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The Influence of Pulsed Magnet Heating on Maximal Value of Generated Magnetic Field

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The influence of pulsed magnet heating on the maximal value of the generated magnetic field is described. The operation of pulsed generator consisting of a capacitor bank, thyristor switch and wire wound pulsed inductor was analysed. The maximum value of the generated magnetic field and pulse duration of pulsed magnet was limited by Joule heating and mechanical stresses. Using *Matlab*® *Simulink*® software, a flexible model for simulation of thermodynamic processes in pulsed magnet was developed. The calculated results of the maximal value and distribution of magnetic field were verified experimentally and acceptable compliance was 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 have been used in many scientific laboratories for fundamental and technological investigations. For this purpose, the system consisting of a capacitor bank, thyristor switch and wire wound coil is most acceptable due to the progress achieved 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 are the most attractive systems for the construction of pulsed generators for daily experimentation. The same can be stated for thyristor switches applicable in pulsed generators. Modern thyristors can switch current in the order of 50 kA in single mode operation, they are reliable enough, not noisy and provide good signal synchronization. Moreover, they can be connected in series and parallel to increase values of operational voltage and current [2]. The 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 as a multilayer wire wound coil with internal and external reinforcement. Such construction ensures sufficiently long life operation and magnetic field homogeneity acceptable for carrying out qualitative measurements. During the operation huge current induces the Joule heat in a coil winding and the 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 resulting in further coil disintegration. The design of non-destructive pulsed coils is a complicated technical problem and a complex analysis of construction should be performed to ensure a long term coil operation [4]. Electromagnetic, thermodynamic, mechanical processes taking place during pulsed coil's operation have been analysed by different rules [5, 6].

The present article reports the results of an analysis of thermodynamic processes using *Matlab*® *Simulink*® software and coil heating influence on the generated magnetic field.

2. SUBJECT & METHODS

The simplified structure of a pulsed magnetic field generator consists of a capacitor bank, switch and pulsed coil. Therefore, the simplest energy transformation equation would be the following:

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

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, such as copper or aluminium, are not mechanically strong and are out of the application in magnetic fields exceeding 25-30 T limit. Therefore, a compromise should be made to find the optimal ratio between conductivity and mechanical strength. Micro-composite materials, such as Cu-Nb or Cu-Ag, combining good conductivity and mechanical strength, were developed and applied in pulsed coil design. Such pulsed magnets were produced as 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 a few milliseconds. Therefore coil heating is close to adiabatic process and the evaluation of heat dissipation to layers (insulation, reinforcement) surrounding the conductive wire is not needed. The heating process of multilayer construction can be treated as heating of separate layers.

Knowing the measured (experimental) and simulated results and comparing them, the best numerical solution could be found. which could later be used to determine heating influence on the amplitude of the generated magnetic field in any coil. The model for the determination of current and magnetic field pulse transient processes was designed using electrical circuit which consists, as mentioned, of a capacitor bank, thyristor switch, line cables and an inductor (pulsed coil) itself connected in series. The diagram of such circuit is shown in Fig.1.

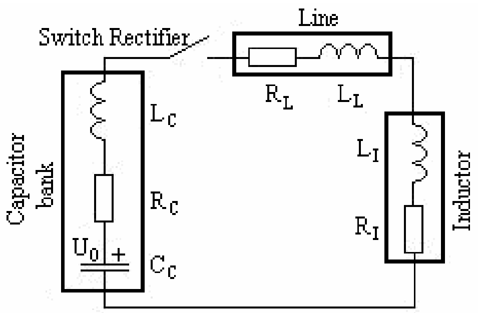

Fig 1. Pulsed inductor control circuit.

Parameters L_C, R_C, were not taken into account, while line cables were considered to be very short (inductor is very close to the capacitor bank's output leads), therefore parameters $L_L, R_L \to 0$. On the other hand, pulsed coil parameters L_I, R_I are more significant than L_C, R_C and L_L, R_L for most real applications (equation (1)).

C_C is the capacitor bank capacitance, charged to a voltage U_0. The discharge of the capacitor bank through the inductor could be defined according to the second Kirchhoff's law for the circuit when the SCR is on:

$$U_0 = R_I i(t) + L_I \frac{di(t)}{dt} + \frac{1}{C_C} \int i(t)dt. \qquad (2)$$

The Laplace transformation for the equation given above is:

$$U_0(s) = R_I I(s) + L_I sI(s) + \frac{I(s)}{C_C s}. \qquad (3)$$

Having $U_0(s)$ as an input and circuit current $I(s)$ as an output for magnetic field calculation we obtain a transfer function in a form:

$$W_{Circuit}(s) = \frac{I(s)}{U_0(s)} = \frac{\frac{1}{L_I s + R_I}}{1 + \frac{1}{(L_I s + R_I)} \frac{1}{C_C s}}. \qquad (4)$$

The obtained transfer function corresponds to the model created in *Matlab® Simulink®* and is shown in Fig.2.

