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Inductors for High Magnetic Field Generation

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Introduction

High magnetic field generation is a very actual area of electronics and applied physics. Many important discoveries were done by the application of high magnetic fields. At present time more and more researchers are involved in this area and the fruitful co-operation between laboratories takes place. For generation of magnetic fields higher than 2 T, core-free solenoids, superconductive solenoids, or hybrid systems are used [1]. However, in any case these methods are very expensive and could be installed only in large modern laboratories and centers. The highest permanent magnetic field achieved in hybrid magnet is 45 T (NHMFL, USA).

One of the obvious ways to design higher magnetic field facilities is the application of pulsed power technique. This technique becomes the alternative of steady magnetic fields in many applications. However, a pulsed magnetic field generation requires extraordinary attention on generating facilities. Recently European scientists and engineers had put great efforts to make the progress in pulsed magnetic field areas. One of their tasks is to develop a non-destructive 100 T magnet with long pulse duration [2]. These works were sponsored by European Union. As the result, is the realisation of 80 T pulsed magnet useful for scientific applications. Laboratories in Grenoble, Toulouse, Amsterdam, Oxford, Berlin have accumulated the best know-how of high magnetic field technology are continually improving their facilities.

One of the future ways of pulse power technique is the miniaturisation of components which are required for pulsed magnetic field generation. Higher fields entail short pulse duration in small bore. Researches are putting efforts to miniaturise experimental set-ups and to adapt them to shorter pulse duration and lower energy. As a result of these efforts, pulse power facilities become available for wider scientific community.

There are different techniques to generate repetitive and non-repetitive magnetic fields. In the first case a magnetic field does not destroy inductor, in the other case magnetic field fully or partially disintegrates the construction. In any case the generation of high magnetic fields involves hard technical problems. The destruction of the inductor by Joule heating, mechanical and electrical overloads should be taken into consideration.

Discharging the energy bank through the inductor during a short period of time induces adiabatic heating of the windings and ultra-high mechanical stresses. A magnetic field of 100 T generates an axial stress of 4 GPa which exceeds the ultimate tensile stress limit of the most conductors for a few times. Copper wire-wound coils without special reinforcement can generate pulsed fields up to 20 T only. Inductors are still the most complicated part of high magnetic field facilities. An insignificant mistake in inductor's design follows the drastic failures in pulsed magnetic field experimentation. Therefore, the complete analysis of inductor constructions is necessary.

In Vilnius High Magnetic Field Centre which is joint Institution of Semiconductor Physics Institute and Vilnius Gediminas Technical University, various inductors for high magnetic field generation are investigated. Compact laboratory equipment is applied for pulsed magnetic field generation up to 48 T at room and liquid nitrogen temperatures. The new construction to generate higher pulsed magnetic fields is under development at this moment. Preliminary experimentation and future steps of inductor design are determined. The investigations are supported by the Lithuanian Science and Studies Foundation under the contract No.K-058.

Single turn inductor

A magnetic field generated by the ideal single turn coil is determined by the equation:

$$B = \mu_0 \mu H = \mu_0 \mu \frac{I}{D}, \tag{1}$$

here μ_0 is a magnetic constant, μ is area magnetic permittivity (for high magnetic field applications μ =1), I is current, D is single turn diameter. Real single turn coils have an inner and outer diameters d and D, respectively, and axial width h. Therefore, it is necessary to introduce a form-factor K [3] for evaluation of coil geometry influence on generated magnetic field. For most applications

$$\frac{D}{h} \approx 1, . \frac{D}{d} \approx [1{,}5-2], . K \approx 0{,}6 . \tag{2}$$

The schematic diagram of pulsed magnetic field generator with the single turn inductor is shown in Fig.1

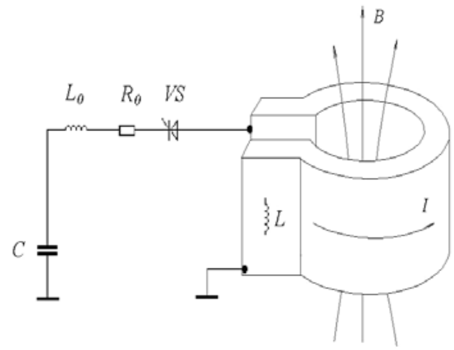

Fig.1. The schematic diagram of pulsed magnetic field generator with single turn inductor.

