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The Investigation of Thermodynamic Processes in Pulsed Coils with Crowbar Circuit

S. Bartkevičius, J. Novickij
Department of Electrical Engineering, Vilnius Gediminas Technical University,
Naugarduko str .41, LT-03227, Vilnius, Lithuania, phone: +370 52 744762; e-mail: elektrotechnika@el.vgtu.lt

Introduction

Nowadays pulsed power technologies have become top interest for engineering and the development of high magnetic field facilities is increased very much. Pulsed magnets are effective tools in many fields of applied sciences and a lot of unique investigations are done in solid state physics, biology, electronics and other technological sciences [1].

For scientific investigations, especially in the field of applied physics and electronics it is necessary to have compact, secure pulsed power magnetic field generators, which can be easily used under laboratory conditions. For this purpose the system consisting of capacitor bank, high power thyristor switch and reinforced wire wound pulsed coil is most acceptable [2, 3].

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 50-200 kJ with operation voltage 3-10 kV is the most attractive way to construct pulsed generators for daily experimentation. Discharging the energy bank by thyristor switch through the pulsed coil a half-sinus shape pulse of magnetic field pulse up to 50 T and 1-10 ms in duration can be generated. Modern commercially available thyristors able to switch current in order of 50 kA in single mode operation and they are enough reliable, not noisy and assure good signal synchronization [4].

Most critical part of pulsed magnetic field generator is a pulsed coil. New constructing materials as polyamide and glass fibres, Cu-Ag, Cu-Nb microcomposite wires are applied in pulsed coil construction. Winding insulation using modern material like *Kapton*®, with further reinforcement with *Zylon*®, carbon fibre composites allows constructing non-destructive pulsed coils for magnetic field generation in the range of 50 T, where usual materials are out of the application due to destructive overloads [5].

The design of non-destructive pulsed coils is a complex technical problem requiring the analysis of multiphysical phenomena because coils operate under very heavy mechanical, thermal and electrical overloads occurring due to Lorence force and Joule heating [6]. Electrically, a pulsed coil is just a heater. During operation huge current induces the Joule heat in a coil winding and operation temperature increases very much. Rapid heating during pulsed coil operation leads to changes of electrical properties of applied materials. Moreover coil heating is close to adiabatic process and dissipation of heat is insignificant. Coil heating strongly influences the maximum value of generated magnetic field and the overheating can damage interlayer insulation. Pulsed coils have to be pre-cooled with liquid nitrogen to avoid critical thermal overloads which follow further coil disintegration. Thermal capacity of windings could be also increased constructively using a wire with greater cross-section [7].

The progress in computing technologies is resulted in fast development of numerical methods and computational technologies for multi-physical phenomena, including coupled fields and thermal effects as well [8].

Simulation involves the solution of linear or non-linear partial differential equations and various coupling mechanisms, such as magnetic field with electrical circuits, thermo-electro-magnetic field coupling, thermo-electro-structural analysis, electromagneto-thermoelasticity and multiphase flows can be analyzed successfully.

The possibility to use powerful hardware and software for data simulation of designed pulsed coils allow to analyze electromagnetic, thermodynamic, mechanical processes improving the construction, predicting available failures, increasing the efficiency of energy transformation [9, 10].

In present article thermodynamic processes taking place in pulsed coils with crowbar circuit were investigated. Process modelling was carried out using *Matlab*® *Simulink*® software. Usually crowbar circuit is connected in parallel with pulsed coil and used to increase magnetic field pulse duration.

In our research crowbar circuit consisted of high power diode and resistive ballast was applied to cut a pulse after maximum of current was reached. By such way thermal overloads of winding were decreased significantly and better reliability of pulsed coils could be forecasted.

Model description

The common structure of pulsed magnetic field generator consists of capacitor bank, switch and pulsed coil itself connected in series. In addition a crowbar circuit is connected with a pulsed coil in parallel as shown in Fig.1.

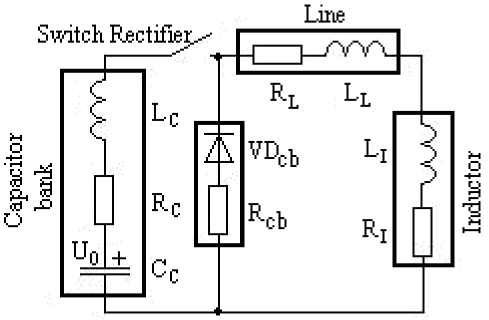

Fig. 1. Pulsed inductor control circuit with crowbar

Over the negligibility of self inductance and resistance L_C, R_C of capacitor bank, thyristor switch and connectors L_L, R_L these parameters are not taken into consideration in circuit model. It is specified using capacitance of capacitor bank C_C, pulsed coil inductance and resistance L_I, R_I and resistance of crowbar ballast R_{cb}. Diode VD_{cb} is idealized here to work simply as a switch element to shorten the circuit when adequate voltages are applied to its terminals. Capacitor bank is charged to a voltage U_0.