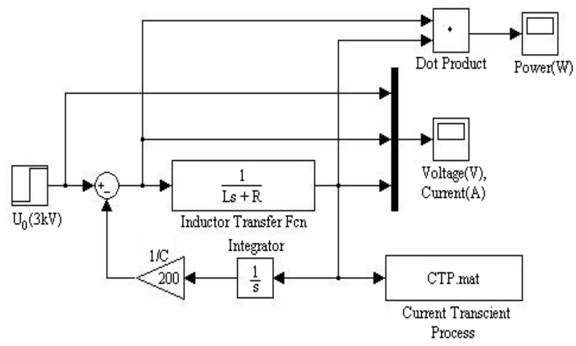

Fig 2. Inductor control circuit *Matlab® Simulink®* model for capacitor bank charged to U_0=3 kV, C=5 mF.

The presented model is controlled by the author's program. Having initial geometrical (size ratios, wire mass parameters, layers' parameters) and electrical (specific resistivity, resistance, inductivity, etc.) inductor parameters, the maximal value of the current pulse, magnetic pulse and magnetic field distribution can be given. The simulation for every time moment recalculating Joule heating, temperature and resistance (specific resistance) increase are performed.

First of all, basic inductor geometrical (inner radius a_1, outer radius a_2, inductor length $2b$, size ratios $\alpha = a_2 / a_1$, $\beta = b / a_1$ filling factor λ, number of wounds per layer n_1, number of layers n_2, total number of wounds N, resistivity ρ as well as form factor $F(\alpha, \beta)$ and starting temperature T_0) parameters must be given. Using these, other essential parameters, such as inductor wire length l, inductance L and initial wire resistance R are calculated [8]:

$$L = a_1 \frac{\mu_0 \pi (\alpha + 1)^2}{8\beta} N^2 F(\alpha, \beta); \qquad (5)$$

$$R = \frac{\pi \rho(T) N^2 (\alpha + 1)}{2 a_1 \lambda \beta (\alpha - 1)}. \qquad (6)$$

Using the glass fibre wire isolation and one *Zylon®* layer for reinforcement technology for n_2 wiring layers we obtain $4n_2$ layers for inductor's cross-section if the metal reinforcement container is not considered. The mass m (the density must be given for wire material) and specific heat c are calculated for each layer in order to evaluate the temperature increase during the pulse. The parameter c, as known, is unique for every material and is dependent on temperature as well.

The program runs the simulation, records the current transient and, using the current value $i[N]$ at the time moment $t[N]$, calculates Joule heating and temperature increment for each wire layer:

$$dQ_j = i^2[N]R_j dt;$$
$$c_j = c_j(T); \quad (6)$$
$$dT_j = \frac{dQ_j}{m_j c_j}.$$

Finally, the specific resistance $\rho_j = \rho_j(T)$ and resistance $R_j \sim \rho_j$ for each wire layer are calculated and used for another simulation. The cycle is repeated until current impulse value diminishes to 1% of its maximum.

The change of the resistance influences the current value for the time moment $N+1$ and the duration of the current impulse completely changing the current transient process and achieved magnetic field maximum.

The temperature distribution of a six-layer Cu-Nb wire-wound coil insulated with glass fibre and enforced with *Zylon®* is shown in Fig.3.

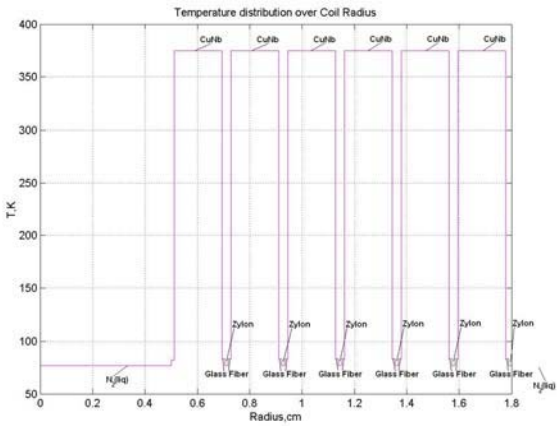

Fig.3. Temperature distribution over coil radius (I = 12,8 kA, t = 3 ms).

The generated magnetic field B along the inductor's axis, when the current value is known, can be calculated using the formula

$$B = \mu_0 \frac{NI}{a_1}\left[\frac{F(\alpha,\beta)}{2\beta(\alpha-1)}\right], \quad (7)$$

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 radii 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 former mentioned form factor of the solenoid. The maximal value of pulsed current can be found from differential equation (3) for every time moment. Its analytical form would be $I = \frac{U}{\omega L}\exp(-\gamma t)\sin(\omega t)$. There $\gamma = \frac{R(T)}{2L}$ 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.