The energy is stored in capacitor bank *C*. The single turn inductor has an inductance *L*. R_0 and L_0 is the resistance and an inductance of connectors, capacitors and the switch *VS*. A magnetic field pulse is generated discharging the capacitor bank over the single turn coil. Energy balance equation is as follows:

$$\frac{CU^2}{2} = \frac{LI^2}{2} + \frac{L_0 I^2}{2} + I^2 R_0 t \,. \qquad (3)$$

The typical inductance *L* of single turn coil is 1-10 nH. The efficiency of energy transformation strongly depends on active and reactive losses of electric circuit. Losses due to inductance L_0 are one of main technical problem because of difficult decrease of the inductance L_0 less than 1nH. This means that the efficiency of above described method is about 50% in the best case and about 20% at usual conditions. Another technical problem is the ultra-high value of rise time and the amplitude of current pulse. The short rise time requires a precise ignition of switchers and a synchronization of data recording equipment. In the most applications the rise time of the pulse is 1-5 microseconds, the operating voltage in the capacitor bank is 20-60 kV. A minimal current of 500 kA is required to generate the pulsed magnetic field up to 100 T in a few millimeters area. During generation of a magnetic pulse, the coil is influenced by pressure up to 4 GPa and it is destroyed during few microseconds. In weaker magnetic fields the radial shock wave strongly deforms the wire. Single turn inductors provide semi-destructive facilities of pulsed magnetic field generation. But it is acceptable in investigations of fast physical processes. The measuring data is registered faster than the pressure destroys the coil and testing sample.

The generation of pulsed magnetic fields of 100 T and higher is a complex problem involving nonlinear flux diffusion, heating and mechanical deformations. Therefore, it requires careful and routine analysis including numerical simulations and physical experimentations. The optimization of capacitor bank, distributing circuit, switchers, single turn coil geometry performs the good basis for reproductive scientific experiments in pulsed magnetic fields up to 300 T [4].

One of possible implementation of pulsed magnetic field generation by a single turn inductor is the usage of pulsed transformer as shown in Fig.2.

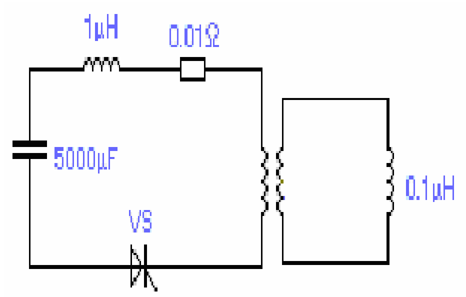

Fig.2. Single turn inductor with transformer

The pulsed transformer adjusts the low inductance of the pulsed magnetic field inductor with the impedance of discharging circuit. The circuit becomes less critical to R_0 and L_0. A significantly high inductance of primary winding permits to get the longer pulse duration. The operating voltage can be reduced to 3-5 kV and semiconductor switchers can be used. But in any case a transformer may be introduced into single turn inductor scheme very carefully. High pulsed power transformer design isn't trivial. It means that electric and magnetic losses of a transformer should be evaluated.

Flux concentrator

The flux concentrator as one of available pulsed transformer modifications is shown in Fig.3.

