



VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

FACULTY OF ELECTRONICS

DEPARTMENT OF ELECTRICAL ENGINEERING

UGUR AYDIN

INVESTIGATION OF PULSED MAGNETIC FIELD INDUCTORS

Master's degree Thesis

Electrical energetics systems engineering study programme, state code 621H62002

Modern electrical power engineering specialisation

Electrical and electronics engineering study field

Vilnius, 2014

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OBJECTIVES FOR MASTER THESIS

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Vilnius

For student Ugur Aydin
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Master Thesis title: Investigation Of Pulsed Magnetic Field Inductors

Approved on, 201... by Dean's decree No.
(day, Month) (year)

The Final work has to be completed by, 201.....
(Day, Month) (Year)

THE OBJECTIVES:

1- Investigation of pulsed magnetic field generation by pulse generators and developing a reliable model of pulse generator using computer tools.

2- Investigation of pulsed magnetic fields generated using different pulsed magnetic inductors experimentally and developing simulation models in various computational tool environments. Comparing results from simulations and experiments to test reliability of simulation models.

3- Developing a pulsed magnetic field inductor design algorithm while conducting research on materials and analysing mechanical and thermal behaviour of inductors during operation in order to propose a 40 T pulsed magnetic inductor design for colossal magnetoresistive sensor testing.

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(Date)

Vilnius Gediminas Technical University

Electronics faculty

Electrical Engineering department

ISBN ISSN

Copies No.

Date-....-....

Electrical energetics systems engineering study programme bachelor (master) thesis.

Title: **Investigation of pulsed magnetic field inductors**

Author: **Ugur Aydin** Academic supervisor: **dr. prof. Nerija Žurauskienė**

Thesis language

☐ Lithuanian

☒ Foreign (English)

Annotation

In this master of science thesis pulsed magnetic field inductors were investigated. First of all pulse generator as a whole was studied and it was modelled by using computer tools. The reliability of model was tested experimentally and proven. Experiments on readily designed various pulsed magnetic field inductors were performed to investigate pulsed magnetic flux density distribution in the center of inductor bore. In addition to this, computer models were developed to conduct previous analysis to obtain magnetic flux density distribution in the center of inductor bores and accurate results compared to experimental ones were obtained. Finally pulsed magnetic field inductor design algorithm was developed by using previous models in addition to electrophysical process analysis in inductor windings during pulse generation. Using this algorithm inductor design for colossal magnetoresistive sensor testing application was proposed.

Structure: introduction, literature review, research and experiments, general conclusions, references.

Thesis consist of: 75 p. text without appendixes, 49 pictures, 11 tables, 92 bibliographical entries.

Keywords: Pulsed magnetic field inductors/coils, pulsed magnets, pulsed magnetic fields.

Vilniaus Gedimino Technikos Universitetas

Elektronikos fakultetas

Elektrotechnikos katedra

ISBN ISSN

Egz. sk.

Data-....-....

Elektros energetikos sistemų inžinerijos studijų programos baigiamasis magistro darbas

Pavadinimas: **Impulsinio magnetinio lauko induktorių tyrimas**

Autorius: **Ugur Aydın**

Vadovas: **dr. prof. Nerija Žurauskienė**

Thesis language

☐

Lithuanian

☐

Foreign (English)

Anotacija

Šiame magistro darbe yra tiriami impulsinio magnetinio lauko induktoriai. Iš pradžių yra išnagrinėjamas ir sumodeliuojamas impulsinio magnetinio lauko generatorius. Modelio patikimumas yra patikrinamas eksperimentiškai. Atlikti eksperimentai, kurių metu ištirtas magnetinio srauto tankio pasiskirstymas induktorių centre. Taip pat atliktas magnetinio srauto tankio induktorių centre modeliavimas ir rezultatų palyginimas su eksperimentiniais rezultatais. Taip pat atliktas impulsinio magnetinio lauko induktorių modeliavimas, įskaitant mechaninius ir termodinaminius procesus juose. Naudojant šį algoritmą, pasiūlyta induktoriaus, skirto milžiniškos magnetovaržos jutiklių tyrimams iki 40 T, konstrukcija.

Struktūra: įvadas, literatūros apžvalga, tiriamoji ir eksperimentinė dalis, pagrindinės išvados, literatūros sąrašas.

Darbo apimtis 75 puslapiai be priedų, 49 iliustracijos, 11 lentelių, 92 bibliografiniai šaltiniai.

Raktiniai žodžiai: Impulsinio magnetinio lauko induktoriai/ritės, impulsiniai magnetai, impulsiniai magnetiniai laukai.

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code 621H62002

Modern electrical power engineering specialisation

LABEL OF MASTER THESIS

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Student's	Weighted	Grade	Point	Average
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Master Thesis title: Investigation of pulsed magnetic field inductors

Master Thesis is properly prepared and can be presented for defence at Commission granting Master's degree.

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MASTER THESIS**

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(Study programme, academic group no.)

**DECLARATION OF AUTHORSHIP
IN THE FINAL DEGREE PAPER**

June 2, 2014

I declare that my Final Degree Paper entitled „Investigation of Pulsed Magnetic Field Inductors“ is entirely my own work. The title was confirmed on November 13, 2012 by Faculty Dean's order No. 299el. I have clearly signalled the presence of quoted or paraphrased material and referenced all sources.

I have acknowledged appropriately any assistance I have received by the following professionals/advisers: Prof. Dr. Nerija Žurauskienė.

The academic supervisor of my Final Degree Paper is Prof. Dr. Nerija Žurauskienė.

No contribution of any other person was obtained, nor did I buy my Final Degree Paper.

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List of Abbreviations and Symbols

List of Abbreviations

FEM	Finite element method
FEA	Finite element analysis
IACS	International annealed copper standard
EMP	Electromagnetic pulse
EMPT	Electromagnetic pulse technology
PEMF	Pulsed electromagnetic field
CAT	Computerized axial tomography
MRI	Magnetic resonance imaging
FDA	Food and drug administration
rTMS	Repetitive transcranial magnetic stimulation
EMML	Electromagnetic missile launcher
PDE	Partial differential equation
CMR	Colossal magnetoresistive
UTS	Ultimate tensile strength
USB	Universal Serial Bus

List of Symbols

L, C, R	Inductance, capacitance, resistance values respectively
I, J	Current, Current density
E	Energy
U_0	Voltage value that capacitor is charged prior to switching
V_L, V_C, V_R	Voltage values of inductor, capacitor and resistor respectively
I_L, I_C, I_R	Current values on inductor, capacitor and resistor respectively
f	Frequency
γ, ω_0, ω	Damping coefficient, resonant frequency, frequency of current and voltage of RLC circuit
B_z, B_r	Axial magnetic and radial magnetic flux density
B_0	Magnetic flux density in the center of inductor bore
F	Density of turns in inductor

a_1, a_2, a	Inner, outer radius of inductor and radius of first inner layer from the center of wire
$2b$	Length of inductor
$2d$	Width of single turn inductor
h	Axial width of helix inductor
α	Ratio of inductor outer radius to inner radius
β	Ratio of inductor length to inner diameter
N_1, N_2, N	Number of layers, number of windings in each layers and total number of turns of inductor
λ	Filling factor
$E(m), K(m)$	First and second order elliptic integral
t	Time
T	Temperature
v	Width of the inductor's layer
m	Mass
c, k	Specific heat constant and thermal conductivity of material
Q	Heat amount
ρ	Density
ρ_r	Resistivity
κ	Conductivity
S, A	Cross section and surface area
τ	Pulse duration
σ_t	Tensile strength of material
$\sigma_r, \sigma_z, \sigma_h, \sigma_{VM}$	Radial stress, Axial stress, Hoop stress, Von misses stress respectively
F	Force
F_L, F_{Lr}, F_{Lz}	Lorentz force, radial and axial Lorentz forces respectively
p	Magnetic pressure
δ	Skin depth
μ_0, μ_r, μ	Magnetic permeability in vacuum, relative permeability and permeability
H	Magnetic field strength
H_{gap}, H_{pen}	Magnetic field strength in the gap between the tool inductor and workpiece, penetrated magnetic field
M, χ_m	Magnetization and magnetic susceptibility
l	Length of projectile
l_w, S_w	Length and cross section area of inductor wire

Aim of the Work

The aim of this work involves investigation of pulsed magnetic field inductors, operation principle of pulse generators and developing computer based models for pulse generators and pulsed magnetic field inductors in order to investigate magnetic flux density distribution, stress and thermal analysis in inductors besides, develop inductor design algorithm.

Tasks of the Work

1. To develop computer based model for pulse generators in order to adopt operation principles of pulse generators and define a model to use for prospective simulations.
2. To create mathematical-computer based inductor model to analyse magnetic flux density in pulsed inductors.
3. To develop computer based models to analyse thermodynamic and magnetomechanic processes in pulsed inductors.
4. Using the models that are developed to create a basic inductor design algorithm in order to propose pulsed inductor design for colossal magnetoresistive sensor testing.

Introduction

High magnetic fields have essential importance in many research areas and for industrial applications as well. As a result, generation of high magnetic fields emerges to a technology branch of growing relevance. The use of magnetic fields up to 1 T has been used in many technical applications for many years. Large electromagnets for medical diagnostics and polarized permanent magnets are only two examples among numerous applications. Nowadays, huge and unique inductor systems for the generation of higher magnetic fields up to 9 T are in use in particle accelerators (e.g. Large Hadron Collider) and up to 14 T for fusion generator International Thermonuclear Experimental Reactor (ITER) which is under construction. Superconducting magnets up to 23 T are in use combined with various measurements in solid state physics, chemistry, and biological sciences, in order to open new eras in science. Power consuming resistive magnets based on the design of Francis Bitter [1] are limited to about 33 T and hybrid inductors made of Bitter magnets placed in large superconducting inductors are available up to 45 T [2] and will probably never go beyond 50 T due to technical and financial limits. For this reason, pulsed inductors are in the interest nowadays. Generation of magnetic flux density beyond 45 T provides opportunities to observe what we cannot observe before. For instance, investigation of high magnetic fields provides opportunities to determine fundamental physical material properties such as effective mass, shape of the Fermi surface, critical surfaces and together with low temperatures opportunities are to understand superconductivity, magnetic field induced phase transitions, quantum critical points in which small changes in materials properties at very low temperature have dramatic effects on physical behavior [3]. On the other hand from the applied science point of view, various researches are ongoing on some biological treatment methods based on electromagnetic pulse technologies. In addition to this, pulsed magnetic fields with further developments are promising for some industrial and defence applications such as electromagnetic forming, electromagnetic missile launchers and coil guns.

Pulsed magnetic field inductors can be divided into two general classes: non-destructive and destructive. Non-destructive pulsed inductors must solve the high stresses generated in the inductor windings during pulse. These stresses typically reach to 1.4 GPa [4], which is greater than the strength of most materials. Moreover, during pulse generation due to Joule heating inductor windings are heated and in some cases insulation failure may occur due to overheating. When we take into account that copper wire-wound inductors without special reinforcement can generate pulsed fields up to 20 T only it is easy to understand that pulsed magnets require a careful design and modelling [8]. As such, pulsed magnet technology relies on state of the art materials research. The highest magnetic field reached by non-destructive pulsed magnet 100.75 T was reached by Los Alamos National Laboratory on the 22 of March 2012. Destructive pulsed magnets sidestep the strength of materials problem and are designed to explode with every pulse. Since the intense magnetic field exists only as long as it takes a shock-wave to propagate through the magnet the pulse duration is limited to a few microseconds. The highest magnetic field reached by destructive magnet was 1000 T. It is available at Los Alamos National Laboratory and at Sarov, Russia [96]. Therefore, the design and investigation of different pulsed magnetic field inductors, and developing simulation models in various computational tool environments are of great importance.

1. Pulsed Magnetic Fields and Inductors (Literature Review)

1.1. Fundamentals of the Pulsed Magnetic Field Generation

To generate a pulsed magnetic field by using a pulse generator, three main components are necessary: an energy storage system, a switch and an inductor. 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 basic experimentations. The stored energy in capacitor bank is discharged by main switch through the pulsed inductor. 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 they assure good signal synchronization [5]. Therefore, thyristors are usually used as main switch. In this way a half-sinus shape pulse of magnetic field pulse up to 50 T and 1-10 ms in duration can be generated [6]. The inductor basically consists of a set of conductors that is made from a highly conductive material, usually a special copper or aluminum alloy and designed in order to provide desired magnitude of magnetic field as self-destructively or non-destructively. The basic pulse magnetic field generation circuit diagram is shown in Fig. 1 [7].

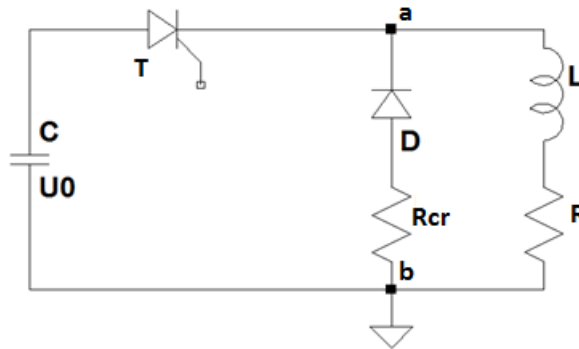


Fig.1. Simplified circuit diagram of pulsed magnetic field generation system

The capacitors bank is charged with a voltage U_0 that is typically 3-10 kV for basic pulse generations [6]. The discharge circuit operates via thyristors, to discharge the capacitors into a magnetizing inductor (with resistance R and inductance L). Thyristors are robust in principle but very sensitive to overrating, they will be destroyed immediately if any of the specifications, most importantly voltage and current is exceeded. The fundamental parameter of magnetization systems is based on the energy of the pulse. The capacitor bank and the inductor of the system create an oscillating (damped) circuit, i.e. the energy $E = \frac{1}{2}CU^2$ which is stored in the capacitors is transferred into the inductor with a magnetic energy $E = \frac{1}{2}LI^2$ and vice versa if circuit is assumed not to have crowbar branch that is connected between nodes a and b in the Fig.1. Therefore, it can be stated that the most simple pulse generator is a simple RLC circuit with a discharge switch. The equation of RLC circuit is given below [8].

$$L \frac{dI(t)}{dt} + RI(t) + \frac{1}{C} \int I(t)dt = 0 \quad (1)$$

Assuming that at the beginning capacitor voltage is U_0 and no current flowing in the circuit, the solution of differential equation is following:

$$I(t) = \frac{U_0}{\omega L} e^{-\gamma t} \sin \omega t \quad (2)$$

By using capacitor discharging equation capacitor voltage can be found as shown below:

$$V_c(t) = U_0 e^{-\gamma t} \left(\frac{\sin \omega t}{\gamma \omega} + \cos \omega t \right) \quad (3)$$

Here $\gamma = R / 2L$, $\omega_0 = 1 / \sqrt{LC}$, $\omega = \sqrt{\omega_0^2 - \gamma^2}$

These equations are useful for current determination for any circuits with linear RLC components. Usually capacitor banks include crowbar circuit. In Fig. 1 crowbar circuit is connected between nodes a and b . Crowbar circuit consists of crowbar diodes connected across the capacitors usually with a variable resistor in series. These diodes begin to conduct current at voltage reversal which occurs shortly after peak field. The reason that it does not occur at the peak field is due to inductor resistance. Crowbar circuit has effect of prolonging the pulse in addition it increases the capacitor lifetime since capacitors are sensitive to reversal charging. Long decay times achieved with low crowbar resistances are used only in inductors that does not heat up during the operation. Otherwise, the decay time is shortened by the increased resistance [9]. Typical wave shapes of the current with and without crowbar circuit is shown in Fig. 2. The operation and effect of crowbar circuit on pulse will be studied more detailed in later sections.

In typical industrial applications, the duty cycles are high and since the inductor receives large amounts of energy, the inductor experiences thermal increases in temperature and high mechanical stresses. In some cases inductor is designed to produce ultra-high magnetic field that is above 100 T and allowed to be destroyed which makes the inductor destructive type. However, usually non-destructive operation of inductors are desired and in this case thermal and mechanical limitations of materials require careful design of inductors. Non-destructive magnets can be short-pulse or long-pulse. The "short" and "long" is a reference to how long the magnetic field lasts. In this context, long is relative – at most 2 seconds. Short is measured in milli or micro seconds [9]. Inductor types are studied detailed in the next section.

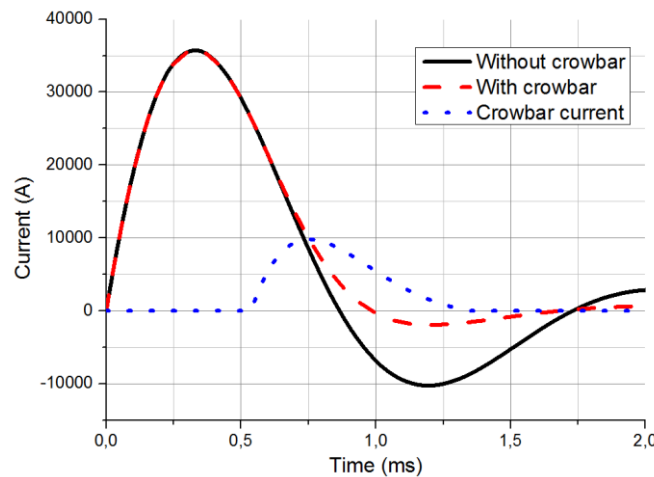


Fig.2. Typical waveforms of the current with and without crowbar circuit.

1.2. Inductor Types

In the operation of pulsed magnetic field generation inductors are the most critical component and needs to be carefully chosen and designed depending on the application. In this chapter inductor types to generate pulsed magnetic fields will be studied briefly.

Basically types of inductors for pulsed magnetic field applications can be divided into single turn, helix and wire wound inductors [5]. These inductors can be destructive or non-destructive depending on the required peak field and field duration. As destructive inductors single turn inductors are the most favorable because of relatively small cost in addition to easiness on construction and will be studied in this section. On the other hand for non-destructive operation multi-layer inductor design is commonly used in applications due to non-destructive high magnetic field generation ability with relatively low costs and risks [9].