The analysis of transient processes can be divided into two processes before and after current will reach a maximum at moment t_M and therefore the following equations are given:

$$
\begin{aligned}
&t = [0 \div t_M] \rightarrow U_0 = R_I i(t) + L_I \frac{di(t)}{dt} + \frac{1}{C_C}\int i(t)dt,\\
&t = [t_M \div 0] \rightarrow 0 = L_I \frac{di(t)}{dt} + (R_{cb} + R_I) i(t).
\end{aligned}
\tag{1}
$$

Laplace transformation for equations given above is:

$$
\begin{aligned}
&U_0(s) = R_I I(s) + L_I sI(s) + \frac{I(s)}{C_C s},\\
&0 = L_I sI(s) + (R_{cb} + R_I) I(s).
\end{aligned}
\tag{2}
$$

Having $U_0(s)$ as an input and circuit current $I(s)$ as an output for magnetic field and heating calculation we obtain transfer functions that correspond to the model built in *Matlab*® *Simulink*® and shown in Fig. 2. This model doesn't differ from the one given in [7], just after $t = t_M$, element C_C is excluded and by means of programming the modeling environment is switched to another model that is shown in Fig. 3. U_0 falls immediately to 0 V because the capacitor bank is disconnected from the circuit.

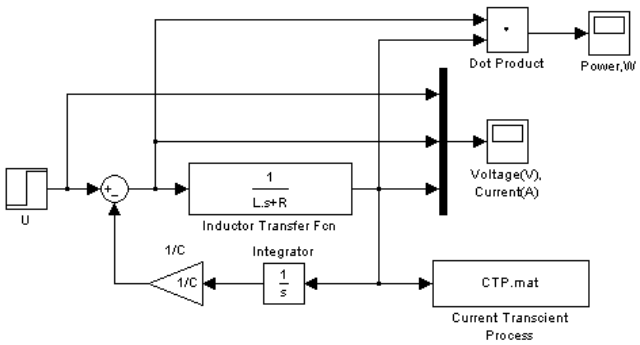

Fig. 2. Inductor control circuit *Matlab*® *Simulink*® model for capacitor bank charged to U_0=3 kV, C=10,8 mF

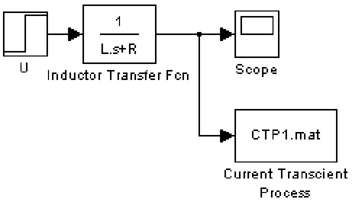

Fig. 3. Circuit model after disconnecting capacitor bank

The model is controlled by specially written program. Having initial coil geometrical parameters as coil size ratios, layers parameters, wire mass parameters and electrical parameters as specific resistivity, resistance, inductivity the maximal value of current pulse is given. The simulation for every time moment recalculating the Joule heating, heat dissipation, temperature and resistance (specific resistance) increase are performed. All the data is recorded and can be analyzed in many different ways. The approach is flexible and universal because it is fully programmable and is not limited for one specific operation.

The first law of thermodynamics and Fourier's law of heat conduction describe thermal fields. Neglecting velocity for the mass transport of heat the parabolic equation of temperature conduction is considered [11]:

$$
\rho c(T)\frac{\partial T}{\partial t} - \nabla \cdot [\mathbf{K}(T)]\nabla T = \hat{q}, \tag{4}
$$

here T – the temperature; ρ – the density; $c(T)$ – specific heat, which might depend on the temperature; $[\mathbf{K}(T)]$ – conductivity matrix which might be ortothropic or temperature dependent; $\hat{q}$ – heat generation rate per unit volume. It is assumed that all effects are in the Cartesian reference frame, where ∇ represents the gradient and $\nabla\cdot$ represents the divergence operator. The equation is non-linear and requires iterative solution procedure. In some cases specific heat $c(T)$ and conductivity $K(T)$ can be assumed constant and results of linear thermal analysis can be sufficiently accurate. The detailed description for iterative control of such models for thermodynamic processes calculation when elements mentioned above as well as circuit resistances (R_I, R_{cb}) are dependent on temperature can be found in [7].

Numerical simulation

For the numerical simulation a prototype of 50 T class pulsed coil was chosen. The winding had 12,0 mm inner, 38,0 mm outer diameters and it was 48,0 mm in length. A construction consisted of 4 layers (10 turns in each layer) of Cu-Nb micro-composite wire (4,2 mm x 2,37 mm, 65 % IACS, UTS = 1,2 GPa). Every turn is insulated with *Kapton*® film, wet impregnated and reinforced with *Zylon*® epoxy resin composite and finally put into external maraging steel cylinder. A cross-section of pulsed coil is shown in Fig. 4.