The above mentioned real current pulse form solution to determine its maximum is not that easy to be found analytically because of non-linearity of resistance $R(T)$ and therefore the modelling would be a more appropriate way to do this.

During the discharge the pulsed coil is heated and the resistance R has a non-linear dependability on temperature. Using the software package described above, the simulation of the maximal value pulsed current was done and is shown in Fig.4.

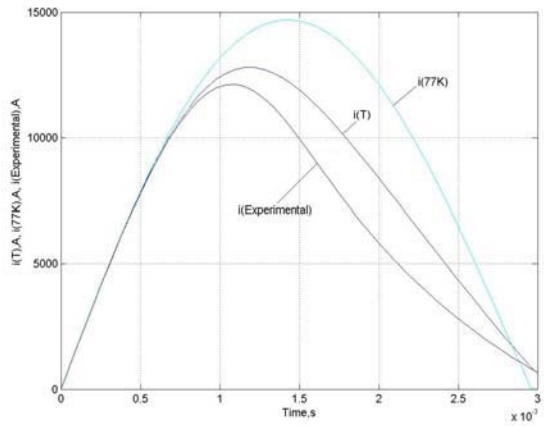

Fig.4. Current pulses without, with Joule heating and measured respectively.

The simulated results of pulsed current were verified experimentally, using a current shunt connected in series with the tested pulsed coil. The distribution of axial magnetic field was simulated also and is shown in Fig.5.

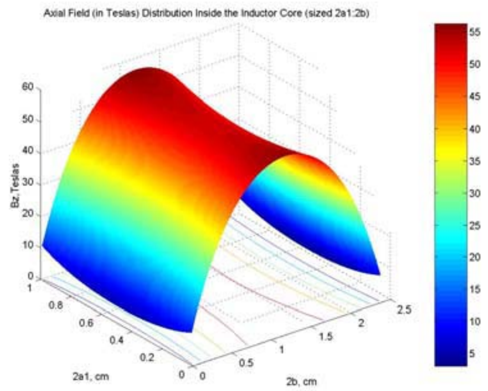

Fig.5a Distribution of axial magnetic field in inductor bore.

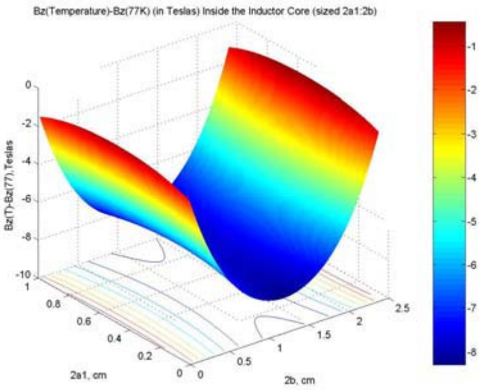

Fig. 5b Difference between the actual magnetic field and the field where Joule heating is not taken into account.

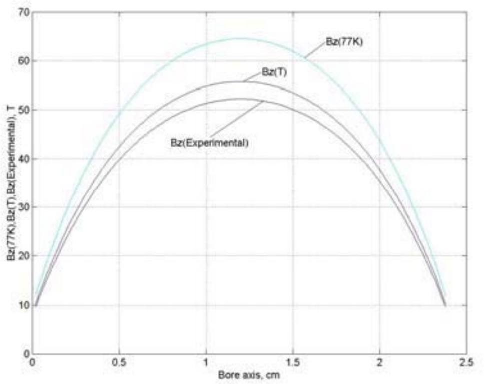

Fig.6. Distribution of experimentally measured and simulated magnetic fields along inductor bore.

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 are shown in Fig.6.

The measurements were performed at the temperature close to liquid nitrogen temperature (same temperature was used in simulations). The array of pick up inductive coils was positioned in the central area of the coil and it was shifted discretely to apply the 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 the thermal, mechanical and electrical overloads taking place in the pulsed magnet. In order to measure the magnetic field distribution during one experiment, the application of the array of four identical sensors was very useful.

3. Results

The analysis and data simulation using *Matlab® Simulink®* software were performed. Due to Joule heating, the temperature inside the coil generating magnetic pulses of 50 T order can increase up to 300 degrees or over during a few milliseconds and this can lead to a dramatic change of material properties and coil failure. Furthermore, the resistance increment diminishes the current and the generated magnetic field is by 10-15% lower than under ideal conditions.

4. Discussion/Conclusions

Due to adiabatic character of the heating process, the increase of thermal capacity with coil pre-cooling can protect it from thermal failure. A liquid nitrogen environment, as mentioned above, is usually used for this purpose. Further improvements of the applied model have to be done to increase the compliance between the calculated and measured results.

Acknowledgment

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