1.2.1. Single Turn Inductors

Although recent developed high-strength materials they can tolerate up to 100 T without being damaged. Above 100 T the magnetic pressure exceeds the strength of any material that can be used in inductor windings. Therefore, for high-field designs only single-use, exploding inductor designs can be considered. Single-turn inductor designs are generally best for high field applications (destructive) for several reasons: The main reason is that it is cheaper and easy to construct. Another reason is multiple-turn inductors introduce higher inductance that can limit the current, rise-time, and resulting peak magnetic field that can be achieved [8].

The most simple inductor design is a single-turn loop. The magnetic flux density B on the axis of the inductor with radius a and with current I is given in equation (4) [8]. Maximal current can be found by solving equation (2).

$$B_z(z) = \frac{\mu_0 I a^2}{2(z^2 + a^2)^{3/2}} \quad \text{where } B_z(0) = 0.5\mu_0 \frac{I}{a} \quad (4)$$

Here, z is measured along the axis from the center of the inductor. The inductance for a single-turn inductor is $L \cong d / dI [\pi\mu_0 a^2 B_z(0)] = \pi\mu_0 a / 2$ [8].

However, equation (4) is an approximation. Since they assume that the current is in an infinitesimally small filament. Because of the high currents needed to produce high fields and the resulting high current densities, these conductors must have finite thickness. For a thick axisymmetric, single-turn solenoid, assuming uniform current density, with width $2d$ and inner and outer radii a_1 and a_2 respectively, the on-axis field is [8], [10]:

$$B_z(z) = \frac{\mu_0 I}{4d} \left\{ \frac{d-z}{a_2-a_1} \ln \left(\frac{a_2 + \sqrt{a_2^2 + (d-z)^2}}{a_1 + \sqrt{a_1^2 + (d-z)^2}} \right) + \frac{d+z}{a_2-a_1} \ln \left(\frac{a_2 + \sqrt{a_2^2 + (d+z)^2}}{a_1 + \sqrt{a_1^2 + (d+z)^2}} \right) \right\} \quad (5)$$

The inductance for this inductor can be estimated by multiplying $B_z(0)$ from equation (4) by $L = \pi a_1^2 / I$ [8].

The schematic diagram of pulsed magnetic field generator with the single turn inductor is shown in Fig.3

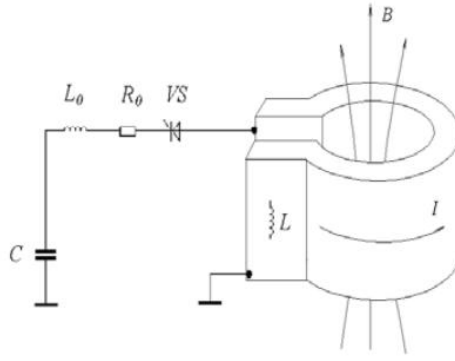


Fig.3. The schematic diagram of pulsed magnetic field generator with single turn inductor [5]

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 inductance of connectors, capacitors and the switch VS . A magnetic field pulse is generated discharging the capacitor bank over the single turn inductor. Energy balance equation is as follows [5]:

$$\frac{CU^2}{2} = \frac{LI^2}{2} + \frac{L_0 I^2}{2} + I^2 R_0 t \quad (6)$$

The efficiency of above described method is about 50% in the best case and about 20% at usual conditions. One of the main effect on efficiency is losses due to the inductance L_0 and because of difficulty decreasing the inductance L_0 less than 1 nH. Another technical problem is the short rise time and the high amplitude of the 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 μ s, 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 inductor is influenced by pressure up to 4 GPa and it is destroyed during few microseconds [5].

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 inductor geometry performs the good basis for reproductive scientific experiments in pulsed magnetic fields up to 300 T [11].

One of possible implementation of pulsed magnetic field generation by a single turn inductor is the usage of pulsed transformer as shown in Fig.4 [5].

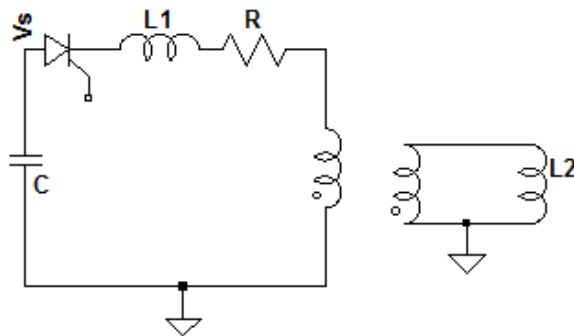


Fig.4. Single turn inductor with transformer

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 switches can be used. But in any case a transformer may be introduced into single turn inductor scheme very carefully. High pulsed power transformer design is not trivial. It means that electric and magnetic losses of a transformer should be evaluated [5].

A single-turn copper inductor design, driven by a strip-line transmission line, as done by Portugall [12] and duplicated by Mielke that is shown in Fig.5. The inductor has a 10 mm inner diameter and is 10 mm wide. The conductor thickness is 3 mm. Not shown in the figure is the mylar insulation that is placed between the two conductors of the transmission line during the shot, and which extends into the inductor region, forming a loop. This design has been used for fields up to 2 megagauss (200 T). A picture of an identical inductor, but after being fired, is shown in Fig. 6 [8].



Fig. 5. Two-megagauss single-turn inductor design, courtesy C. Mielke, LANL. [13], [8]



Fig. 6. Same inductor assembly after a shot, courtesy C. Mielke. [13], [8]

1.2.2. Helix Inductors

Helix inductors can be used for pulsed magnetic field generation up to 60-70 T [14]. A helix could be made by machining hard materials such as copper-beryllium alloys, steel or others. There are two main advantages of these kind of inductors. First, they are able to withstand high mechanical stress and they can be cooled efficiently with liquid nitrogen. Compared to single turn inductors usually helix inductors have higher inductance 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 [5]:

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

Here, $j_0 = \frac{IN}{ah \ln(b/a)}$ is initial current density, I is current, N is number of turns, a_1 , a_2 , h is inner, outer radius and the axial width of the helix, respectively.

Magnetic field in the helix centre is determined by formula [5]:

$$B = B_0 \frac{1}{\ln(a_2/a_1)} F \ln \left[\frac{a_2 \left(1 + \sqrt{(2a_1 + h)^2 + 1} \right)}{a_1 \left(1 + \sqrt{(2a_2 + h)^2 + 1} \right)} \right] \quad (8)$$

Where, $B_0 = \mu_0 \frac{IN}{h}$ is initial magnetic field, $F = \frac{NS}{h(a_2 - a_1)}$ is density of turns and S is cross section of a turn.

Optimal geometry is obtained when $\frac{a_2}{a_1} = 6$, $\frac{h}{2a_1} = 2$.

The capacitor bank connection is done in the same way as the single turn inductor. If non-destructive high magnetic field generation is desired the helix should be reinforced to avoid the destruction. A helix inductor without and with such reinforcement is shown in Fig. 7 [5].

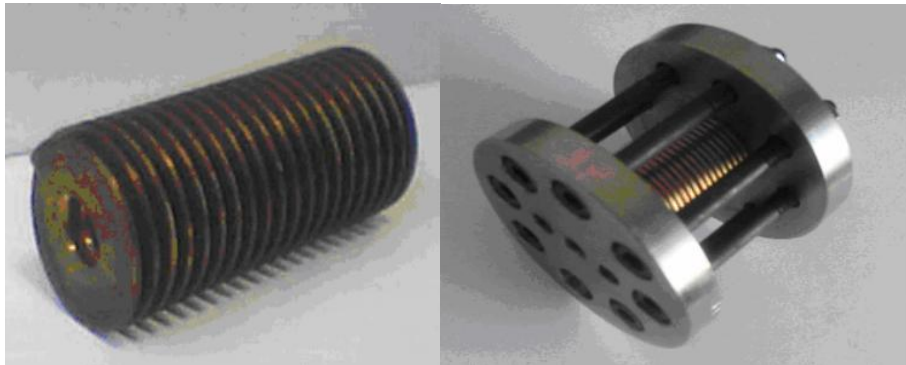


Fig. 7. Helix inductor without and with reinforcement [5]

The maximum magnetic field generated by helix inductor can be determined by maximum current on the windings. The maximum current depends on inductance of helix inductor, capacitance of capacitor bank, voltage U_0 , and active losses on circuit R . The maximum current can be determined by solving the equation (2) of RLC circuit.

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 overheating. The temperature increases more than 100 $^{\circ}\text{C}$ (373 K) during the pulse. Moreover, the shock wave can deform the inductor and initial dimensions can be changed and the non-linear inductance takes place. However, for preliminary evaluations of maximal pulsed magnetic field generated by pulsed inductors as mentioned non-linearity may not be taken into the consideration [5].

From the non-destructive inductor design perspective, the maximum current is determined by thermal and mechanical stress limit of the material that is used to construct inductor and reinforcement if needed. Therefore, to ensure reliable non-destructive operation thermal and mechanical stress analysis is required. The analysis methods will be explained briefly in next chapters.

1.2.3. Wire Wound Inductors

The application of wire wound inductors is the most obvious way to construct pulsed magnets with long pulse duration and good field homogeneity [15]. For this reason, this type of inductors are widely used in the high magnetic field generation applications. The operation principle of pulsed magnetic field generator with wire wound inductor is shown in Fig.8 [5].

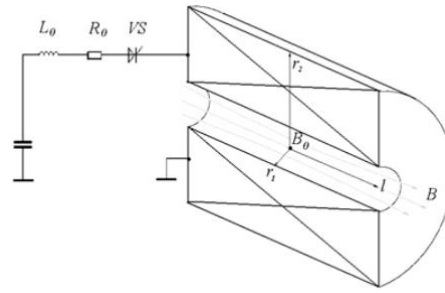


Fig.8. The operation principle of wire wound inductor [5]

Wire wound inductors fulfill the constant current density condition and generated magnetic field B in central area can be calculated by the formula [15] :

$$B = \mu_0 \frac{NI}{r_1} \left[\frac{F(\alpha, \beta)}{2\beta(\alpha - 1)} \right] \quad (9)$$

Where μ_0 is the magnetic constant, N is the number of turns, I is the current a_1 , a_2 , $2b$ are inner, outer radius and length of the inductor respectively, $\alpha = a_2 / a_1$, $\beta = 2b / 2a_1$ are relative sizes and $F(\alpha, \beta) = \beta \ln \left(\frac{\alpha + \sqrt{\alpha^2 + \beta^2}}{1 + \sqrt{1 + \beta^2}} \right)$ is the form factor of the solenoid.

The axial and radial magnetic fields created by a current loop might be calculated at any given point [16]:

$$B_z(r, z) = (\mu_0 / 2\pi) I_{\max} \left(\frac{1}{\sqrt{(a+r)^2 + z^2}} \right) \cdot \left(\frac{a^2 - r^2 - z^2}{(a-z)^2 + z^2} E(m) + K(m) \right) \quad (10)$$

$$B_r(r, z) = (\mu_0 / 2\pi) I_{\max} \left(\frac{1}{\sqrt{(a+r)^2 + z^2}} \right) \cdot \left(\frac{a^2 + r^2 + z^2}{(a-z)^2 + z^2} E(m) - K(m) \right) \quad (11)$$

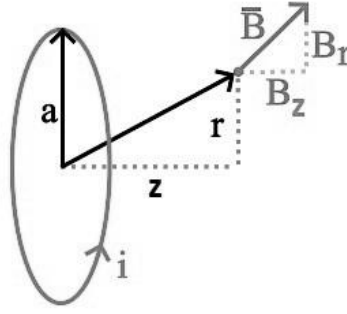


Fig.9. Current loop and axial and radial components of magnetic field

Where, r, z is radius and height of any point where B is calculated (from the center point of inductor $(0,0)$), a radius of the loop which carries current (see Fig.9), $E(m), K(m)$ is elliptic first and second order integrals when $m = 4ar / ((a+r)^2 + z^2)$.

When inductor has N_2 windings and N_1 layers, the distribution of axial and radial magnetic fields can be calculated:

$$B_z(r, z) = \sum_{i=1}^{n_z c_z} \sum_{j=1}^{n_i c_r} B_{z,ji}(r, z) \quad (12)$$

$$B_r(r, z) = \sum_{i=1}^{n_z c_z} \sum_{j=1}^{n_i c_r} B_{r,ji}(r, z) \quad (13)$$

Where, c_r and c_z multiplication factors.

The maximal current can be calculated by the same way using equation (2) as described in previous section for RLC circuit.

This kind of pulse 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 inductors without the construction reinforcement [5].

For higher magnetic fields the most common construction of pulsed magnetic field inductors is multi-layer inductors and multi-section inductors with internal reinforcement. Designing process of this inductors is complex task and needs careful analysis. Before designing the inductor the thermodynamic and stress analysis should be done. Based on thermodynamic analysis type of the material for optimum resistance and optimum cross section of conductor should be determined. Thermal capacity of windings can be increased constructively using a wire with greater cross-section to avoid the overheating and depending on conductor resistance current density should be determined as thermal limit would not be exceeded [17], [5]. Thermal analysis could be done by using finite element method (FEM) and its softwares.

On the other hand from the mechanical perspective as the main component of the Lorentz force is in radial direction the easiest way to reinforce an inductor is to mount a heavy reinforcement at the outside. It protects the inductor from the exploding. However, the inner layers of inductors are stressed more than outer ones. The deformation of the inner layers is the main reason of the inductor failure as shown in Fig.10 [5].



Fig.10. Destructed pulsed solenoid [5]

The first layers could be wound with high strength conductor as they are exposed the highest mechanical forces. Next layers could be wound with weaker conductor, but of more electrically conductive material. As mentioned before a special inner and outer reinforcement is required to ensure non-destructive operation. For inner reinforcement Zylon+Epoxy composition can be used and for outer reinforcement steel shell might be used [9]. Inductor design materials will be studied more detailed in a later section.

The approximated relationship between maximum mechanical stress and magnetic field is calculated as [9]:

$$B = \sqrt{2} (1 - 1/\alpha) \sqrt{2\mu_0\sigma_t} \quad (14)$$

Here σ_t is the tensile strength of wire, α is the ratio of outer to inner radius.

Mechanical behavior is, however, of multi-axial character and solid stress analysis is required for strength evaluation. Therefore as the most efficient numerical tool FEM should be used. However, calculations are difficult when solving multi-physics problems. To overcome this difficulty some FEM simulation packages could be used as they offer flexibility and efficient solutions.

Detailed thermal and mechanical analysis are beyond this thesis, however it will be mentioned briefly in the next chapter.

1.3. Thermal and Mechanical Aspects

In the operation of pulsed magnetic field generation, which was mentioned in section 1.1, the most critical component is the pulsed inductor. During the operation pulsed inductors experience mechanical, thermal and electrical overloads occurring due to Lorentz force and Joule heating [17]. Thermal and mechanical limits of materials make the pulsed inductor design a complex task. There are many different choices for the combination of materials; while the insulator in these inductors always must have superior strength, the conductor can be either soft or contribute to the strength as well. The stronger conductor usually has a higher electrical resistivity, which has to be compensated for by a lower current density to keep the heating to the same level. Also inductors with internal reinforcement are from the mechanical, thermal and manufacturing points of view well suited for the generation of very strong pulsed magnetic fields [18].

In recent years many new materials with unique technical parameters have been developed in pulsed inductor design to overcome mechanical stress and thermal limits. Such microcomposite conductors like Cu-Nb, Cu-Ag combine good conductivity (65-75% of the International Annealed Copper Standard (IACS)) and high mechanical strength (ultimate tensile strength in order of 1-1,5 GPa) are applicable. Winding insulation using modern material like Kapton, glass fibers and further reinforcement with Zylon, carbon fiber composites allows to construct non-destructive pulsed inductors (at least for 100 pulses) for magnetic field generation in the range of 50-70 T, where usual materials are out of the application due to destructive overloads [9],[19].

Electrically, a pulsed inductor can be assumed as a heater. During operation huge current induces the Joule heat in an inductor winding and operation temperature increases very much. Rapid heating during pulsed inductor operation leads to changes of electrical properties of applied materials. Moreover inductor heating might be close to adiabatic process and dissipation of heat is usually insignificant. Inductor heating strongly influences the maximum value of generated magnetic field and the overheating can damage interlayer insulation limiting the lifetime of the inductor. Therefore, pulsed inductors might be pre-cooled with liquid nitrogen to avoid critical thermal overloads which follow further inductor disintegration. Thermal capacity of windings could be also increased constructively using a wire with greater cross-section [17].

Joule heating and temperature increment for every wire layer can be calculated using the current value $i[N]$ at the time moment $t[N]$ [17]:

$$dQ_i = i^2[N]R_i dt; \quad c \cdot m = c_i(T); \quad dT_i = \frac{dQ_i}{m_i c_i} \quad (15)$$

Heat dissipation for every layer j must be computed using equation (16) recursively.

$$dQ_j = k_j(T)A_j \frac{dT_{-j,j}}{v_n} dt \quad (16)$$

Here m is mass (the density must be given for every material), A is surface area, v layer width, c is specific heat and k is thermal conductivity and are calculated for every layer in order to evaluate the heat dissipation to the surrounding layers and the environment during the pulse. The parameters c and k are unique for every material and they are as well dependent on temperature [17]. Also dependency of wire material resistivity on temperature and magnetic field (magnetoresistance effect) and the derivative of the field (skin effect) should be taken into account during analysis to obtain more realistic results [9].

If an efficient heat dissipation design has been incorporated into the inductor, the heating effect will be reduced to an acceptable working temperature for safe operation. Also some other arrangements with values of circuit components of pulse generator can be done to avoid overheating effect. The pulse duration must be short to keep the energy dissipation within acceptable limits and thus, small L and C values are favored to generate short pulse. This requires high voltage of the capacitor bank [20]. In addition to this, the application of crowbar with resistive ballast strongly influences transient processes in the circuit and cut them after maximum current has been reached. Therefore, temperature rise would decrease drastically and overheating due to Joule heating can be avoided even without initial cooling [6]. The effect of crowbar circuit on current in the inductor will be discussed later

more detailed. The dependency of pulse duration τ on inductance and capacitance values can be found approximately by equation (17).

$$\tau \cong K\pi\sqrt{LC} \quad (17)$$

Here, K is a constant which varies with value of series resistance connected to inductor. Therefore, it can be concluded that it depends on circuit characteristic i.e. over-damped, under-damped, critically damped. K equals to 1 in case of under-damped and 2 in case of critically-damped circuit. Pulse duration for circuits having over-damped characteristic can be assumed roughly as in the case of critically-damped circuit characteristic. From the equation (17) it is seen that pulse duration is proportional to values of inductance of inductor and capacity of capacitor bank.

