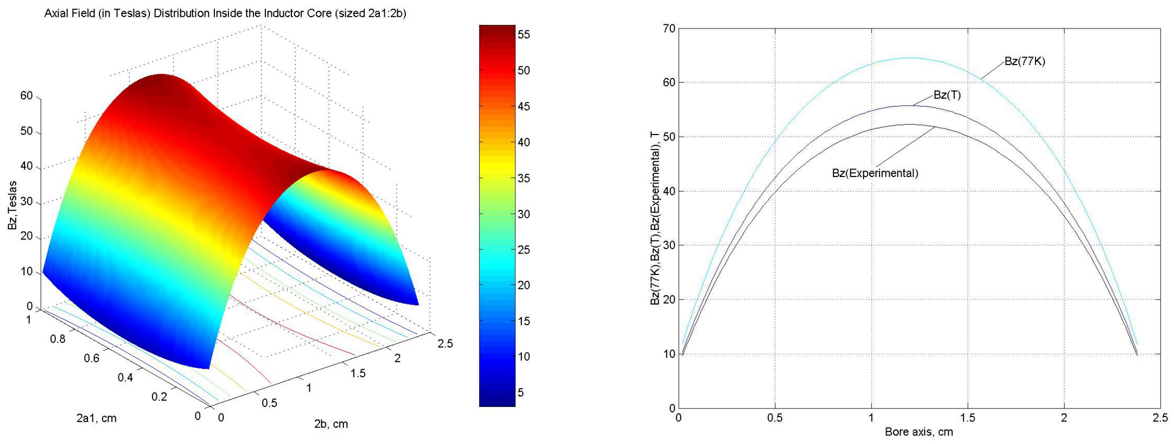


Fig.2. Current pulses without, with Joule heating and measured respectively

Simulated results of pulsed current were verified experimentally using a current shunt connected in series with tested pulsed coil. The distribution of axial magnetic field was simulated also and is shown in Fig.3(a). The distribution of axial magnetic fields along the inductor axis simulated without and with Joule heating was verified experimentally using calibrated array of four pick up inductive coils and a multi channel digital memorised oscillograph for the pulse registration and it is shown Fig.3(b).



(a) (b)

Fig.3. Distribution of axial magnetic field in inductor bore (a) and distribution of experimentally measured and simulated magnetic fields along inductor bore (b)

Measurements were done at the temperature close to liquid nitrogen temperature. The array of pick up inductive coils was positioned in central area of the coil and it was shifted discretely to apply magnetic field distribution. The difference between simulated and measured results was about 10% and can be acceptable for most applications. It was difficult to repeat identical experimental conditions for series of experiments due to thermal, mechanical and electrical overloads that take place in pulsed magnet. Therefore the application of the array of four identical sensors in order to measure magnetic field distribution during one experiment was very useful.

3. Results and conclusions

The analysis and data simulation using Matlab Simulink software were done. Due to Joule heating the temperature inside the coil generating magnetic pulses of 50 T order can increase up to 300 degrees and more during few milliseconds and this can lead to dramatic change of material properties and coil failure. Furthermore, the resistance increment diminishes the current and generated magnetic field is 10-15% lower than in ideal conditions. Due to adiabatic character of heating process the increase of thermal capacity with coil pre-cooling can protect it from the thermal failure. Further improvements of applied model have to be done to increase the compliance between calculated and measured results.

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