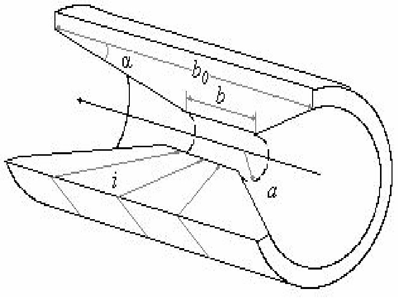

Fig.3. Operation principle of a flux concentrator

Primary winding current *I* generates the magnetic flux *H*. A secondary winding of pulsed transformer is made as a solid cylinder with central hole and an axial slit. Induced current flows on the surface of the cylinder and it does not penetrate into conductor volume**.** If the skin layer is insignificant comparing with inner hole and slit dimensions, the magnetic flux can be concentrated in the inner hole. The reactive resistance of flux concentrator should be higher than in the active one and is determined by equations [5]:

$$\begin{cases} R' = R_1 + (R_2 + R_3)n^2\left[(kl - m)/(l + 1 - 2m)\right]^2, \\ L' = n^2 L_3\left[l - (kl - m)^2/(l + 1 - 2m)\right], \end{cases} \qquad (4)$$

where R_1, R_2, R_3, and L_1, L_2, L_3 are resistance and inductance of the primary, the secondary winding and inner hole, respectively, M_{12}, M_{13} are mutual inductances, $k = \left(\frac{M_{12}^2}{L_1 L_2} \right)^2$, $l = \frac{L_2}{L_3} = \frac{L_1}{n^2 L_3}$, $m = \frac{M_{23}}{L_3} = \frac{M_{13}}{nL_3}$, $k \approx 1$. Magnetic energy E_L ,losses E_R, and efficiency ε can be determined as:

$$\begin{cases} E_R = \left(\pi R^/ / 4\omega \right) i_1^2, \\ E_L = \frac{1}{2} L^/ i_1^2, \\ \varepsilon = \frac{1}{2} L_3 i_2^2 / \frac{1}{2} L^/ i_1^2 = \left(kl - m \right)^2 / (l + 1 - 2m), \\ \left[l(l + 1 - 2m) - (kl - m)^2 \right]. \end{cases} \quad (5)$$

If a concentrator has a cone inner hole its efficiency is determined by the equation:

$$\varepsilon^/ = \varepsilon \left\{ b_0 / \left[b + a \sin \alpha / \left(1 - \cos \alpha \right) \right] \right\}, \quad (6)$$

here a is a hole radius, b is the width of strong field area, b_0 is the total width of the concentrator.

The maximal efficiency equals 0,3 when the cone angle equals 45^0. This means that in the best case 30% of electric energy will be transformed into magnetic one. Taking into account all factors, the efficiency of magnetic flux concentrator can be about 25%. The picture of fabricated concentrator and pulsed transformer with flux concentrator mounted in it is shown in Fig.4.

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Fig.4. Pulsed transformer and flux concentrator

The flux concentrator was supplied with 10 kJ energy capacitor. The maximal pulsed magnetic field up to 20T was generated. One of advantages of flux concentrator is the possibility of fast inductor replacement during the experiment. Therefore, it is possible to generate pulsed magnetic field with different field distribution. Required gradients can be achieved by the change of inner concentrators. The concentrator is more mechanically stable than a coil, and continuous operation at high current levels and magnetic fields can be performed [6].

Helix inductor

Helix inductors can be applied for pulsed magnetic field generation up to 60-70 T [7] (see Fig.5).

A helix could be made by machining hard materials such as cooper-beryllium alloys, steel or others. The main advantages of such inductors are possibility to withstand large mechanical strength and ability of perfect cooling with liquid nitrogen. In comparison to single turn coil design, this helix has higher inductance and better field homogeneity. Magnetic field pulse duration could be obtained up to 100-200 μs. The current distribution in helix is non-uniform and specified as

$$j = j_0 \frac{a}{r}, \quad (7)$$

here $j_0 = \frac{IN}{ah \ln(b/a)}$ is initial current density, I is current, N is the number of turns, a, b, h is inner, outer radius and the axial width of the helix, respectively.