Another limitation is due to strength limits of materials used in inductor. Magnetic forces in the inductor wires, insulations and reinforcements should not exceed the ultimate tensile strength limit to ensure reliable non-destructive operation. In addition to the analysis of thermodynamic processes in multi-layer inductors the structural-stress analysis should be performed as well [17]. The process starts with the calculation of magnetic field density distribution in the inductor windings while using the current value which was obtained during thermodynamic analysis. Next step is to calculate Lorentz forces and stresses that occur on inductor's windings and reinforcement layers. The calculated axial, radial, hoop and, finally, Von Misses stresses give us an idea of inductor's reliability for multi-time use. Stresses that exceed material's yield strength at any point may lead to the plastic material deformation which might have following consequences: if stresses would exceed materials' tensile strength, inductor would be damaged, its windings would be short-circuited, reinforcement would be damaged and no longer would have function as it should, inductor would become unusable; if stresses would exceed materials' yield strength, inductor's geometry would change which would lead to the change of inductor's inductivity, resistance and, therefore, to unpredicted processes in it during the next pulse. If a long-life inductor is aimed, all the above mentioned consequences must be avoided [21].

As radial stresses are caused by axial magnetic field, they act as inductor's expanding forces towards outer reinforcement cylinder and could be computed:

$$\sigma_r(r, z) = j \int_{a_2}^r B_z(r, z) dr \quad (18)$$

Axial stresses are caused by radial magnetic field and act as inductor's compressive force along inductor's bore axis:

$$\sigma_z(r, z) = j \int_0^b B_r(r, z) dz \quad (19)$$

Where: r , z are radius and height of any point where B is calculated (from the inductor centre point (0,0)); σ_r is radial stress, σ_z is axial stress, a_2 is outer radius, $2b$ is the inductor length [21].

Hoop stress for each given z is calculated according to formula given in [16]:

$$\sigma_h(r, z) = \frac{(B_z^2 + B_r^2)}{2\mu_0} \cdot 2 \frac{r}{a} \cdot \frac{\alpha - r/a}{(\alpha - 1)^2} \quad (20)$$

Here, a is the radius of the first inner winding; r is the radius of the calculated point and α is the ratio of outer radius of inductor to inner radius of inductor. If the radial stress σ_r and/or axial stress σ_z is present in addition to hoop stress, the criterion for mechanical failure (related to plastic deformation) is Von Misses stress. The Von Misses criteria to evaluate the sum stresses then is [9]:

$$\sigma_{VM} = \sqrt{\frac{(\sigma_h - \sigma_r)^2 + (\sigma_h - \sigma_z)^2 + (\sigma_r - \sigma_z)^2}{2}} \quad (21)$$

During the operation of pulsed inductor the main component of the Lorentz force occurs in radial direction. The detailed analysis can be seen in [21] and [9].

1.4. Applications of Electromagnetic Pulse Technology in Applied Sciences

The electromagnetic pulse technology (EMPT) provides non-contact processes for joining, welding, forming and cutting of metals by the produced electromagnetic forces by inductor. Non-magnetic metals such as aluminum tubes can also be processed, as an eddy current is temporarily induced in the skin of the tubes [22]. Pulsed electromagnetic fields also effective on reducing pain, healing wounds, depression and various other recoveries. Another application of EMPT is coil guns in the area of defence and military technologies. On the other hand pulsed magnetic fields are subject of fundamental sciences, i.e. physics, biology, chemistry, as well. Since higher magnetic fields than permanent magnets offer can be achieved by pulsed magnets it provides us opportunity to see what we were not able to see before. However, in this section focus will be on the mentioned applied science applications of pulsed electromagnetic fields since fundamental science applications require a lot more background on those subjects.

1.4.1. Industrial Applications of the Electromagnetic Pulse Technology

Electromagnetic forming is a forming technology using pulsed magnetic field to apply Lorentz' forces to workpieces without direct mechanical contact and a working medium. Electromagnetic forming is high speed process due to nature of electromagnetic pulse generation. Workpieces are made of highly electrically conductive materials preferably. Using electromagnetic pulse technology (EMPT) hollow profiles can be compressed or expanded and flat or three-dimensionally preformed sheet metal can be shaped and joined as well as cutting operations can be performed [23]. Some of the products procured by using EMPT can be seen in Fig.11.

In electromagnetic forming process the high magnetic fields, which are necessary to form metals with high electrical conductivity, are generated via a pulse generator which corresponds to a resonant circuit. The operation principle was briefly explained in section 1.1. The forming machine can be modeled as in the Fig.12.

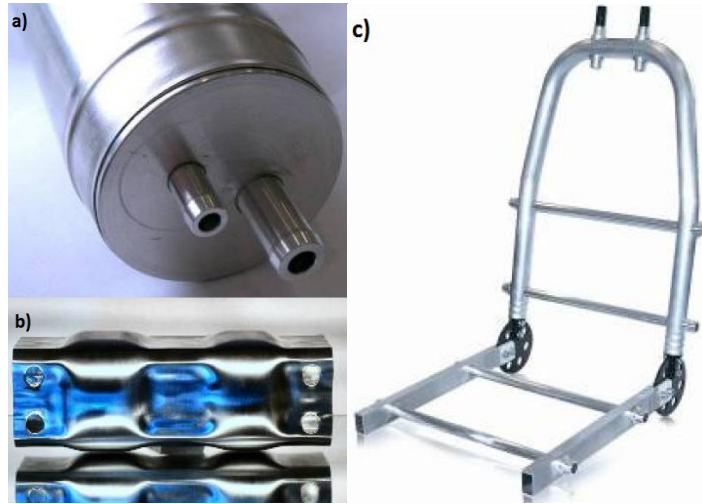


Fig.11. a) EMPT welding of a pressure vessel for air condition systems ($\varnothing 75\text{mm}$ diameter aluminum), b) Simultaneous EMPT forming and EMPT cutting of a crash box, c) EMPT crimping of dissimilar materials for lightweight seat structures of cars and aircraft [24], [22].

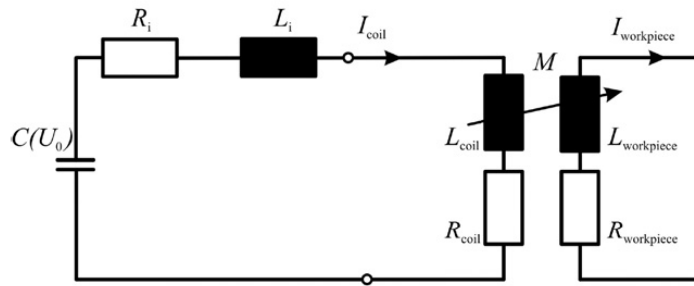


Fig.12. Circuit Diagram of EMP for industrial applications [24]

In this circuit the energy stored in capacitors $E = \frac{1}{2}CU^2$ is transferred into inductor as magnetic energy $E = \frac{1}{2}LI^2$ and vice versa. The resulting current value $I(t)$, which has a highly damped sinusoidal oscillation character, is determined by the electrical properties of resonant circuit components and can be found by equations (1-2) which was given before. The magnetic field which is concentrated between the workpiece and the tool inductor is related to current. This magnetic field creates eddy currents that flow in the opposite direction in the workpiece according to Lenz's law. These currents are flowing through the surface of the workpiece due to skin effect. As a result, the tube wall experiences a radial force acting inwards (see Fig.13) [22]. The magnetic pressures for forming of metallic materials are in the range of 100 N/mm^2 . To generate these pressures, it is necessary to apply pulsed currents in the range from 100 kA to around 2000 kA [22].

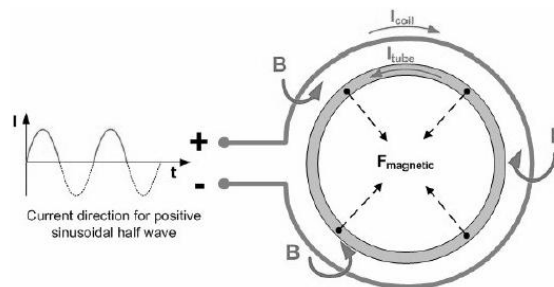


Fig.13. Metallic tube inserted into an electromagnetic inductor. Inductor current, eddy currents and forces are shown for the positive half wave of the alternating current [22]

A magnetic pressure, also called Maxwell pressure, acts nearly orthogonal onto the workpiece surface. Deformation of the workpiece starts in areas close to the windings of inductor as the magnetic pressure acts only in these areas. This pressure causes a plastic deformation of the workpiece by exceeding the flow stress. In Fig.14 based on this, directions of the current, the magnetic field lines and the pressure during electromagnetic compression, electromagnetic expansion and electromagnetic sheet metal forming is shown [23].

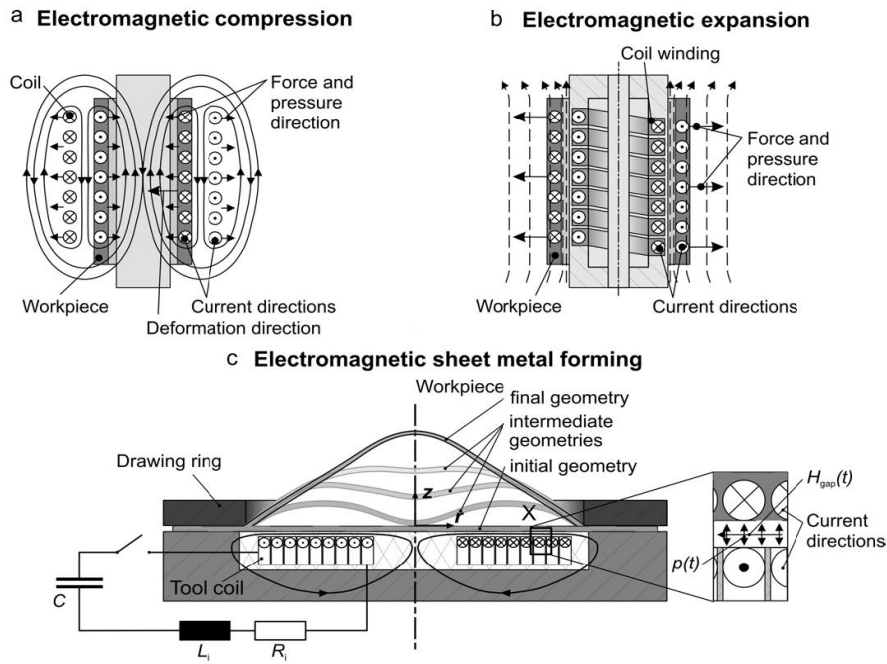


Fig.14. Directions of the current, the magnetic field lines and the pressure during a) electromagnetic compression, b) electromagnetic expansion, c) electromagnetic sheet metal forming [23].

The most important parameters that influence the process are: energy level, induced current, electrical conductivity and the mechanical properties of the workpiece material and the geometry. In order to perform successful EMP forming process current should flow as close as possible to the surface of the material to be deformed [23].

The depth of penetration of the current into the workpiece called skin depth δ mainly depends on the specific electrical conductivity κ of the workpiece and the frequency f of the closed electrical circuit [23].

$$\delta = \frac{1}{\sqrt{\pi f \kappa \mu_0 \mu_r}} \quad (22)$$

where μ_0 represents the magnetic permeability in a vacuum and μ_r is the relative permeability of the material with eddy currents induced.

Equation (22) shows clearly that the conductivity of workpiece and frequency of current are very important parameters to create a successful EMP generation for forming process. The frequency of an electromagnetic pulse system comes mainly from the type and the amount of capacitors. In addition to this, other circuit components have effect on pulse duration. It was shown approximately in equation (17) and explained. In Table 1 the electrical conductivity characteristics of some technically relevant materials are represented. At

present, the conductivity of structural steel represents the minimal value for accomplishing direct EMP forming process. If the material's conductivity is below that of structural steel, ohmic losses will cause an undesired heat generation inside the workpiece. This eventually would cause a significant decrease in the magnetic pressure amplitude. One way to overcome this challenge is to use a driver. Driver is a thin walled aluminum or copper ring which is placed in a forming area. With a driver, non conductive material is also formable by EMPT. Structural steel is applicable for driverless EMPT. However, for EMPT forming of stainless steels today the use of driver rings is preferred [25].

Table 1. Electrical conductivity of some technical relevant materials [26]

Material	Electrical Conductivity [1m/Ω.mm ²]=[10 ⁶ S/m]
Copper - Cu (Pure)	58.82
Gold - Au (Pure)	45.45
Silver - Ag (Pure)	64.51
Aluminum - Al 99.9	37.67
Aluminum 6082	24-28
Magnesium - Mg 99.9	21.7
Magnesium AZ91	6.6-7.1
Structural steel	9.3
Stainless steel 301	1.4

The electromagnetic pulse systems used in industry generally have a discharging frequency in the range 6 to 30 kHz. Nowadays, in industry typically electromagnetic pulse systems have the life time of the capacitors is more than 2 million pulses, with scheduled maintenance intervals for the high power switches approximately every 500,000 pulses. The discharging currents are between 100 kA and 2000 kA at a voltage of 10 kV to 16 kV, depending on the model [22].

1.4.1.1. Use of Fieldshaper

In the operation of EMP forming applications, commonly for electromagnetic compression, an additional component is usually used which is so called fieldshaper. Fieldshaper is positioned between tool inductor and workpiece. A fieldshaper is a usually axis-symmetric component made of an electrically high conductive material, which features one or more axial slots as shown in Fig. 15 [23].

As described before, in the process of pulse generation sudden discharge of capacitor causes a damped oscillated current flowing through the tool inductor which induces electromagnetic field according to first Maxwell equation and according to second Maxwell equation a current is induced in the conductor which is vicinity of the inductor that is in our case a field shaper. Due to the skin effect and Lenz's law this induced current flows opposed to the inductor current at the outer surface of the fieldshaper. At the axial slots the current is directed to the inner surface of the fieldshaper (the so-called concentration area). Here

the current direction is the same as in the tool inductor. Initially the magnetic field is shielded by the induced current and therefore limited to the gap volume [23].

Fieldshaper has typically much smaller concentration area than outer surface of it. Therefore, at the concentration area higher current density and higher field strength is obtained (see Fig.16). Due to this magnetic field current is induced in the workpiece that is places in the region of the concentration area, which in turn shields the magnetic field. As a result of this current and magnetic field Lorentz forces are acting on tool inductor, fieldshaper and workpiece. To observe deformation of the workpiece these Lorentz forces have to reach and exceed the flow stress of the workpiece material [22], [23].

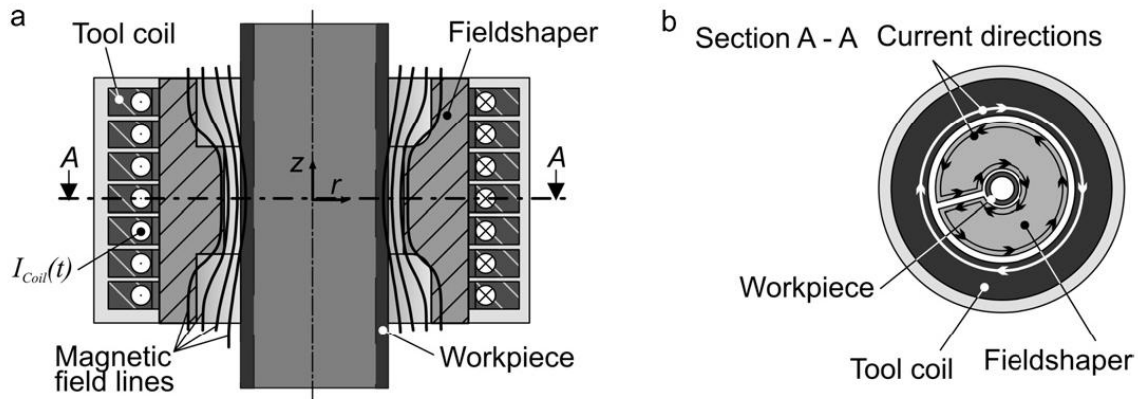


Fig.15. a) Sketch of the magnetic field distribution for a fieldshaper featuring a step, b) current directions in tool inductor fieldshaper and workpiece [27], [28].

The most important advantage of using fieldshaper in operation of electromagnetic forming is that the tool inductor experience significantly less mechanical loading compared to direct acting inductor (i.e. without fieldshaper). This results higher inductor life-time. Nowadays electromagnetic forming machines with fieldshapers are used with up to 2.000.000 pulses lifetime in industry [22]. The reason behind this correlation is that, in case of correctly choice of the size ratio of the fieldshaper surface in the concentration area and the outer fieldshaper surface, the forces between the fieldshaper and workpiece are significantly higher than the forces between the tool inductor and fieldshaper. Furthermore, it has been shown that fieldshapers can be used in order to adjust the diameter and length of an existing tool inductor to different workpieces and forming tasks, respectively, so that the flexibility of the process is increased significantly [23], [29]. This flexibility can be increased by the detailed design of the fieldshaper [23].

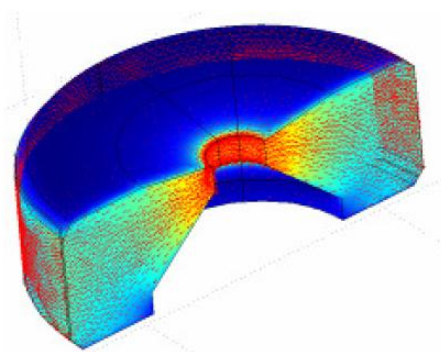


Fig.16. Concentration of the electromagnetic field in the fieldshaper [22]

On the other hand, the use of fieldshaper brings disadvantages. One of the disadvantages is inhomogeneity in the magnetic field resulting inhomogeneity in the force distribution along the circumference of the workpiece. Both, the magnetic field and the force feature a local minimum in the area of the axial gap(s) in the fieldshaper which is more significant the higher the gap width is [23]. The other disadvantage is that the process efficiency is reduced with fieldshaper inclusion. Reasons for this effect are additional resistive losses in the fieldshaper and losses of inductive energy due to inefficient inductive coupling of the tool inductor, fieldshaper, and workpiece and due to additional gap volumes [30]. However, these losses can be reduced and thus the process efficiency can be increased if the fieldshaper material is of high electrical [31].