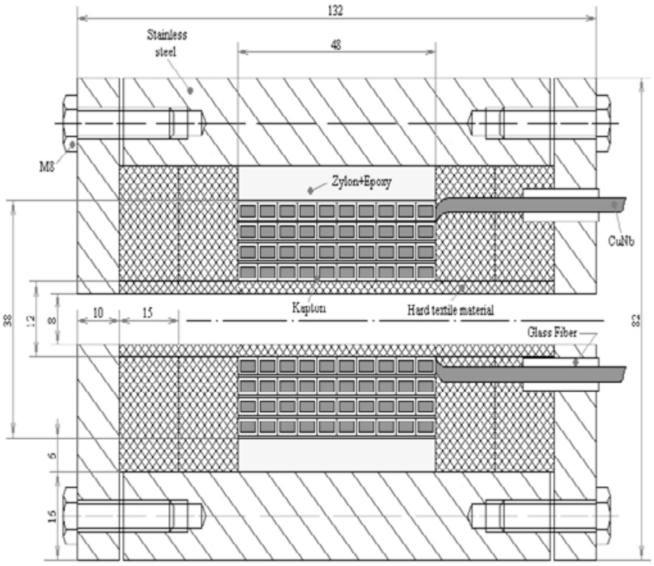

Fig. 4. A cross-section of pulsed coil

All simulations were done for coil operation at initial 293 K temperature. Capacitor bank of total capacity of 10800 μF was charged up to $U_0 = 3\ \text{kV}$. Calculated electrical parameters for pulsed coil were $R(293\text{K}) = 0{,}0093\,\Omega$, $R(77\text{K}) = 0{,}002\,\Omega$, $L = 12{,}2\ \mu\text{H}$.

Results of numerical simulation of current transient processes in pulsed coil with crowbar circuit are shown in Fig. 5.

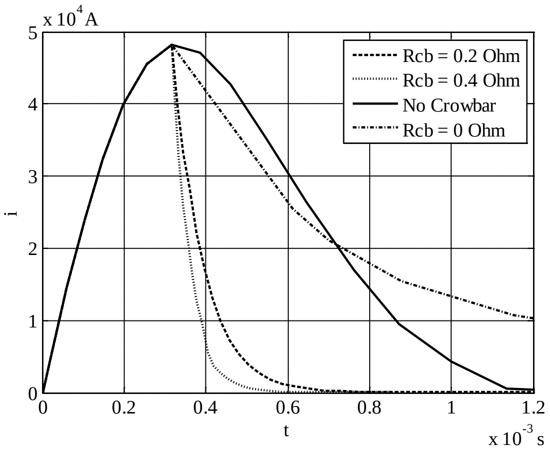

Fig. 5. Current transient processes in pulsed coil with crowbar circuit operated initial at 293 K temperature

For most experiments with pulsed magnetic field a rise time of pulse and a maximum of amplitude are important. The application of crowbar strongly influences on transient processes in the circuit. Depending on resistance of crowbar resistive ballast a fall time of generated pulse has changed at wide range. As a result a temperature transient process in Cu-Nb windings of described pulsed coil has changed too and shown in Fig. 5.

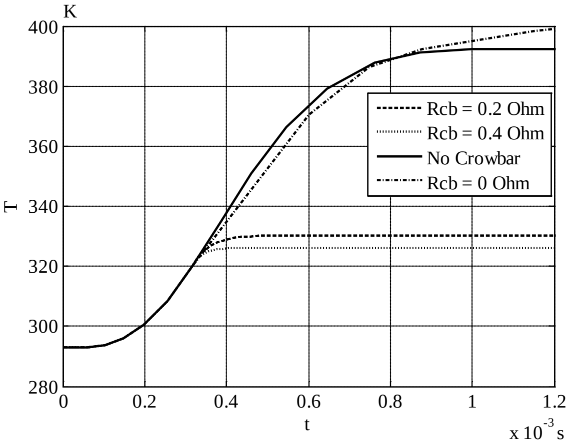

Fig. 6. A Temperature transient processes in pulsed coil with crowbar circuit

As seen in Fig. 6 the temperature after the pulse inside the coil with a crowbar and resistive ballast has significantly decreased. This circumstance allows avoiding of thermal overloads in windings and finally lets to ensure long life operation of pulsed coil. Pulsed coil was tested experimentally. The observed shape of magnetic field pulse was close to sinusoidal one at time of 0,4 ms (approx. quarter of period) and decreased exponentially during next 0,2 ms and was close to numerically simulated transient process.