Fig.5. Helix inductor

Magnetic field in the helix centre is determined by formula:

$$B = B_0 \frac{1}{\ln(b/a)} f \ln \left[\frac{b}{a} \frac{1 + \sqrt{(2a/h)^2 + 1}}{1 + \sqrt{(2b/h)^2 + 1}} \right], \quad (8)$$

here $B_0 = \mu_0 \frac{IN}{h}$ is initial magnetic field, $f = \frac{Ns}{h(b-a)}$ is turns density, s is turn cross-section.

Optimal geometry is obtained when $\frac{b}{a} = 6$, $\frac{h}{2a} = 2$.

The helix inductor is connected with capacitor bank in the same way as the single turn coil. A helix should be reinforced to avoid the destruction. Completely assembled construction of the helix inductor is shown in Fig.6

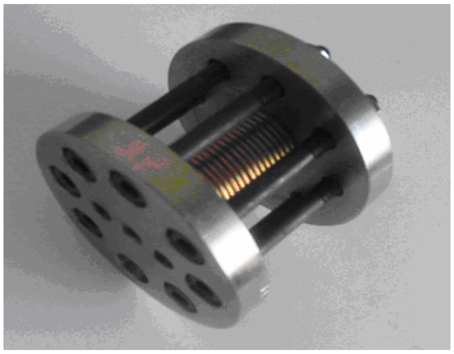


Fig.6. Helix construction of the pulsed magnet

The maximal value of pulsed magnetic field generated by fabricated helix inductor is determined only by maximal current. The maximal current depends upon the helix inductance *L*, bank capacitance *C*, voltage *U,* and active circuit losses *R*. The maximal peak of the current in *RLC* circuit can be found from the equation:

$$\begin{cases} L\dfrac{\mathrm{d}^2 I}{\mathrm{d}t^2} + R\dfrac{\mathrm{d}I}{\mathrm{d}t} + \dfrac{1}{C}I = 0, \\ I = \dfrac{U}{\omega L}\exp\left(-\gamma t\right)\sin\,\omega t, \\ I_{\max} = \dfrac{U}{\omega L}\exp\left(-\dfrac{\gamma}{\omega}arctg\,\dfrac{\omega}{\gamma}\right), \\ \gamma = \dfrac{R}{2L}, \omega = \sqrt{\omega_0 - \gamma}, \omega_0 = \dfrac{1}{\sqrt{LC}}. \end{cases} \tag{9}$$

These equations are useful for current determination for any circuits with linear *RLC* components. Of course, during the high magnetic pulse the inductor is heated and the resistance *R* is non-linear. Usually inductors are pre-cooled by liquid nitrogen to avoid the heat overload. The temperature increases more than 100^{o}C during the pulse. Moreover, the shock wave can deform the inductor and initial dimensions can be changed and the non-linear inductance takes place. For preliminary evaluations of maximal pulsed magnetic field generated by pulsed inductors a mentioned non-linearity can not be taken into the consideration.

Multi-section inductor

The application of wire wound coils is the most obvious way to construct pulsed magnets with long pulse duration and good field homogeneity [8]. Therefore, coils are useful for the most measurements in high magnetic field range. The operation principle of pulsed magnetic field generator with wire wound inductor is shown in Fig.7

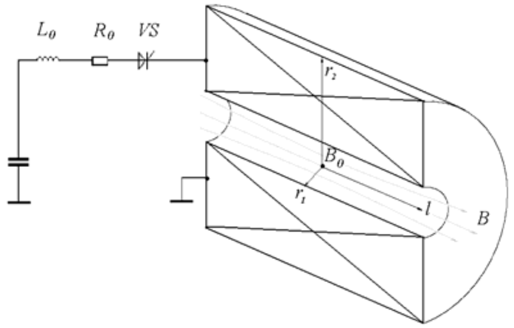


Fig.7. The operation principle of wire wound inductor

Wire wound coils fulfill the constant current density condition and axial magnetic field can be calculated by formula:

$$B = \mu_0\frac{NI}{r_1}\left[\frac{F(\alpha,\beta)}{2\beta(\alpha-1)}\right], F(\alpha,\beta) = \beta\ln\frac{\alpha+\sqrt{\alpha^2+\beta^2}}{1+\sqrt{1+\beta^2}}, \tag{10}$$

here μ_0 is magnetic constant, *N* is the quantity of turns, *I* is a current, r_1, r_2, l are internal, external radius and the length of a solenoid, respectively, $\alpha = \frac{r_2}{r_1}$, $\beta = \frac{l}{2r_1}$ are relative sizes. The maximal current can be calculated by the same way as described above for *RLC* circuit with the helix. The only difference is the value of inductor inductance *L*.