1.4.1.2. Basic Mathematical Equations for EMP Forming

For a target-oriented dimensioning of electromagnetic forming processes, knowledge about the relevant process parameters as well as their influences and dependencies is essential and has therefore been a topic of intensive research since the 1960's up to now. Determination of the acting loads and the resulting deformation of workpiece is an important aspect as a result. The parameters that influence the acting loads can be listed as machine parameters, tool parameters and workpiece parameters. Important machine parameters are the capacity, the inner inductance, the inner resistance, the ringing frequency and the charging energy. Tool parameters are properties as, e.g. the geometry, the inductance, and the material of the inductor, the fieldshaper properties, and the die/mandrel. Important workpiece parameters are the geometry, the material, the electrical conductivity, and the mechanical properties (e.g. flow stress and strain at failure). This means that with the same energy stored in capacitor, significantly different loads and forming results might be obtained with different parameters of machine, inductor and the workpiece. As a result charging energy alone is not enough to describe loads [23].

To be able to make comparison between experimental studies in which different equipment is used, the course of the inductor current (i.e. frequency and maximum current) and the temporary course besides, the local distribution of the magnetic field strength and the magnetic pressure can be used to give a more detailed description of the acting loads [23].

Lorentz forces acting on the workpiece can be determined based on current and magnetic flux density as following:

$$\vec{F}_L = \vec{J} \times \vec{B} \quad (23)$$

Here, $\vec{F}_L$ is Lorentz force, $\vec{J}$ current density and $\vec{B}$ magnetic flux density. Calculation of magnetic flux density for different inductor types were given in previous sections.

Disregarding the component of the magnetic field strength that is oriented in the direction of the workpiece thickness i.e. the radial component in the case of tube forming and the z-component in the case of sheet metal forming – the current density equals the negative derivative of the magnetic field strength H with respect to the radius r as shown in equation (24) and the with respect to the z-coordinate, respectively, as shown in equation (25) [23].

$$\vec{J} = -\frac{\partial H}{\partial r} \quad (24)$$

$$\vec{J} = -\frac{\partial H}{\partial z} \quad (25)$$

The magnetic flux density is the result of the product of the permeability μ and the magnetic field strength. Thus, the radial forces acting on a tubular workpiece F_{Lr} can be calculated using equation (26) [24]:

$$F_{Lr} = -\mu H \frac{\partial H}{\partial r} = -\frac{1}{2} \mu \frac{\partial(H^2)}{\partial r} \quad (26)$$

In the same way, the forces acting on a sheet metal workpiece can be calculated as in equation (27):

$$F_{Lz} = -\mu H \frac{\partial H}{\partial z} = -\frac{1}{2} \mu \frac{\partial(H^2)}{\partial z} \quad (27)$$

These volume forces acting on the workpiece can be transformed mathematically to virtual surface forces, the so-called magnetic pressure p [23]. The pressure difference between two points in the wall of the workpiece can be determined by integrating the acting forces over the distance and thus, the overall pressure acting on a tubular workpiece can be calculated by using the inner radius r_i and the outer radius r_o of the tube as integration limits [32]:

$$p(r, t) = \int_{r_o}^{r_i} F_L(r, t) dr = \frac{1}{2} \mu (H_{gap}^2(t) - H_{pen}^2(t)) \quad (28)$$

Similarly in the case of sheet metal forming, the lower and the upper surface of the workpiece can be used as integration limits [24]. In both tube and sheet forming process the magnetic pressure depends only on the magnetic field strength in the gap between the tool inductor and workpiece H_{gap} and on the penetrated magnetic field H_{pen} [23].

If the skin depth is small in comparison to the thickness of the workpiece, the penetrated magnetic field is frequently neglected and so the magnetic pressure can be calculated by the simplified equation (29) [23]:

$$p(r, t) = \frac{1}{2} \mu H_{gap}^2(t) \quad (29)$$

This simplification is applicable when ratio of skin depth and inner radius of workpiece is less than 0.2 and the ratio of wall thickness and skin depth is not smaller than 2 [33]. According to Dietz *et al.* [34], this simplification is acceptable if the wall thickness equals at least 1.5 times the skin depth.

1.4.2. Biological Applications of Electromagnetic Pulse Technology

As time-varying or pulsed electromagnetic fields (PEMFs) create microcurrents in the tissues of body PEMF therapy is effective. These microcurrents elicit specific biological responses depending on field parameters such as amplitude, frequency, and waveform [35].

The body contains multiple electromagnetic fields with each tissue and organ having a unique electromagnetic signature. Computerized Axial Tomography (CAT) scans and Magnetic Resonance Imaging (MRI) scans take advantage of these unique signatures to create a map of the body's tissues using pulsed electromagnetic fields. While the diagnostic

benefits of PEMFs are accepted and widely used, medical practitioners are still realizing the therapeutic benefits of PEMFs [35].

Piezoelectric properties of bone was reported by Japanese scientists in 1954. This finding opened new doors for further research showing that damaged bone responded therapeutically to electric fields and pulsed electromagnetic fields. Then in 1995, scientists at the University of Kentucky found that each type of soft tissue responds favorably to specific electromagnetic frequencies [35],[36].

After that, peer reviewed clinical research documenting the biological and therapeutic effects of PEMFs has increased dramatically. This research resulted development of many types of effective PEMF devices. However, the Food and Drug Administration (FDA) has cleared relatively small number of these devices for treating specific conditions. As clinical evidences continues to increase, and as patients demands increase for effective but safer medical therapies change in this seems inevitable in this. Since the FDA cleared the first therapeutic PEMF device over 30 years ago, there have been safety alerts issued for any of these devices. This reflects the overall safety of short sessions of therapeutic PEMFs [35].

The benefits of PEMF therapy have been documented in multiple peer-reviewed clinical studies for a wide range of medical conditions. Randomized double-blind, placebo controlled clinical trials using PEMF therapy have shown beneficial effects for chronic low back pain, fibromyalgia, cervical osteoarthritis, osteoarthritis of the knee, lateral epicondylitis, recovery from arthroscopic knee surgery, recovery from interbody lumbar fusions, persistent rotator cuff tendinitis, depression, and multiple sclerosis [35], [37]-[46].

In October of 2008, the FDA cleared a PEMF device using repetitive transcranial magnetic stimulation (rTMS) for the treatment of Major Depressive Disorder in adult patients who failed to achieve satisfactory improvement from prior antidepressant medication. In a multicenter clinical trial, approximately half of the patients experienced significant improvement in depression symptoms, and approximately a third of the patients experienced complete symptom relief at the end of six weeks [35], [47].

1.4.2.1 The future of PEMF therapy

The future of PEMF therapy is promising given the findings of early research in a wide variety of health conditions. For example, preliminary data in clinical studies shows rTMS has promise in treating schizophrenia, post-traumatic stress disorder, obsessive-compulsive disorder, Alzheimer's disease, and Parkinson's disease [35], [48]-[52].

In relation to cardiovascular disease, studies show how PEMF therapy may reduce blood glucose levels, blood viscosity, total cholesterol, and triglycerides, while raising high-density lipoprotein (HDL) [53]-[54]. These studies will hopefully lead for further investigation. Another study shows how PEMF therapy may accelerate the healing of damaged brain tissue following acute stroke [35], [55].

In light of the emergence of drug resistant bacteria, clinical studies show how PEMF therapy could one day become part of the standard of care in inhibiting *Staphylococcus aureus* infections and augmenting antibiotic therapy [56]-[57]. Complicating the issue of antibiotic resistance are biofilms, dynamic mucous-like cities in which bacteria live and thrive. Biofilms protect bacteria and assist in bacterial cell-to-cell communication and in the exchange of genetic information. The same bacterium living outside a biofilm is less

susceptible to antibiotics when living in a biofilm. Studies indicate PEMF therapy may effectively address this dangerous bacterial diversity [35], [58]-[59].

Studies also suggest that PEMF therapy may one day be used to treat cancer. Findings show PEMF therapy induces apoptosis of cancer cells, inhibits the growth of malignant tumors, modulates the immune system via cytokines as an anti-tumor effect, and may act synergistically with chemotherapy and photodynamic therapy to combat tumor growth [35], [60]-[63].

1.4.3. Coil Guns

The most commonly used way of projection in military, by means of gunpowder, has many disadvantages including additional weight, volatility and limited velocity. This fact enhanced scientists to look for more efficient way to launch projectiles [64]. Electromagnetic launchers emerged on this need.

Generally electromagnetic launchers are categorized into two kinds of systems: railguns and coil guns. A railgun is a purely electrical gun that accelerates a conductive projectile along a pair of metal rails. It contains two parallel metal rails with a sliding conductive projectile. The acceleration of the projectile is achieved by a power supply acting mainly as a current source and providing a huge current [64]. The railgun is suitable for small projectiles and conceptually simple [65]. However, it has inherent problems and limitations. For example, need of huge current flow through rails and its heating effect that is damaging rails.

On the other hand, in a coilgun, a current is passed through a solenoid rather than rails, creating a magnetic field which draws a projectile to the center of the inductor. If the current is stopped quickly, it continues out of the barrel at rapid speed. Many coilguns involve multiple stages of inductors which are triggered in series for maximum acceleration [66]. Coilgun is not suitable for small projectiles, but only for large launch masses. Especially, the capacitor-driven inductive coilgun which is almost free from the friction between barrel and sleeve is recommended for rapid acceleration. It can be easily installed and used in multi-shot applications. [65], [67]-[68].

The coilgun operates by quickly discharging a large amount of energy from a capacitor through an inductor, creating a strong magnetic field through the inductor. This strong field induces magnetization in the slug, causing microscopic dipoles to align with the field in a lower energy state. Because the inductor is a solenoid of finite length, the produced magnetic field decays in strength axially away from the edge of the inductor. The aligned dipoles feel a force proportional to the gradient in the magnetic field [66]:

$$F = \mu_0 \nabla (M \cdot H) \quad (30)$$

Where M is the projectile magnetization and H is the applied field. If x is the position of the right side of the projectile, and l is the length of the projectile the total force is:

$$F = \int_{x-l}^x \mu_0 \frac{d}{dx} (\chi_m H^2) S dx \quad (31)$$

$$F(x) = \mu_0 S \chi_m (H(x)^2 - H(x-l)^2) \quad (32)$$

Where S is the cross sectional area of the projectile, χ_m magnetic susceptibility. This equation for the force on the slug gives a non-linear second order ordinary differential equation [66].

If the current were sustained indefinitely, after being accelerated from one side of the inductor, the projectile would encounter an opposite gradient on the other side which would apply a force back towards the center of the inductor. Thus, a coil gun with constant current would simply cause the projectile to oscillate within the inductor. If the slug reaches the other side of the inductor while significant current is still running in the inductor, the slug will experience a force toward the center of the inductor, slowing its motion. This effect is commonly called suckback, and is undesirable for coil gun operation. However, if all of the charge is drained from the capacitors quickly, before the projectile reaches the other side of the inductor, there will be no repelling force and the projectile will continue on to exit the barrel [66].

Induction coil guns developed at Sandia National Laboratories consist of short-length, solenoidal electromagnets that are stacked end-to-end to form a barrel as shown in Fig. 17. The inductors are energized sequentially to create a single wave of magnetic energy moving from breech to muzzle just slightly faster than the speed of the accelerated projectile. The color density in the inductor cross-section in Fig. 17 represents the magnitude of the current in each inductor. Each of the barrel inductors shown in Fig. 17 is energized by its own capacitor bank [69].

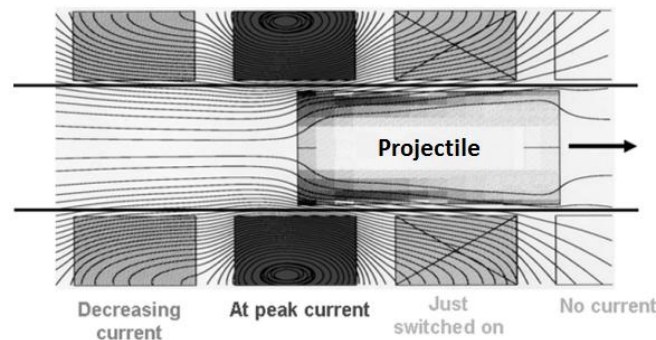


Fig. 17. Cross-section view of axisymmetric coil gun with contours of flux lines [69]

To create the traveling magnetic wave in the barrel that is near-synchronous with the location of the projectile, a real-time detector locates the projectile and the gun's firing system generates the trigger to the main closing switches of the capacitor banks of the individual inductors. The discharge of current into successive inductors ideally creates a boundary condition of magnetic field for the projectile that is near-constant, allowing the projectile to be magnetized with near-dc currents. These induced currents therefore penetrate more deeply into the conductor resulting in less localized heating at the conductor surface than if higher frequency field variation occurred. To achieve such a field variation and a smooth acceleration, it is important to utilize inductors whose length is short compared to the diameter, and the risetime of the current in the inductor must be about the transit time of the projectile length through that inductor. As the projectile speed increases from the breech of the gun to the muzzle, the current risetime, which is also the time to

transfer the energy stored in the capacitor bank to the inductor, decreases proportionally [69].

The launch thrust and acceleration can be tailored to the needs of the projectile since the stored energy in each bank is adjustable. However, a uniform acceleration profile that is near the projectile's maximum acceleration capability yields the desired muzzle velocity with the shortest length gun [69].

Potential uses of coil guns generally are related with defence technology. Some of the applications in this area are given in the following. An experimental 45-stage DARPA coil gun mortar design is 22% efficient, with 1.6 megajoules kinetic energy delivered to a round [70]. In 2011, development was proposed of an 81mm coil gun mortar to operate with a hybrid-electric version of the future Joint Light Tactical Vehicle [71], [72]. Electromagnetic aircraft catapults are planned, including on board future U.S. Gerald R. Ford class aircraft carriers. An experimental induction coil gun version of an Electromagnetic Missile Launcher (EMML) has been tested for launching Tomahawk missiles [73]. A coilgun based active defense system for tanks is under development at HIT in China [74].

Coilgun potential has been perceived as extending beyond military applications. Challenging and corresponding to a magnitude of capital investment that few entities could readily fund, gigantic coilguns with projectile mass and velocity on the scale of gigajoules of kinetic energy (as opposed to megajoules or less) have not been developed so far, but such have been proposed as launchers from the Moon or from Earth. More detailed information can be found in [75]-[78].

2. Analysis of Current Waveform Using Matlab Simulink®

To have reliable magnetic pulse generation the duration of pulse to be generated has to be studied well to prevent unwanted effects such as overheating of inductor. Also, as described before in some applications pulse duration of magnetic field is important. For instance, in EMP forming applications the pulse duration must be small to obtain small skin depth that is necessary for EMP forming process to be successful and in some biological treatment and experimentation processes longer pulses are required. Since duration of magnetic pulse proportional to current pulse duration in the inductor investigation of current pulse is enough to estimate the pulse shape and duration of generated magnetic field.

Inductor current waveform and duration is effected by circuit components i.e. capacitance of capacitor bank, inductance of inductor, series and parallel resistance to inductor and capacitor. The importance of crowbar circuit which consists of a crowbar diode and resistance and which is connected parallel to inductor emerge here. The crowbar circuit provides possibility under certain circumstances to control pulse duration easily by changing the resistance that is connected to crowbar diode in series. Also it can be arranged to prevent capacitor to be charged to negative polarity and this extends life time of capacitor bank. In this section circuit models with and without crowbar circuit will be explained. Two different circuit models according to their switching type of capacitor bank will be studied. In addition to this, simulation results and experimental comparison will be shown. As modeling and simulation of circuits some software packages can be used such as LtSpice®, Pspice®, Proteus®. These softwares are easy to use and they offer high speed of modelling, simulating besides accuracy. In addition to this circuits can be modeled by using Matlab Simulink®. Eventhough it is time consuming and complicated to model pulse generator in Matlab Simulink®, it provides full control on mathematical equations of circuit. Therefore mathematical analysis is easier when required. In this section pulse generator will be modeled by using Matlab Simulink® in order to adopt better understanding of the operation principles of pulse generators with and without crowbar circuit while demonstrating mathematical equations of models.

2.1. Modelling Pulse Generator in Matlab Simulink® without Crowbar Circuit

It was shown in section 1.1 that the pulse generator without crowbar circuit is actually a series RLC circuit and analysis for inductor current and capacitor voltage was done with equations (2-3). Eventhough, if we include the crowbar circuit until the capacitor voltage value reaches to zero during discharging the circuit is series RLC circuit. Only after capacitor voltage is below zero crowbar diode is forward biased and that branch can be taken into account. Therefore, in the first place modelling of RLC circuit will be studied. For analysis of series RLC circuit a circuit diagram shown in Fig. 17 will be considered.

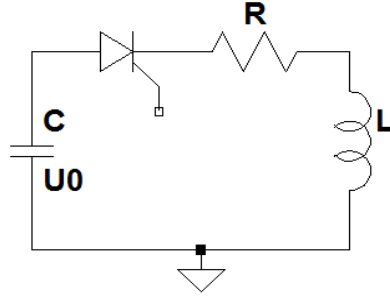


Fig.17. Series RLC circuit diagram

In the beginning assume that capacitor is charged to voltage value U_0 and that the switch is as an ideal switch. In these conditions the inductor voltage can be found as following:

$$V_L(t) = V_C(t) - V_R(t) \quad (30)$$

The next step is to find inductor current $I_L(t)$ that is equal to capacitor current $I_C(t)$ and capacitor voltage $V_C(t)$ that is given in equation (31) and equation (32) respectively. And lastly voltage drop on resistance R that is $V_R(t)$ is given by equation (33).

$$I_C(t) = I_L(t) = \frac{1}{L} \int V_L(t) dt \quad (31)$$

$$V_C(t) = U_0 - \frac{1}{C} \int I_C(t) dt \quad (32)$$

$$V_R(t) = I_C(t) \cdot R = I_L(t) \cdot R \quad (33)$$

Now all the required equations are obtained to build model in Matlab Simulink®. The built model is shown in Fig.18.