Conclusions

The analysis of thermodynamic processes taking place in pulsed coils with crowbar and resistive ballast has been carried out. The numerical simulation of pulsed current, magnetic field and temperature rise was done.

Great overheating due to Joule heating takes place in pulsed coil during operation. The longer pulse duration the more critical thermal overloads are observed. The application of crowbar with resistive ballast strongly influences transient processes in the circuit and cut them after maximum of current has been reached. Therefore temperature rise decreased drastically and overheating due to Joule heating can be avoided even without initial cooling. Applied model was verified experimentally and acceptable compliance of experimental and numerically simulated results was achieved.

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The analysis of thermodynamic processes in pulsed coils with crowbar circuit and resistive ballast is described. Great overheating due to Joule heating takes place in pulsed coil during operation. The influence of crowbar circuit on generated pulse shape and coil overheating is analyzed. The model was carried out using *Matlab® Simulink®* software and applied for numerical simulation of transient processes that took place in winding of pulsed coil. The numerical simulation of pulsed currents and temperature rise were carried out for different values of resistive ballast using the same experimental equipment and laboratory conditions. Depending on resistance of the crowbar resistive ballast fall time of generated pulse has changed at wide range and as a result temperature rise in Cu-Nb windings of pulsed coil has changed too. Using 0,2 – 0,4 Ohm ballast temperature rise decreased drastically and overheating due to Joule heating has been avoided even without initial cooling. Applied model of transient processes took place in pulsed coils with crowbar circuit and resistive ballast was verified experimentally and acceptable compliance of experimental and numerically simulated results was achieved. Ill. 6, bibl. 11 (in English; abstracts in English, Russian and Lithuanian).

С. Барткевичюс, Ю. Новицкий. Исследование термодинамических процессов в импульсных магнитах с замыкателем // Электроника и электротехника. – Каунас: Технология, 2010. – № 4(100). – С. 99–102.

Рассматриваются термодинамические процессы, происходящие в импульсных электромагнитах с дополнительной цепью замыкателя, состоящей из диода и баластного сопротивления. Моделирование термодинамических процессов проызведено, используя программный пакет *Matlab® Simulink®*. Модель электромагнита позволяет имитировать реальные процессы нагрева обмотки электромагнита при протекании импульсного тока. Оценивается влияние нагрева обмотки электромагнита на максимальное значение импульсного тока. Установлено, что нагрев проводника, близкий по характеру адиабатическому процессу, приводит к значительному изменению активного сопротивления обмотки электромагнита, что приводит к уменьшению эффективности электромагнита. Использование замыкателя сопротивлением 0,2–0,4 Ω позволяет значительно уменьшить перегрев обмотки импульсного электромагнита за счёт сокращения длительности переходных процесов тока в обмотке. Результаты численного эксперимента сравниваются с результатами реального физического эксперимента и достигнуто приемлемое соответствие результатов. Ил. 6, библ. 11 (на английском языке; рефераты на английском, русском и литовском яз.).

S. Bartkevičius, J. Novickij. Impulsinių magnetų su kirtikliu termodinaminių procesų tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2010. – Nr. 4(100). – P. 99–102.

Pateikta termodinaminių procesų, vykstančių impulsinėse ritėse su kirtikliu ir balastine varža, analizė. Skaitinei imitacijai pritaikytas programų paketas *Matlab® Simulink®*, leidžiantis sudaryti impulsinės sistemos termodinaminį modelį. Imitavimo tikslas buvo nustatyti grandinės su kirtikliu ir varžiniu balastu įtaką impulsinės ritės įšilimui, išnagrinėti temperatūros kaitos dinamiką. Sudarytas modelis pritaikytas eksperimentiškai patikrintiems ir dar projektuojamiems induktoriams. Remiantis gautaisiais apvijų impulsinių srovių ir įšilimo pereinamaisiais procesais nustatyta, kad įšilimas impulso metu gali turėti daug įtakos impulso formai ir amplitudei. Panaudojus kirtiklį su balastine 0,2–0,4 Ω varža pavyko gerokai sutrumpinti pereinamuosius procesus ir sumažinti apvijų šiluminę apkrovą net nesant išorinio aušinimo. Taip pat pasiektas pakankamas skaitmeninių eksperimentų tikslumas ir galimybė modelį ir gautus rezultatus taikyti termodinaminiams ir elektromagnetiniams procesams impulsiniuose induktoriuose prognozuoti, induktoriams tobulinti ir elektriniams parametrams parinkti. Il. 6, bibl. 11 (anglų kalba; santraukos anglų, rusų ir lietuvių k.).