This kind of pulsed generators can generate magnetic pulses of 2-20 *ms* in duration. The mechanical overload due to Lorentz force is the main limitation of amplitude of the pulsed magnetic field. The non-destructive peak field up to 20-25 T is available for copper wire wound coils without the construction reinforcement. The main component of the Lorentz force is in radial direction. Therefore, the easiest way to reinforce a coil is to mount a heavy reinforcement at the outside. It protects the coil from the exploding. However, the inner layers of coils are stressed more than outer ones.

The deformation of the inner layers is the main reason of the inductor failure as shown in Fig.8.

Fig.8. Destructed pulsed solenoid

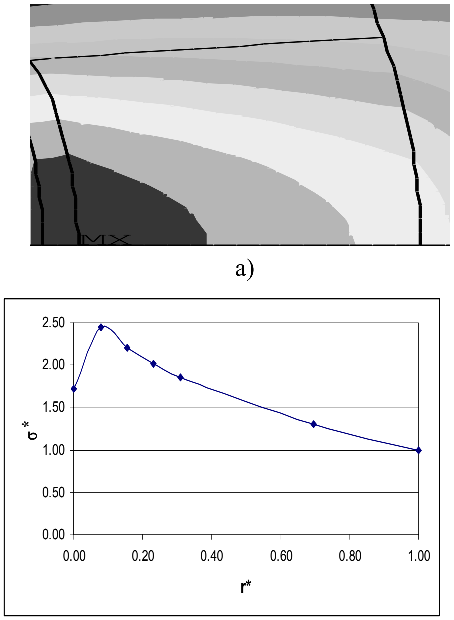
For the first estimation the failure criteria for maximal available magnetic field inductor can be calculated as [9]:

$$B = \sqrt{2}\left(1 - \frac{1}{\alpha}\right)\sqrt{2\mu_0\sigma}\,, \tag{11}$$

here σ is the maximal allowable mechanical stress, α is the ratio of outer and inner diameter.

Mechanical behavior is, however, of multi-axial character and solid stress analysis is required for strength evaluation. The finite element method as the most efficient numerical tool has been applied for simulation of the non-linear multi-physic problems. The coupled magneto-mechanical axi-symmetric finite element model [10] was used for numerical analysis of pulsed generators. The winding and external reinforcement were considered as two different deformable media. The multi-dimensional stress field is characterized by the stress intensity σ.

The cross-sectional distribution of stress intensity in the winding under action of Lorentz forces presented in Fig.9 show that the highest values occur in the central cross-sectional plane. The deformed shape of the coil is also depicted. The radial variation of the relative stress intensity $\sigma^* = \sigma/\sigma_{\min}$ shows in the limits of tolerance of numerical model that the stress peak occurs in the vicinity of internal boundary. On the basis of experience and numerical results it was found that an internal reinforcement can significantly improve the effective mechanical strength of the inductor.



a)

b)

Fig 9. Cross-sectional (a) and radial (b) variations of the stress intensity in the winding volume

Further analysis of stress distribution in coils with internal and external reinforcement has followed the coil separation into few sections with boundary reinforcement [11]. The cross-section of this inductor is shown in Fig.10.