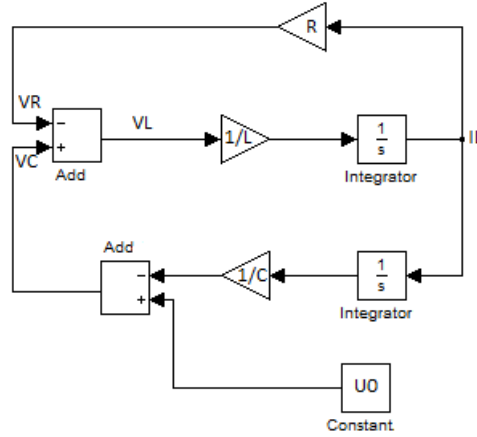


Fig.18. Matlab Simulink® model of series RLC circuit

2.2. Modelling Pulse Generator in Matlab Simulink® with Crowbar Circuit

In this section analysis of inductor current generated by pulse generator including crowbar branch will be studied. As mentioned in the previous section crowbar branch will be activated when the capacitor voltage reaches the zero during discharge. Therefore, in case of ideal crowbar diode we can assume our circuit with a switch on the crowbar branch that will

be closed when the capacitor voltage from series RLC circuit will reach to zero. This circuit diagram is shown in Fig.19. Here D represents the ideal diode that will activate the crowbar circuit and it will be assumed as an ideal switch that is activated when negative voltage is applied to that branch. As main switch to start discharging of capacitor thyristor is used and in analysis of circuit it will be assumed as ideal as well.

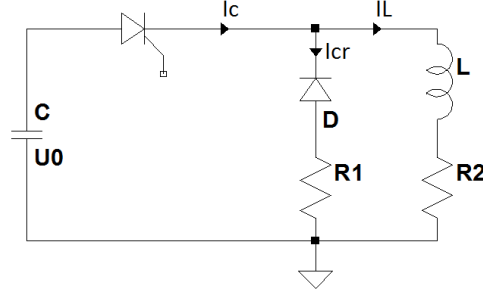


Fig.19. Pulse generator circuit diagram with activated crowbar branch

The equations that is necessary to model this circuit will be found next. First of all, as in the series RLC circuit analysis inductor voltage $V_L(t)$ must be found and that is shown in equation (34). The next step is to find the inductor current with equation (35) and to find current on crowbar branch $I_{cr}(t)$ shown in equation (36). After that we can sum these two current to find capacitor current and therefore, its voltage shown in equation (37) and (38) respectively. All these equations are given below.

$$V_L(t) = V_C(t) - V_{R_2}(t) \quad (34)$$

$$I_L(t) = \frac{1}{L} \int V_L(t) dt \quad (35)$$

$$I_{cr}(t) = \frac{V_C(t)}{R_1} \quad (36)$$

$$I_C(t) = I_L(t) + I_{cr}(t) \quad (37)$$

$$V_C(t) = U_0 - \frac{1}{C} \int I_C(t) dt \quad (38)$$

The Matlab Simulink® circuit model which represents the circuit given in Fig.3. can now be modeled in and it is shown in Fig.20.

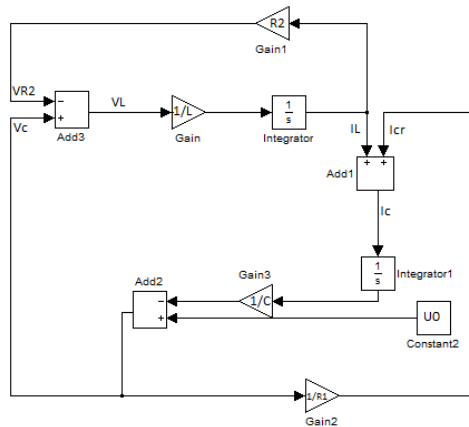


Fig.20. Matlab Simulink® model of pulse generator with activated crowbar circuit

The circuits of pulse generator without crowbar branch and with activated crowbar branch was modeled in Matlab Simulink®. However, when we consider these two circuits one question rises that is when to close switch on the crowbar branch and how? As described before the switch will be closed when capacitor voltage will reach to zero during discharge. Regarding series RLC circuit characteristic which might be critically-damped, over-damped or under-damped (see Fig.21) the switching time varies. To determine the circuit characteristic general equation of circuit that was given with equation (1) must be considered. If derivative of this equation is taken the following result is obtained:

$$\frac{d^2 I(t)}{dt^2} + \frac{R}{L} \frac{dI(t)}{dt} + \frac{1}{LC} I(t) = 0 \quad (39)$$

Here damping coefficient γ equals to $\gamma = R/2L$ and resonant frequency $\omega_0 = 1/\sqrt{LC}$. Relation between γ and ω_0 indicates the circuit characteristic. In case, $\gamma > \omega_0$, $\gamma = \omega_0$ and $\gamma < \omega_0$ circuit is over-damped, critically-damped and under-damped, respectively. It was mentioned before when circuit characteristic is under-damped, critically-damped or over-damped the pulse duration time can be found approximately by using equation (17).

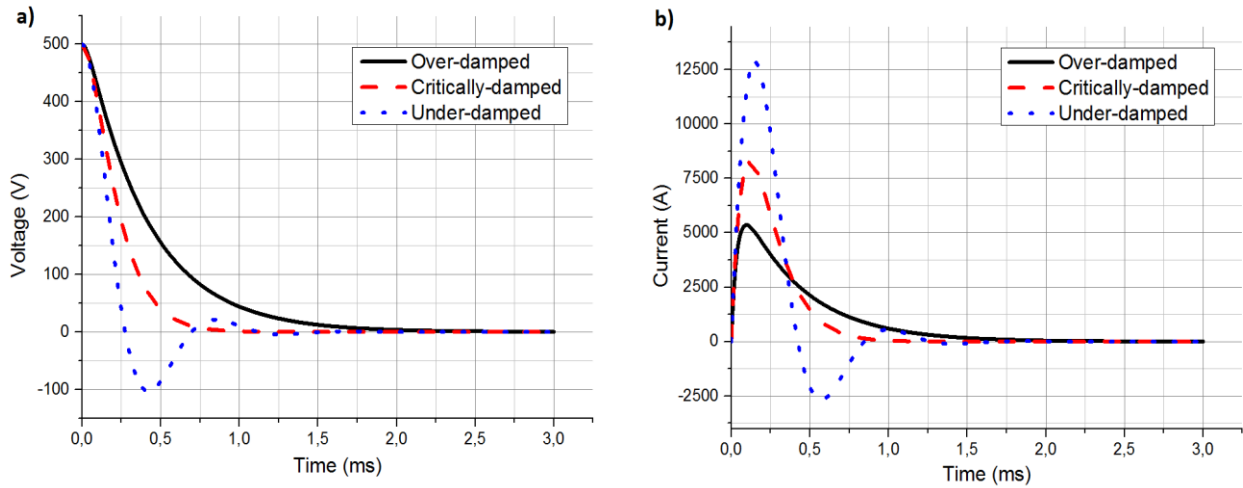


Fig.21 Series RLC circuit a) capacitor voltage, b) inductor current with under-damped, critically-damped and over-damped responses

To model mentioned crowbar operation a signal which indicates the discharging time of capacitor is needed. To obtain this signal the two circuit models that was given can be combined. This combination with some other additions would provide signal to activate crowbar branch. In the previous models ideal main switch was used. However, it is important that when capacitor current reaches zero the main switch which is thyristor in our case must block the reverse polarity current flow. This means a high resistance must be connected to capacitor in series whenever capacitor current reaches zero. After capacitor current reaches zero the rest of the circuit is simple RL circuit with resistance of crowbar and inductor resistance. This RL circuit will be added to model as well and it will be activated when capacitor current reaches zero. The signal when capacitor current reaches to zero will be obtained by a signal latch and proper configuration. The supply voltage of this RL circuit will be obtained from voltage of capacitor i.e. U_0 in main circuit at the moment when capacitor current reaches to zero. After connecting the capacitor voltage to RL circuit with both crowbar and inductance resistance included so that the voltage on inductor V_L can be

found. Finally this V_L will be used in another RL circuit to determine the current flowing on inductor.

After all this arrangements complete Matlab Simulink® circuit model of pulse generator with crowbar circuit was obtained. It is shown in Fig.22.

Reliability of model was tested at Vilnius High Magnetic Field Center which represents joint activities of Semiconductor Physics Institute of Center for Physical Sciences and Technology and Vilnius Gediminas Technical University. During the experiments inductors that are designed to investigate pulsed magnetic field distribution in superconductor tube and for biological pump applications was used. The first inductor was designed by myself having 2 layers, 23 turns in each layer, Epoxy and textile material as insulation between layers. Inductor has $10.4 \mu\text{H}$ inductance and 0.03Ω resistance with electrical contacts included. Second inductor was designed by VGTU scientists also was used for investigations. It is considerably larger than the first one. It has one layer and 117 turns. The inductance of this is 1.957 mH , and 0.74Ω resistance including electrical contacts. As conductor copper was used in both inductors. In both experiments same capacitor bank was used that has 5.4 mF capacitance. The resistance of crowbar is 0.2Ω and additionally to measure current indirectly by using measured voltage 0.1Ω series resistance connected to inductors in both experiments.

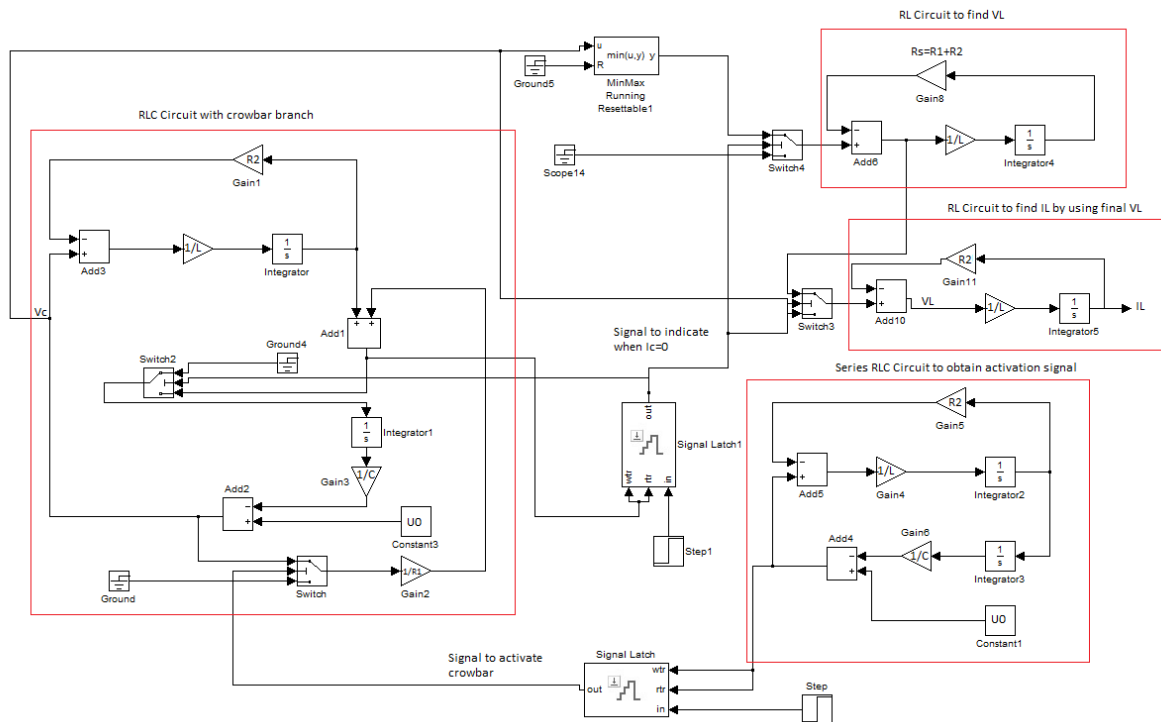


Fig.22. Complete Matlab Simulink® model of pulse generator with crowbar circuit

In the first and second experiments capacitor bank was charged to 28.8 V and 60 V respectively. The current waveforms that are measured and obtained by using Matlab Simulink® model are shown in Fig.23 for both experiments.

Considering results it is observable that there is an error which is up to 3% considering peak current value and 2.5% considering pulse duration. However, this error is insignificant and it can be concluded that Matlab Simulink® model to investigate current waveform of pulse generator inductor is reliable and it can be used to investigate pulse generator behaviour

prior to experiments. Also, other softwares for modelling circuits can be used as well since they are more practical and easier to use.

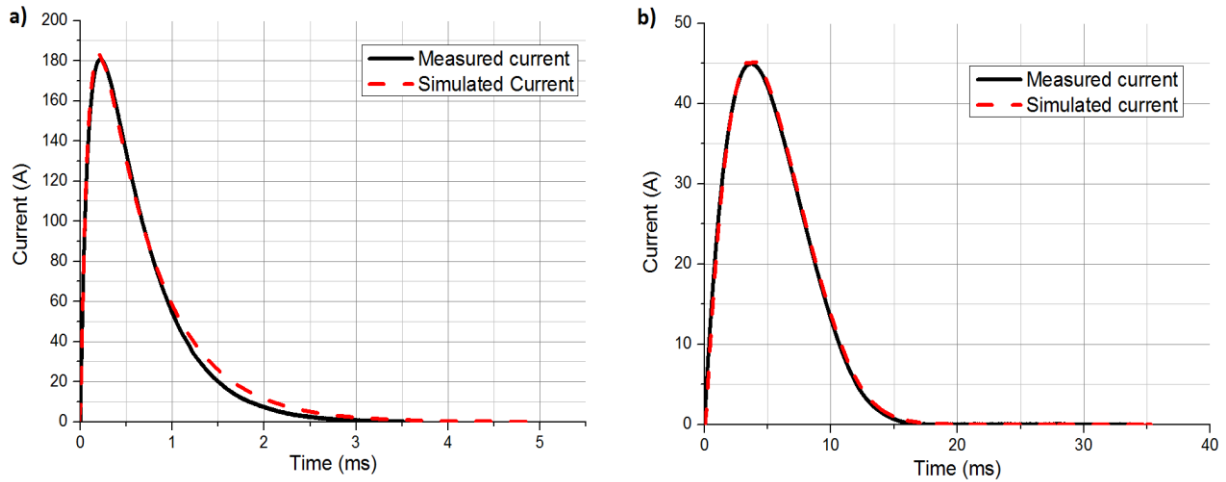


Fig.23. Current waveforms from Matlab Simulink® model and experimental measurement a) with inductor inductance 10.4 μ H b) with inductor inductance 1.957 mH

2.3. Effect of Crowbar Circuit on Current Waveform

In addition to equation (17) the following equation that is obtained from RLC circuit equations can be used for determining pulse duration with higher accuracy since equation (40) takes into account the effect of inductor resistance.

$$\tau = \pi \sqrt{\frac{4L^2C}{4L - R^2C}} \quad (40)$$

According to equation (40), in case of over-damped characteristic equation indicates pulse duration to be an imaginary number. It actually happens due to relatively high series resistance connected to circuit the capacitor discharges very slowly and after relatively long time capacitor voltage reaches to zero without charging to opposite polarity. In critically damped circuits discharge of capacitor shows similar characteristic, i.e. opposite polarity charging of capacitor is not observed. It means in both cases since crowbar diode will not be forward biased crowbar branch will not operate meaning that crowbar branch does not have any effect on circuits that have critically-damped and over-damped response. On the other hand, when circuit has under-damped characteristic capacitor is discharged and charged with opposite polarity over a period and it shows oscillation in case of simple RLC circuit (see Fig. 21). Therefore, when circuit has under-damped response the crowbar diode will be forward biased in case of its existence. In summary, when pulse generator RLC circuit has critically and over-damped characteristic crowbar will not operate and when circuit has under-damped characteristic crowbar diode will be forward biased at a finite time thus, crowbar circuit will operate. Considering this effect, in order to be able to have control on pulse duration by changing crowbar resistance usually pulse generators are designed to have under-damped characteristic.

In case when crowbar diode is forward biased the resistance that is connected to crowbar will have effect on pulse duration. To find this effect in addition to equation (40) another approximation can be used. After crowbar diode is forward biased if resistance value of

crowbar branch is less than capacitive reactance of capacitor bank more current will flow through crowbar branch. If it is assumed that crowbar resistance is ten times smaller than capacitive reactance value at a finite time circuit will become simple RL circuit. After this point current will decay with RL circuit time constant. Pulse duration can be found approximately with equations (41)-(42). Here R_1 and R_L represents the crowbar and the inductor resistance, respectively. X_c is capacitive reactance.

$$R_1 + R_L > 2X_c \Rightarrow \tau = \left(\pi \sqrt{\frac{4L^2C}{4L - R_L^2C}} \right) + \left(\frac{2.5L}{R_1 + R_L} \right) \quad (41)$$

$$R_1 + R_L < 2X_c \Rightarrow \tau = \left(\frac{\pi}{2} \sqrt{\frac{4L^2C}{4L - R_L^2C}} \right) + \left(\frac{5L}{R_1 + R_L} \right) \quad (42)$$

Using the models which were described and built in previous section pulse generator that has under-damped characteristic the effect of crowbar circuit with different resistances will be studied in this chapter to have better understanding. Since crowbar branch does not have any effect on circuits critically and over-damped characteristic circuits with those characteristics will not be studied here.

In the next simulations for simplicity an inductor with one layer will be used. Inductor is assumed having inner radius is 10 mm, outer radius is 11.5 mm and the length is 24 mm. Inductor has 15 turns and as wire copper 100% International Annealed Copper Standart (IACS) was used. The inductance of Inductor will be calculated by Wheeler's formula. Harold Wheeler published a formula which is accurate only for long inductors which have a length to diameter $2b/2a$ ratio greater than 0.4 where b is the half of the inductor length and a is the radius of inductor measured to the center of wire [79]. Since our inductor has ratio $b/a = 1.11$ Wheeler's formula can be used and it is given below.

$$L = \frac{d^2 \cdot N^2}{228.6 \cdot a^2 + 508 \cdot b} \mu H \quad (43)$$

Here a is the radius of inductor in millimeters, measured to the center of wire. N is number of turns. $2b$ is the inductor length in millimeters. For Wheeler's formula the ratio of length and radius of inductor is important. If a/b is less than 3 the above equation is accurate 1%. When $a/b = 5$ Wheeler's formula gives a result about 4% lower [79]. By using this equation inductance of example inductor is found 2.68 μH .

For calculation of inductor resistance equation (44) was used. In equation (44), ρ_r is the resistivity of wire material at the temperature T_0 , l_w and S_w represent the length and the cross section area of wire respectively. Coefficient 1.06 is used to optimize the error for length of wire calculation since during winding operation wire follows a helical path.

$$R = \rho_r(T_0) \frac{1.06 l_w}{S_w} \quad (44)$$

Resistance of inductor found 0.011 Ω . To have more realistic results small contact resistances will be added to inductor resistance and as a result 0.0125 Ω will be used as inductor resistance.

As crowbar resistances 0.08Ω , 0.01Ω , 0.005Ω will be used. By using equation (40) without crowbar branch pulse duration is found 0.39 ms . Capacitive reactance can be found by using this pulse duration and $1/2\pi fC$ equation which yields 0.023Ω . If $R_1 + R_L$ is greater than 0.046Ω equation (41), otherwise equation (42) will be used. The resulting pulse durations by using equations (41) or (42) is given in table 2.

Table 2. Current pulse duration found by different crowbar resistances

Crowbar Resistance	$R_1 + R_L$	Pulse Duration
Without crowbar	∞	$\sim 0.39 \text{ ms}$
0.08Ω	0.0925Ω	$\sim 0.46 \text{ ms}$
0.01Ω	0.0225Ω	$\sim 0.79 \text{ ms}$
0.005Ω	0.0175Ω	$\sim 0.96 \text{ ms}$

A pulse generator circuit with under-damped characteristic was simulated using Matlab Simulink® model of pulse generator with ideal switch having different crowbar resistances. The circuit diagram can be seen in Fig.19. Capacitor was charged to 500 V prior to discharging. Without crowbar branch capacitor is charged to negative polarity since circuit would have under-damped characteristic. With crowbar circuit different resistances on crowbar branch effects the current waveform differently. The difference is that capacitor is charged to opposite polarity with lower voltage level and this is because negative current that charges the capacitor finds an alternative path that is crowbar branch and it is obvious that as the resistance becomes smaller the more current flow through crowbar branch will be observed resulting capacitor to be charged to opposite polarity less and smaller resistance will cause longer current pulse since current will fade slower. According to equations (41)-(42) this effect is expected and it is observed in simulation results and shown in Fig.24 b).

These results were obtained when there is an ideal thyristor switch to start capacitor discharging. If there was an ideal switch which conducts current in both directions the damped characteristic of current would be observable. Because thyristor blocks the negative current flow damped characteristic in Fig. 24 is not observable. However, this does not affect the capacitor bank to be charged to negative voltage. Fig. 24 a) illustrates the capacitor voltage in pulse generator. As can be seen voltage on capacitor reaches to negative peak value and remains at the same value without changing until the end of simulation. It should be noted that in reality eventually capacitor voltage reaches to zero. The reason of this difference is that in simulations capacitor bank was represented as a single ideal capacitor. In reality it consists of complex circuitry. Despite this, the peak values capacitor voltage reaches are reliable. Therefore, Fig. 24 a) is used only to show the maximum values capacitor voltage reaches with different crowbar resistance values. As can be seen from the Fig. 24 a) without crowbar branch capacitor bank was charged to higher negative voltage value. Also smaller crowbar resistance provides smaller negative voltage on capacitor.

As a result, it can be concluded that firstly, under given circuit conditions as crowbar resistance is getting smaller it has effects of extending the original current pulse duration that is obtained by without using crowbar circuit while prolonging the decay time and

secondly, smaller crowbar resistance provides capacitor to be charged to smaller negative voltage.

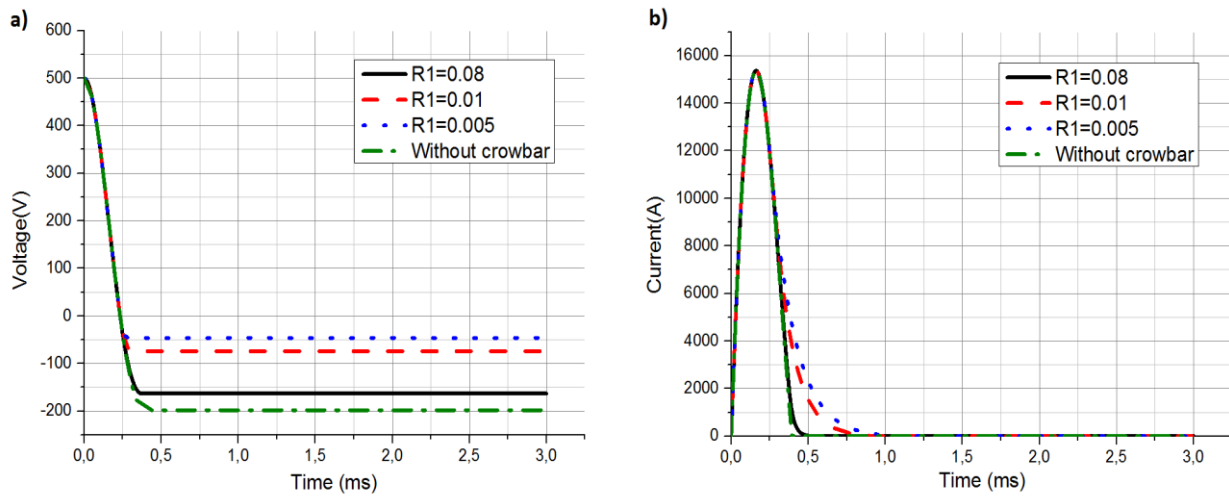


Fig.24. Simulated a) capacitor voltage, b) inductor current waveforms with crowbar branch having different resistance values

2.5. Conclusions of Chapter 2

In this chapter pulse generator operation principle was studied and it was modeled by using Matlab Simulink®. Reliability of model was tested in laboratory and it was proven to be accurate with experimental results with errors 3% considering peak current value and 2.5% considering pulse duration. This means that model can be used in further simulations to obtain current flow in pulsed inductor. Using the same model effects of crowbar circuit were studied. It was shown that pulse generator with lower crowbar branch resistance generates longer current pulse in inductor besides, it provides capacitor bank to be charged smaller negative value. It means that lower crowbar resistance extends the life-time of capacitor bank. It was also explained that operation of crowbar circuit depends on circuit response i.e. over-damped, critically-damped and under-damped. To have shorter pulse crowbar resistance can be chosen relatively higher while letting capacitor bank to be charged to higher negative voltage values. However, it was shown that shorter pulse duration than without crowbar circuit, i.e. RLC circuit cannot be obtained by using only crowbar branch. Additional manipulations on circuit design can be made to have shorter pulse as shown in [6].

3. Analysis on Pulsed Magnetic Field Inductors

In this section experiments and simulations on readily designed pulsed inductors will be studied. Experiments involve measuring inductance, resistance of different inductor designs and magnetic flux density inside them with different supply voltages. In addition to this, results will be compared to analytical calculations and simulations. As computational tools Matlab®, Matlab Simulink® and Comsol Multiphysics® will be used. Experiments were conducted in High Magnetic Field Center for four different inductors. Two of the inductors were designed as having one layer windings which are circular and rectangular shaped conductors. Two other inductors consist of two and four layers of circular and rectangular shaped windings respectively. Mentioned inductors are shown in Fig.25.



Fig. 25. Designed inductors that will be used for magnetic flux density analyses in the center of them. a) Inductor X, b) Inductor Y, c) Inductor Z, d) Inductor W

3.1 Inductor Designs

First single layer inductor which has circular cross section conductor windings has 19.3 cm length and 20 cm inner diameter. The winding of inductor has 1.65 mm diameter. Number of turns of inductor is 117. Wire material is copper with 99% IACS. This inductor will be named as inductor X. Second single layer inductor which has rectangular shaped windings has 11 cm length and 20 cm inner diameter. The windings of inductor has 2 mm height and 4 mm length. This inductor has 26 turns. Wire is Cu-Nb (82% Cu, 18% Nb) microcomposite with 63% IACS. This inductor will be named as inductor Y. These inductors do not include reinforcement. It is because they were manufactured to generate long pulsed low and medium magnetic field instead of short pulse high magnetic fields. These inductors are shown in Fig. 25 a) and b). Cross sections of these inductors are shown in Fig. 26 a) and b).

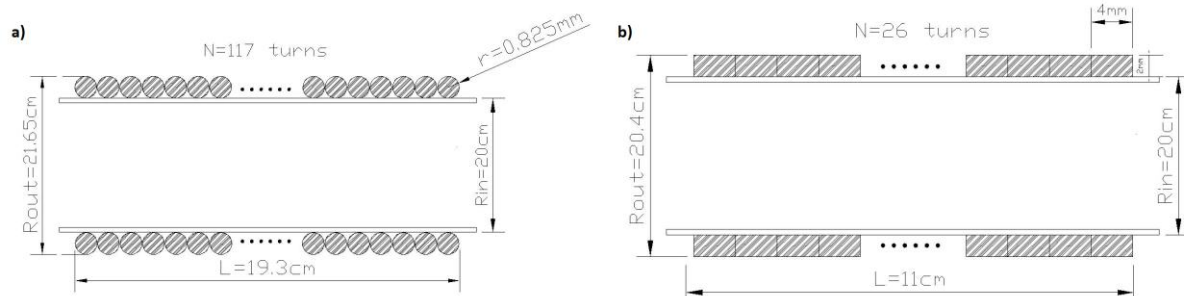


Fig.26. Cross section of a) Inductor X, b) Inductor Y

Third inductor has two layers. Inductor has 40 mm length, 12 mm inner and 20.4 mm outer diameter. Each layer includes 23 turns. Wire used for winding has 1.5 mm diameter and circular shape. Inductor was constructed without inner and outer reinforcement because it was intended to be used in short pulse and low magnetic field pulse generation. Between windings textile material and Epoxy were used as insulation. Wire of this inductor was made of copper 99% IACS. This inductor will be named as inductor Z. Final inductor which has four layers of rectangular shaped windings has 42 mm length, 16 mm inner and 38 mm outer diameter. Wire of windings has 2 mm height and 4 mm length. It has 10 turns on each layer which makes total 40 turns. Since this inductor was manufactured to generate high magnetic field and short pulse, it includes internal and external reinforcement. As internal reinforcement material Epoxy impregnated Zylon was used and external shell was made of steel. As insulation between layers Kapton film was used. The wire is Cu-Nb (82% Cu, 18% Nb) microcomposite with 63% IACS. This inductor is named as inductor W. These inductors are shown in Fig. 25 c) and d). Cross sections of inductor Z and inductor W are shown below. In table 3 parameters of all four inductors are given as summary.

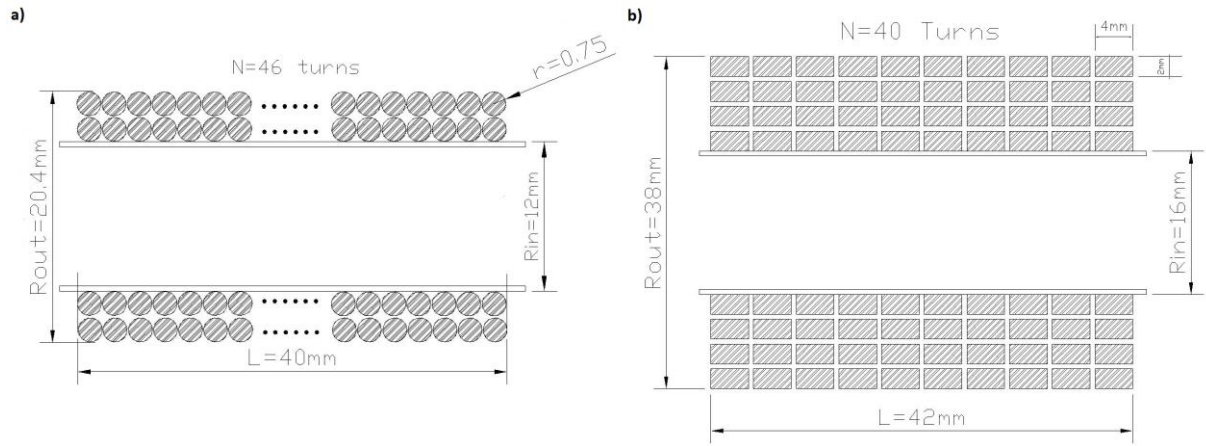


Fig. 27. Cross section of a) Inductor Z, b) Inductor W

Table 3. Parameters of inductor X,Y,Z and W

Parameter	Inductor X	Inductor Y	Inductor Z	Inductor W
Inner radius (a_1)	100 mm	100 mm	6 mm	8 mm
Outer radius (a_2)	101.65 mm	102 mm	10.2 mm	19 mm
Length ($2b$)	193 mm	110 mm	40 mm	42 mm
Number of layers	1	1	2	4
Number of turns in each layer	117	26	23	10
Wire Dimensions	$r = 0.825$ mm	4×2 mm ²	$r = 0.75$ mm	4×2 mm ²
Wire material and conductivity (IACS)	Cu, 99 % IACS	Cu-Nb (82% Cu, 18% Nb) 63% IACS	Cu, 99 % IACS	Cu-Nb (82% Cu, 18% Nb) 63% IACS
Filling Factor (λ)	0.7856	0.945	0.6774	0.6926

3.2. Inductance and Resistance Determination of Inductor Designs

Inductance of inductors can be found by measurement, analytical calculation or simulation. In this section all these methods will be studied. First method is to measure the inductance of inductors. Measurements was done in High Magnetic Field Centre. The equipment used for this measurements was LCR meter E7-8 series with 1 nH inductance accuracy. Resistance of inductors were measured in addition to inductance. Fig. 28 illustrates the device. Measuring process can be done simply by connecting the probes on first and last windings.

Usually measurement gives enough accuracy. However, due to contacts measured resistance and inductance are expected to be higher than considering only inductor itself.

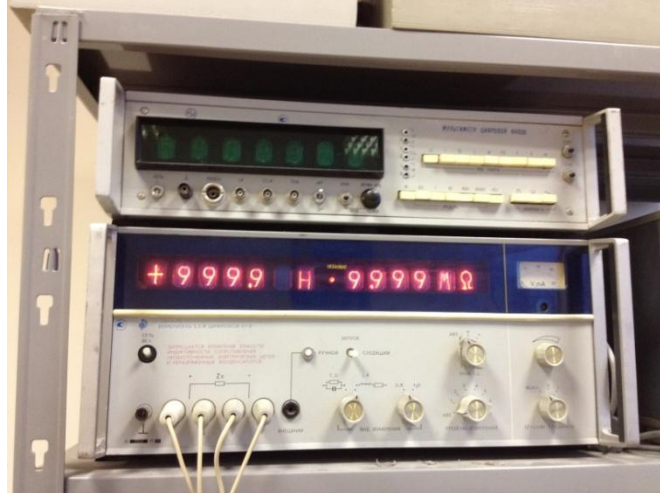


Fig.28. LCR meter E7-8 series

Next method is using analytical calculations to determine the inductances. There have been several formulas proposed with very good accuracy for inductance calculation of different shaped inductors. In this theses since very high accuracy is not needed approximated formulas for inductance will be used. For single layer inductors Wheeler's formula will be used as it is simple and accurate enough. Wheeler's formula was given in previous section in equation (43). As explained before it is accurate for long inductors that has length to diameter ratio $2b/2a$ greater than 0.4. Since all of our single layer inductors are long inductors Wheeler's formula can be used for them. On the other hand for multi-layer inductors equation (45) can be used for good accuracy [81]. Here, a_1 and a_2 is the inner radius and outer radius (in mm) of the inductor respectively. α is the ratio of a_2/a_1 and β is the ratio of b/a_2 where b is the half of the inductor length in mm.

$$L = a_1 N^2 \frac{\mu_0 \pi}{8} \frac{(1 + \alpha)^2}{\beta} \left(1 + 0.9 \left(\frac{1 + \alpha}{4\beta} \right) + 0.64 \left(\frac{\alpha - 1}{\alpha + 1} \right) + 0.84 \frac{\alpha - 1}{2\beta} \right)^{-1} \text{ mH} \quad (45)$$

The final method to obtain inductance of inductors by using FEA software Comsol Multiphysics®. Simulations will be conducted using AC/DC module and 2D axisymmetry geometry and magnetic fields physics will be used. The axisymmetric option allows user to analyze a 3-dimensional model which is rotationally symmetric about an axis. The input is 2-dimensional, but because of the rotational symmetry, user is in fact analyzing a symmetric 3-dimensional problem. For this reason only half of the cross section will be modeled for all three inductors. Inductors were built in air and as wire material copper was used since inductance depends only on inductor geometry. In inductor models magnetic fields physics

and multi-turn inductor domain will be used. Mesh settings were chosen to be fine to have enough accuracy. It must be pointed out that in both Comsol Multiphysics® and analytical model it was assumed that monitoring devices and environment does not have any effects on results. The simulation models and results of inductances for single layer inductors and multi-layer inductors are shown in Fig. 29 and Fig. 30 respectively.