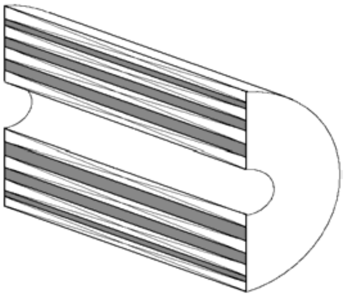


Fig.10. Multi-section inductor

The pulsed inductor consists of a few sections insulated with high-strength fiber. The sections could be made from different conductors. However, the first two layers should be wounded with high strength conductor. Next layers could be wounded with weaker conductor, but of more electrically conductive material. The sections of the coils are joined in series. The relatively thick inter-layer fiber insulation has insured the high mechanical and electrical stability of the construction. To prevent the damage caused by a coil deformation the monitoring of inductance and resistance of the coil should be done after every shot. The separation of a coil into two reinforced sections allows to increase the peak magnetic field about 20%. Magnetic fields up to 40-45 Tesla have become more accessible and non-destructive for copper wound solenoids. The inductor was tested in Vilnius High Magnetic Field Centre where the compact system for pulsed magnetic field generation is developed. The designed inductors were tested at room and liquid nitrogen temperature and the 40 T peak magnetic field was generated. The three section inductor is under the development now. It has a 10mm bore. The inductor is wounded with 1,5 mm copper wire and insulated by impregnated glass fiber and Capron fabric. The self inductance is 100 μH, the resistance - 0.1 Ω at room temperature. The glass fiber carbon intersection reinforcement was done to insure the inside mechanical strength of the construction. Outer reinforcement is done using special martensite steel cylinder with 8 mm wall thickness. The axial pressure was exerted by a ring of screws on the top and bottom surfaces of the outer cylinder. It is necessary to avoid inductor failure at the end of the inductor due to shock wave propagation. The assembled inductor is shown in Fig.11.

The multi-section inductors in comparing with above described inductors are the most acceptable in experiments to measure physical parameters of magnetic and semiconductor materials in pulsed magnetic fields due to the best field homogeneity and long pulse duration. Moreover, the mechanical strength of the construction insures the non-destructive operation in the wide range of pulsed magnetic fields.

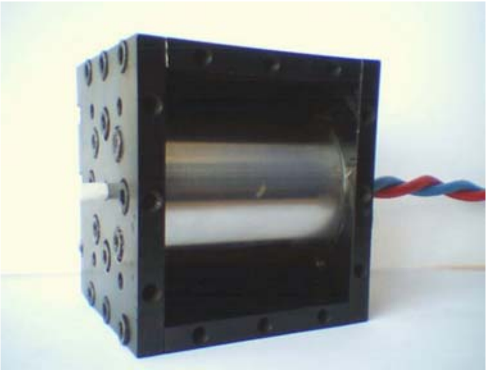


Fig.11. Multi-section inductor

The application of modern extra- strong materials expects the peak fields up to 80 T. Therefore, further development of inductor construction is required and will be done in future.

Conclusions

Repetitive high magnetic field pulses could be generated using single turn inductors, flux concentrators, helix inductors, pulsed coils and multi-section inductors. To insure the long life operation of inductors, mechanical, electrical, heat overloads and stresses should be taken into consideration. The most limited factor is the mechanical stress occurred in inductor due to Lorenz forces.

Single turn inductors can be used in the investigation of fast physical phenomena if experimental data are recorded faster than the inductor's destruction. The magnetic field of 100 T and higher in microsecond range is available.

Flux concentrators and helix inductors can be used as an alternative of single turn inductors in 40-60 T experiments if longer pulse duration is required.

The most universal construction of pulsed magnetic field inductors is multilayer coils and multi-section inductors. Pulsed magnetic fields up to 50-60 T in millisecond range are available. A special inner and outer reinforcement is required to insure non-destructive operation. A multi-section construction of pulsed magnetic field inductor with optimized electrical and mechanical parameters looks very attractive. New materials used for the winding and reinforcement are expected in the progress of magnetic field generation up to 70-80 T.

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J. Novickij, R. Kačianauskas, V. Filipavičius, S. Balevičius, N. Žurauskienė, R. Tolutis. Stipriųjų magnetinių laukų induktoriai // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2004. – Nr.7(56). – P.19–24.