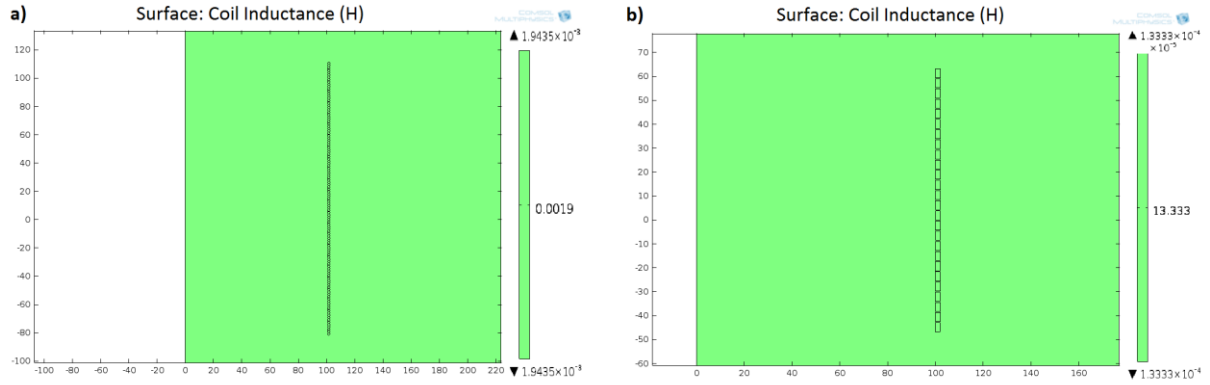


Fig.29. Comsol Multiphysics® simulation results for inductance determination of single layer inductors a) Inductor X, b) Inductor Y

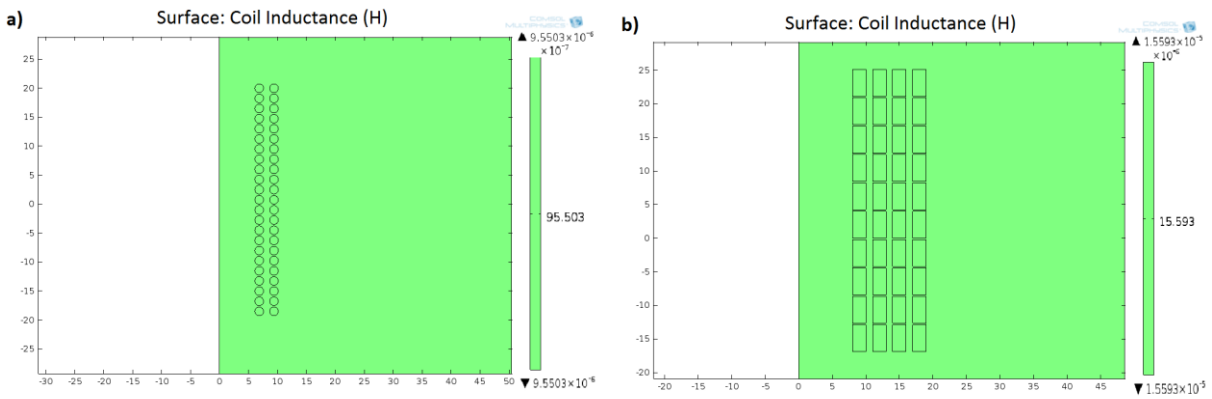


Fig.30. Comsol Multiphysics® simulation results for inductance determination of multi layer inductors a) Inductor Z, b) Inductor W

All methods were performed for inductance determination for four different inductor designs and the results are shown in Table 4. In Table 5 errors between analytical solutions, simulations and experimental measurements are presented. The maximum error is 2% which means all three methods are accurate with each other and can be used for inductance determination.

Resistance of inductors can be found by using the length of wire that is used in the inductor design. However, during experiments usually due to contacts inductor resistance changes. This small changes in resistances have big effect on pulsed magnetic field generation. Therefore, calculated and simulated results might not be accurate comparing to experimental results. Because of this reason it was decided to measure resistances with LCR meter. The results are given in Table 6.

Table 4. Inductor inductance determination results obtained by different methods

	Inductor X	Inductor Y	Inductor Z	Inductor W
Inductances obtained by measuring	$L=1.96$ mH	$L=134.8$ μ H	$L=9.6$ μ H	$L=15.9$ μ H
Inductances obtained by analytical solution	$L = 1.93$ mH	$L=135.1$ μ H	$L=9.54$ μ H	$L=15.5$ μ H
Inductances obtained by simulation	$L=1.94$ mH	$L=133.3$ μ H	$L=9.55$ μ H	$L=15.59$ μ H

Table 5. Error values between analytical, simulation and experimental solution results

	Inductor X	Inductor Y	Inductor Z	Inductor W
Error between analytical solution and experimental results	1.5%	- 0.22%	0.625%	2%
Error between simulation and experimental results	1%	1.1%	0.52%	1.95%

Table 6. Resistances of inductor designs including electrical contacts

	Inductor X	Inductor Y	Inductor Z	Inductor W
Resistance (Ω)	0.74	0.065	0.03	0.03

3.3. Magnetic Flux Density Distribution Analysis in the Center of Inductor Bores

In this section magnetic flux distribution analysis in previously given inductors will be studied. First of all computational studies will be performed. For this reason Matlab Simulink® and Comsol Multiphysics® FEA software will be used. First step is to find current waveform in the inductors with different capacitor voltages. The next step is to analyze magnetic flux density distribution in inductor models by using computational tools i.e. Matlab® and Comsol Multiphysics®. Finally experimental set up will be described and comparison of simulated results and experimental results will be given.

3.3.1. Determination of Current Waveforms in Designed Inductors

Before starting magnetic flux density analysis the current flow in inductors has to be found. For analyzing magnetic flux density distribution in inductors capacitor will be charged to different voltage levels. Current shapes in inductors with different supply voltages will be found by Matlab Simulink® model of pulse generator that was previously explained. Pulse generator circuit scheme that is used is shown in Fig. 19. Pulse generator includes capacitor bank with 5.4 mF capacitance and crowbar circuit with crowbar resistance of 0.2 Ω to have relatively small pulse decay time. Because capacitance is constant it is expected that higher

inductance and resistance of inductors will give longer pulse duration. The current waveshapes for designed inductors with different supply voltages shown below.

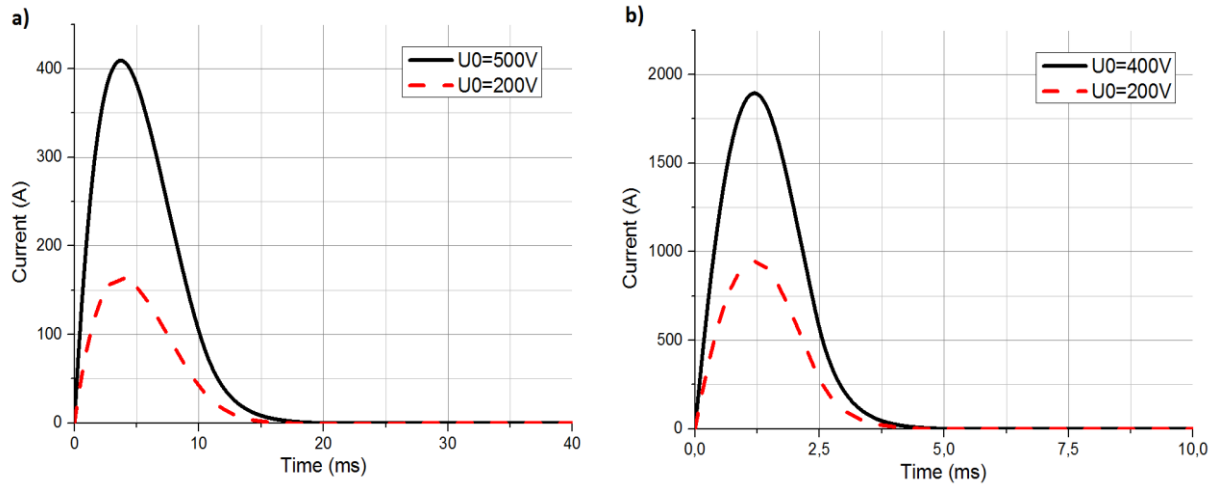


Fig. 31. Current waveforms of single layer inductors with different capacitor voltages: a) Inductor X, b) Inductor Y

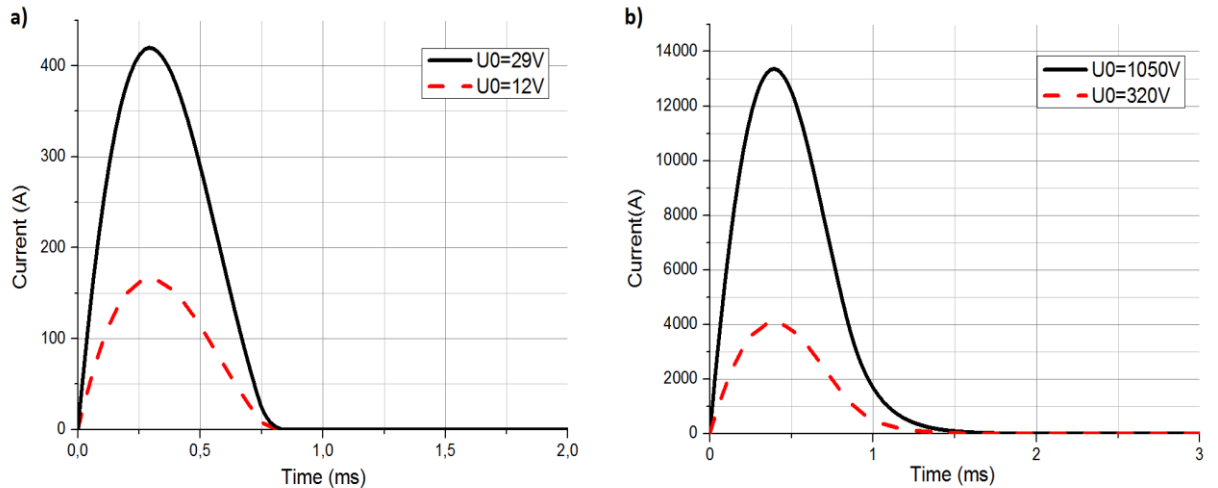


Fig. 32. Current waveforms of multi-layer inductors with different capacitor voltages: a) Inductor Z, b) Inductor W

3.3.2. Magnetic Flux Density Distribution Analysis by Computational Tools in The Center of Inductor Bores

As currents were obtained magnetic flux density distribution analysis can be conducted by using computational tools. For this purpose Matlab® and Comsol Multiphysics® FEA software will be used. First analysis in Matlab® will be performed. Since the main intention is to find the magnetic flux density in the center of the inductor bore equation (9) will be used.

In Comsol Multiphysics® inductor models that were given before while simulating for obtaining inductances will be used. As in inductance determination magnetic fields physics and multi-turn inductor domain will be used. Simulations will be performed in time domain and better meshing than inductance determination simulation will be used. Simulation results of two different inductors will be given here just to present that these computational tools give accurate results with each other. In Fig. 33 magnetic flux density found by using Matlab® and Comsol Multiphysics® in the bore of inductor Y and inductor Z with capacitor

voltage 200 V and 12 V respectively is given. As can be seen the results are accurate and can be used for other inductors as well.

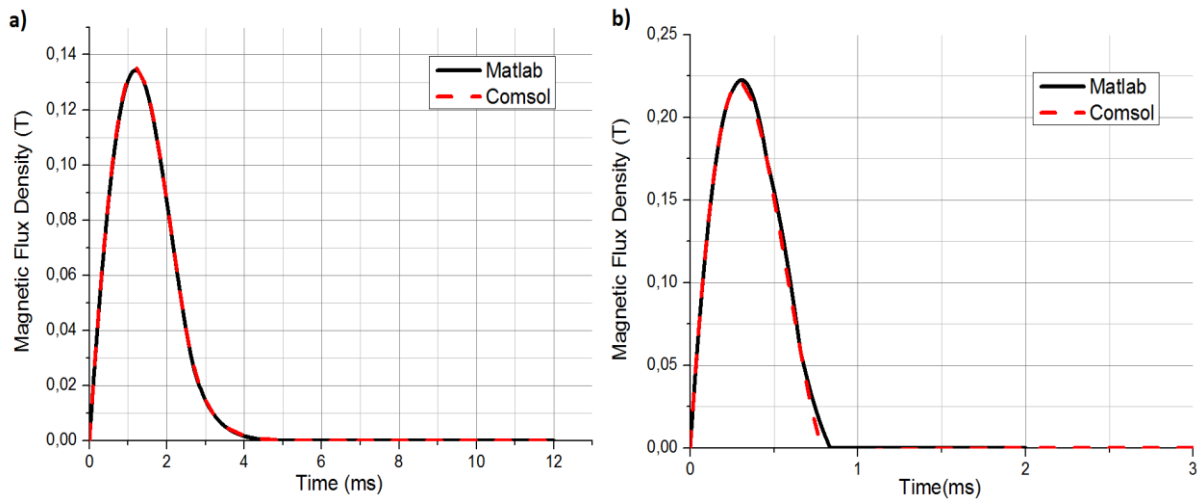


Fig. 33. Magnetic flux density found by Matlab® and Comsol Multiphysics® in the bore of a) Inductor Y , b) Inductor Z with 200 V and 12 V capacitor voltages, respectively.

3.3.4. Magnetic Flux Density Measurement in the Center of Inductor Bores

Experiments were performed to measure magnetic flux density in the center of the bore of inductors in the High Magnetic Field Centre. As pulse generator traditional circuit design with crowbar circuit that was shown before in Fig. 19 was used. 0.2 Ω crowbar resistance added to crowbar branch to have relatively short pulse. As main discharging switch thyristor that has ratings up to 50 kA was connected series to the capacitor. The capacitor bank used in experiments has 5.4 mF and shown in Fig. 34. Capacitor bank can be charged and discharged by a controller manually from 230 V, 50 Hz grid voltage. All experiments performed in room temperature that is 293.15 K.



Fig. 34. Capacitor bank used in experiments with 5.4 mF

Magnetic flux density was measured by using inductive loop sensor. Loop sensor generates electromotive force with changing flux on it (see equation 46). Here N is number of turns on loop sensor. Since $d\phi = SdB$ electromotive force equation can be stated by using magnetic flux density as shown in right hand of equation (46). Here S is the cross section of the inductive loop.

$$\varepsilon = N \frac{d\phi}{dt} = SN \frac{dB}{dt} \quad (46)$$

By using an integrator circuit magnetic flux density can be obtained. During experiments integrator circuit which was designed previously was used and circuit scheme is shown in Fig. 35. The circuit was designed for voltages having sinusoidal waveform. For non-sinusoidal waveforms the measured flux might not be very accurate especially for decay part of waveform. There is also a limit for pulse duration to have good accuracy. This limit is $\tau_{RC} \gg \tau_{Pulse}$. In the integrator circuit resistance and capacitance values are $R = 120k\Omega$ and $C = 0.338\mu F$. Therefore $\tau_{RC} \cong 0.04s$. It can be concluded that pulse durations more than 4 ms will not give good measuring accuracy. However, longer pulse durations can be measured without passive integration circuit and results can be integrated by using computational tools for instance Matlab® or Origin®. In our case measurements for single layer inductors that are having long pulse duration was done without integration circuit. The measured voltage was integrated by using software Origin®. After that integrated voltage was multiplied by integration constant which is $K = 8208.64$. This constant was obtained by using previous experiments with and without integrator circuit connected. The data obtained without using integrator circuit was integrated by Origin® and then it was divided by the data which was obtained by using integrator circuit. This process yields to $1/K$.

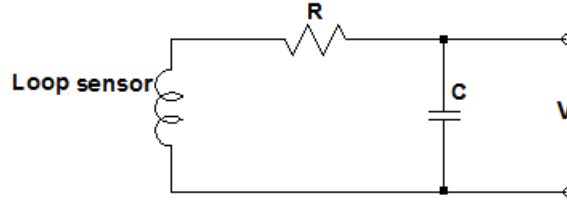


Fig. 35. Integrator circuit scheme for loop sensor

The voltage output can be observed using an oscilloscope. In our case Tektronix DPO 4034 digital phosphor oscilloscope was used (see Fig. 36). Since loop sensor and passive integrator gives a result that is $V = K \cdot B$ to obtain magnetic flux density the output voltage from oscilloscope is divided by the constant K that is equals to 3 mV. Results will be given later in this section. Results were exported to computer environment by using Universal Serial Bus (USB) 2.0 interface.



Fig. 36. Tektronix DPO 4034 digital phosphor oscilloscope

3.5. Results of Experiments and Comparisons with Computations

Experimental results and comparisons with computational results obtained from Matlab® and Comsol Multiphysics® for four different inductors supplied with different capacitor voltages (U_0) is given below. As can be seen from the figures results are accurate. The highest error between experiments and computations is around 5% considering peak field. On the other hand highest pulse duration error is 4%. In both Comsol Multiphysics® and Matlab® it was assumed that monitoring devices and environment does not have any effects on results as stated before. Therefore, it is believed that errors occur due to lack of input to models about all the monitoring devices and environment.