Nagrinėjami impulsiniai induktoriai, naudojami stipriems magnetiniams laukams generuoti. Veikimo principas pagrįstas didelės talpos energijos kaupiklio iškrova per induktorių. Ašinis magnetinis laukas apskaičiuojamas pagal tradicines formules, žinant impulsinės srovės vertę ir induktoriaus geometrinius parametrus. Analizuojamas elektrinės energijos transformavimo į magnetinę efektyvumas. Pateiktos vienos vijos spiralinio induktoriaus, magnetinio srauto koncentratoriaus, kelių sekcijų induktoriaus pagrindinės charakteristikos ir konstrukcijos. Projektuojant impulsinius induktorius, reikia įvertinti elektrinius, šiluminius bei mechaninius veiksnius. Būtent mechaniniai perkrovimai riboja didelių impulsinių magnetinių laukų induktorių sukūrimo galimybes. Norint sukurti patikimą daugkartinio naudojimo impulsinio magnetinio lauko induktorių, būtina spęsti sudėtingą termomechaninį uždavinį. Pirmu artėjamu analizuojamas mechaninių įtempimų pasiskirstymas induktoriuje. Pateikti Lorenzo jėgų ir įtempių skaičiavimo rezultatai. Kelių sekcijų induktoriaus konstrukcija pasirinkta kaip perspektyviausia, projektuojant daugkartinio naudojimo stiprių impulsinių magnetinių laukų induktorius. Il.11, bibl.11 (anglų kalba; santraukos lietuvių, anglų, rusų k.).

J. Novickij, R. Kačianauskas, V. Filipavičius, S. Balevičius, N. Žurauskienė, R. Tolutis. Inductors for High Magnetic Field Generation // Electronics and Electrical Engineering. – Kaunas: Technologija, 2004. – No.7(56). – P.19–24.

Inductors for high magnetic field generation are described. Pulsed magnetic field is generated discharging energy bank through the inductor during a short period of time. Axial magnetic field is calculated by equations using known values of pulsed current and geometric parameters of the inductor. The efficiency of energy transformation is analyzed. The possibility of non-destructive applications of single turn inductor, flux concentrator, helix inductor, and multi-section inductor is discussed. The design of pulsed magnetic inductors requires complex analysis of electrical, thermal and mechanical overloads, and the most limited factor is the destructive mechanical stress. For the first estimation the failure criteria of maximal available magnetic field inductor and the cross-sectional distribution of stress intensity under action of Lorentz forces are presented. The multi-section inductor is chosen as the challenging long life construction for further experimentations in high magnetic field generation area. Ill.11, bibl.11 (in English; summaries in Lithuanian, English, Russian).

Ю. Новицкий, Р. Качанаускас, В. Филипавичюс, С. Балявичюс, Н. Жураускене, Р. Толутис. Индукторы для создания сильных магнитных полей // Электроника и электротехника. – Каунас.Технология, 2004, №7(56). – С.19–24.

Рассматриваются различные конструкции индукторов для создания импульсных магнитных полей. Импульсные магнитные поля генерируются посредством быстрого разряда конденсаторной батареи через индуктор. Величина магнитного поля определяется по известным формулам, зная значения импульсного электрического тока и геометрических параметров индуктора. Сравниваются основные параметры одновиткового, спирального индукторов, концентратора и многосекционной катушки, оценивается эффективность трансформации электрической энергии в магнитную. При разработке конструкции индуктора следует учитывать электрические, тепловые и особенно механические нагрузки. Последние являются основным ограничением при создании неразрушающихся импульсных индукторов. В первом приближении оценивается надежность индуктора и распределение механических напряжений, вызванных действием силы Лоренца в момент разряда конденсаторной батареи через индуктор. Многосекционная конструкция индуктора выбрана для дальнейших исследований как более перспективная в области генерации неразрушающих импульсных магнитных полей. Ил.11, библ.11 (на английском языке; рефераты на литовском, английском и русском яз.).