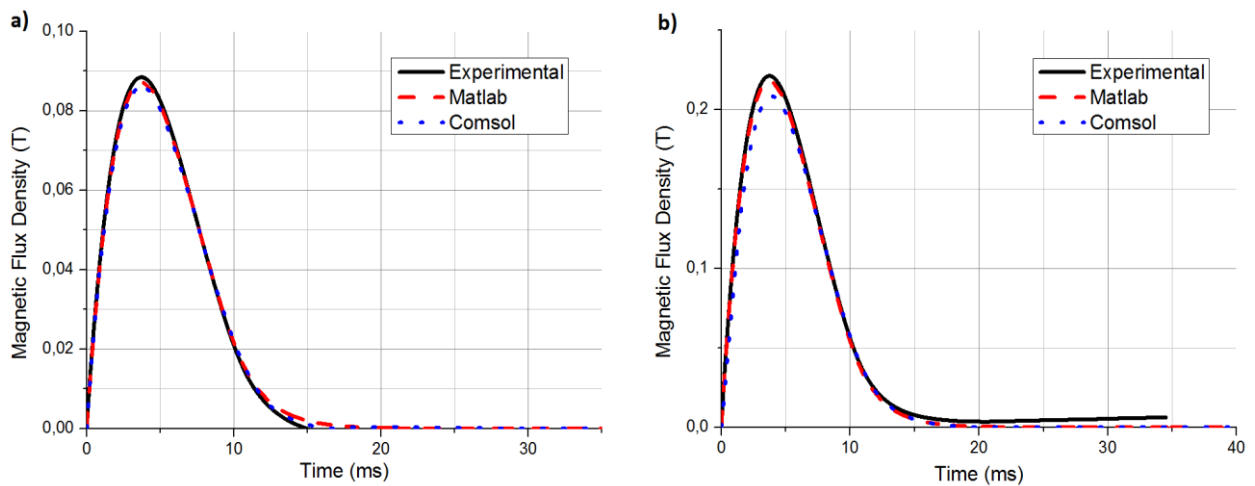


Fig. 37. Magnetic flux density in the center of inductor X a) $U_0 = 200$ V, b) $U_0 = 500$ V

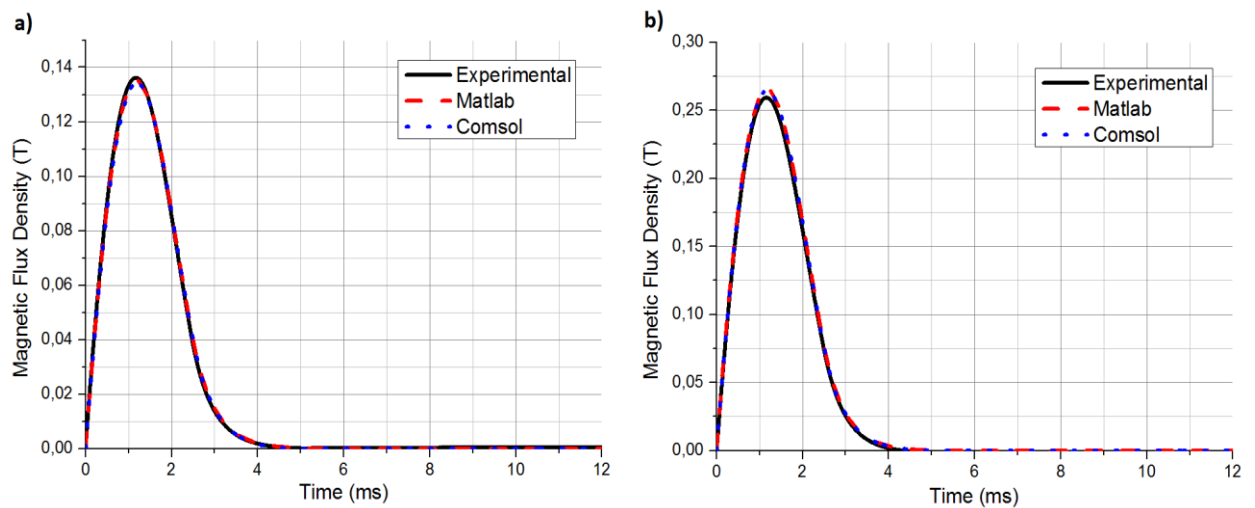


Fig. 38. Magnetic flux density in the center of inductor Y a) $U_0 = 200$ V, b) $U_0 = 400$ V

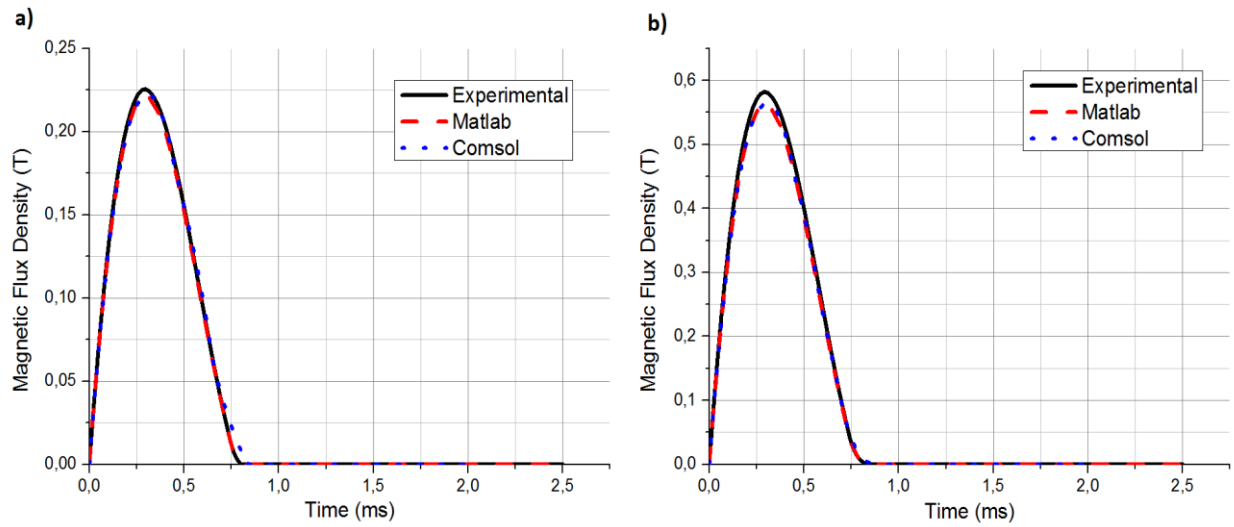


Fig. 39. Magnetic flux density in the center of inductor Z a) $U_0 = 12$ V, b) $U_0 = 29$ V

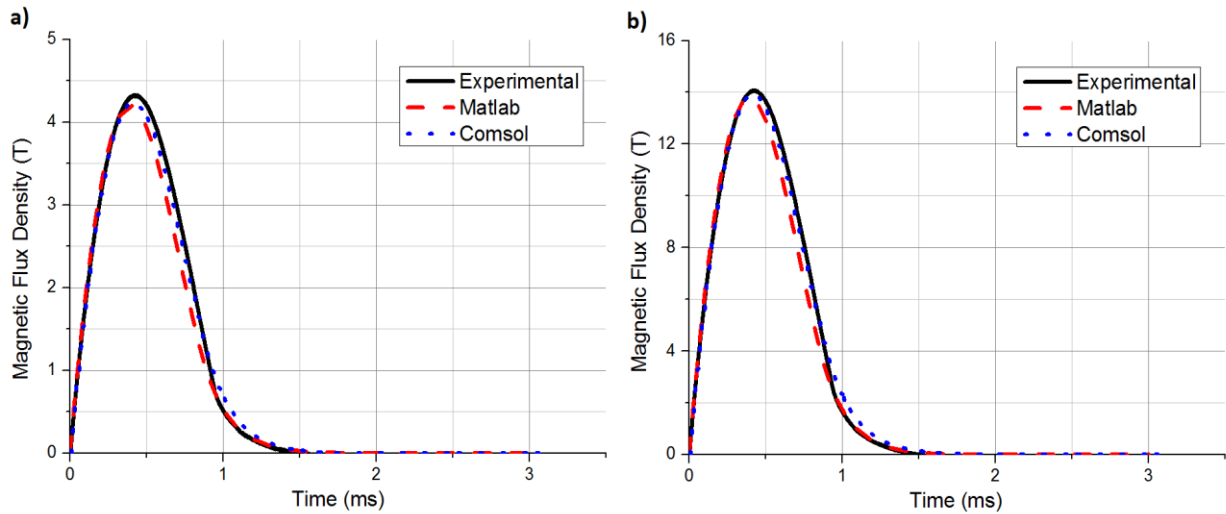


Fig. 40. Magnetic flux density in the center of inductor W a) $U_0 = 320$ V, b) $U_0 = 1050$ V

3.6. Conclusions of Chapter 3

In this chapter magnetic flux density in the center of bores of four readily designed inductors were analyzed. For this purpose first of all inductances of inductors were determined by using computations and experiments. It was shown that results were accurate considering all three methods. In addition to that resistances were measured in the laboratory. Next step was to determine current waveforms in inductors by using Matlab Simulink® model of pulse generator. The waveforms of currents with capacitor bank charged to different voltage values were obtained. As expected inductors with higher inductance and resistance values gave longer pulse durations. Also inductors with higher inductance resulted lower current amplitudes even though they were supplied with considerable higher voltages than inductors with smaller inductance. The resistance also has effect on this in addition to value of inductance. Therefore, compact inductors gives higher current amplitudes with lower capacitor voltages due to low resistance and inductance values as one may expect. Final step was to perform experiments and computations to obtain magnetic flux density in the center of inductors. It was shown that simulations, analytical computations and experimental

results were enough accurate: maximum deviation for peak field was 5% and for pulse duration 4%. To determine magnetic flux density in the center of inductors the performed steps in this chapter can be followed for later simulations. From the equation (9) it is observable that magnitude of field in the inductor bore is proportional to current and inversely proportional to inner radius of inductor. The results presented in this chapter confirmed this. As a result, to achieve high peak fields with smaller current values while sacrificing from longer pulse durations compact inductors are better choices than large inductors. On the other hand, to achieve long pulse durations large coils with higher inductance values are preferable.

4. Inductor Design for Colossal Magnetoresistive Sensor Testing

The optimization of high field pulsed inductors' geometry is a difficult multi-dimensional task. Two main difficulties emerge in pulse generation which are that inductor could be destroyed because of the Joule overheating and it might be damaged by the Lorentz forces acting in its windings. These mentioned factors are directly dependent on inductor's geometry, i.e. on the number of winding layers and windings per layer. Therefore, a detailed analysis of thermodynamic, electromagnetic and mechanical processes is inevitable and will be carried out for different geometrical inductor configurations to reach the goal: a non-destructive inductor that can meet required magnetic field generation.

The inductor is necessary for colossal magnetoresistive (CMR) sensor testing and it should be designed to withstand peak field of 40 T magnetic flux density. There are some requirements and limitations of inductor that will be given later. In the design process the information about required peak field, geometry, pulse duration and material properties of wires and other inductor parts will be used as inputs for specially created inductor design algorithm.

4.1. Inductor Design Materials and Construction

Before inductor design process materials that can be used for inductor design and construction methods will be studied briefly. With the development of copper with finely distributed discontinuous filaments of niobium non-destructive pulsed inductor designs stepped into a new era [9], [82]. Materials containing several components normally follow the rule of mixtures that is overall strength is the weighted average of the strength of the components. However, these micro-composite wires containing very small filaments (with a typical size of μm or less, in an amount of order $< 20\%$ weight) are stronger than expected from the rule of mixtures. These wires are still windable around relatively small radii (down to less than 5 mm as required for the highest fields) and therefore they are well suited for winding high field inductors. These wires with a typical tensile strength of 1 GPa and 70 % IACS (International Annealed Copper Standard) are now commercially available in both Russia, A.A Bochvar Institute of Inorganic Materials and USA, Supercon Inc. [9] Another wire that includes micro-filaments of silver in copper was developed in the National Research Institute for Metals (Tsukuba, Japan) [83]. This wire includes micro-filaments of silver in copper and offers the properties that is in the same range as those of copper-niobium in addition to less complicated manufacturing process. This wire was produced in Japan, Showa Electric Wire and Cable Co. and used to generate record field 80T [84], [85]. Less expensive alternative to micro-filaments containing wires is copper wires with a stainless steel jacket that was developed at Oxford [85]. For these macro-composites rule of mixture is valid. However, excellent performance is obtained due to the strengthening of stainless steel at liquid nitrogen temperature [9].

Wires for compact pulsed field inductors are usually chosen with rectangular cross section. An industrial winding machine is not needed, a lathe and a variable speed motor is adequate preferably controlled by foot pedal. A regulated brake to control the wire tension is required and simple friction break with mechanical feedback, a magnetically operated clutch, or a motor with controllable torque can be used. Coating on soft copper wire with several layers

of insulating varnish is usually applied. Hard wires are insulated with Kapton tape in the spiral form. Inner side of the tape might be coated with a material (e.g. Teflon) that glues the Kapton to the wire when heated. At the outer layers of inductors where the voltage is highest Kapton may cause serious insulation problems. One solution is braiding a glass fibre sleeve around wire [9].

To manufacture an inductor that includes internal reinforcement, a special winding machine is needed to wind a fibre layer with adjustable thickness between each layer of wire while the wire remains continuous [86]. One possible way is winding fibre dry and then vacuum-impregnate the inductor after enclosing it in a tight shell. The best impregnation is obtained by degassing the inductor under vacuum for a day and then impregnate by sucking the epoxy through the winding. After impregnation is done, pressure of 2-5 bar is applied while curing at elevated temperature [9]. A very strong insulating fibre that is sold by Toyobo Co. is Zylon. Since it is very strong it is not convenient for dry winding and vacuum impregnation. Therefore, wet winding of Zylon can be applied. Peak fields up to 79 T have been achieved at the NHMFL with inductors combining Zylon and Cu-Nb micro-composite wire Bochvar Institute. These inductor also includes another material for additional reinforcement that is a multi-phase alloy MP35N (35% Ni, 35% Co, 20% Cr, 10% Mo; with ultimate tensile strength (UTS) 2.6 GPa [9], [87].

As external reinforcement thick-walled steel (maraging) cylinder [88] or titanium alloy [89] or a thick layer of fibre composites or pearlitic steel wires can be used [9].

4.2. Inductor Design Algorithm and Design Proposal For CMR Based Sensor Testing

Colossal magnetoresistance (CMR) based sensor was developed at the Center for Physical Sciences and Technology (CPST) to measure magnetic flux density with high accuracy independently on magnetic field direction [90]. In this chapter an inductor design proposal that can generate $40 \text{ T} \pm 1 \text{ T}$ magnetic flux density will be given to be used in testing of sensor. There are some special geometry requirements for this inductor that is, the inner radius of inductor a_1 must be at least 6 mm and maximum 7.5 mm, the length $2b$ must be more than 20 mm. There is no upper limit for length but to have compact inductor design the limit is assumed to be 50 mm. Pulse duration of generated magnetic field must be between 0.6 ms and 1 ms. Bore radius and pulse duration were chosen small to keep the energy limits therefore required current low.

Inductors will be designed as compact wire wound inductors. There are few reasons why compact inductor design was chosen. First of all these inductors are relatively easy and cheap to manufacture, with a typical weight of few hundred grams to kilograms they are convenient to handle. In addition, they can be operated from a modestly sized energy source. The inductors can be used at field levels close to the limit where the inductor is destroyed since they are expandable. A desirable service life is 300 – 1000 pulses. In case of inductor failure usually the amount of energy released by compact inductors does not cause damage to the measuring apparatus [9]. As a result to have compact designs inductors will be designed having at least 3 layers and number of layers will be named as $N1$.

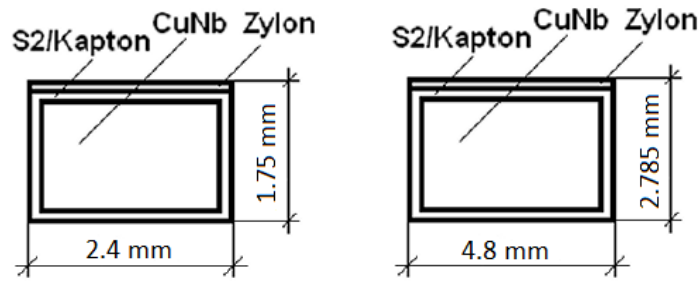


Fig. 41. Cross sections of wire A and wire B with insulation and reinforcement added

As wires of inductor Cu-Nb microcomposite conductor including 18% Nb and 82% Cu and with 65% IACS will be used since it offers good conductivity with high mechanical strength (1.1 GPa UTS) as described in the previous section. There are two wires with different cross sections one has dimensions of $4.2 \times 2.37 \text{ mm}^2$ and the other one has $1.7 \times 0.8 \text{ mm}^2$ in the CPST high pulse power laboratory which were specially purchased for inductor designing purposes from Bochvar Institute. The first wire will be named as wire A and second is wire B. In order to ensure non-destructive multi-use operation under high stresses due to Lorentz forces reinforcement must be added to wires. As reinforcement material Zylon fiber-epoxy composite and as isolation material Kapton film and S2 glass fiber might be used. Reinforcement amount was determined by past experiments and design proposals in [21],[91] for 50 T pulse generation and after running design algorithm which will be given later. Since our aim is to generate 40 T reinforcement and insulation thickness was chosen smaller than the inductor used for generating 50 T. With reinforcement and insulation included wire dimensions become $4.8 \times 2.785 \text{ mm}^2$ and $2.4 \times 1.75 \text{ mm}^2$. Cu-Nb wire properties and cross sections with insulation and reinforcement is shown in Fig.45 and wire geometries, material properties and insulation amounts are given in Table 7. Considering the first and second wire dimensions and required length of inductor number of turns in a layer i.e. N_2 must be between 5 – 10 and 9 – 30 turns.

Table 7. Dimensions of available wires, material properties and insulation amounts

Parameter	Value
Material	Cu-Nb
Composition	82% Cu, 18% Nb
Dimensions	Wire A : $4.2 \times 2.37 \text{ mm}$ Wire B : $1.7 \times 0.8 \text{ mm}$
Conductivity (% IACS)	65 % (293 K)
Winding insulation	S2 glass fiber, Kapton Wire A: 0.15 mm, Wire B: 0.35mm
Internal reinforcement	Zylon (Epoxy impregnated) Wire A: 0.115 mm, Wire B: 0.25mm

The information given above about required limits on required peak field, inductor geometry, pulse duration is summed in Table 8.

Table 8. Requirements of inductor

Parameter	Value
Required peak magnetic flux density (B)	40 T $\pm$ 1 T
Inner radius of inductor (a_1)	Min = 6 mm, Max = 7.5 mm
inductor length ($2b$)	Min = 20 mm, Max = 50 mm
Pulse duration (τ)	Min = 0.6 ms, Max = 1 ms
Number of layers ($N1$)	Min = 3 layers
Number of turns in a layer ($N2$)	Inductor A = 5 – 10 turns, Inductor B = 9 – 30 turns

The created optimized inductor design algorithm is shown in Fig. 42. First step in design of special pulsed inductor is an analysis and estimate the basic parameters such as peak field, pulse duration, bore and available wires to determine the required current and voltage from the supply that is capacitor bank. This step was done by using the given data and shown in Table 8. Next step is to find the required inductance by using given pulse duration and inductor geometry information as inputs in the specially written Matlab® code together with the approximated stress limit. In this step the possible inductor geometry will be found besides resistance of this possible inductor design. After that aimed peak field in addition to found resistance, inductance of inductor will be used in Matlab Simulink® model of pulse generator to find the current. The last step is finding the magnetic flux density distribution and analyzing the stress and temperature transients in the inductor. Results will be saved and inputs that is possible to change will be changed to find optimal design.

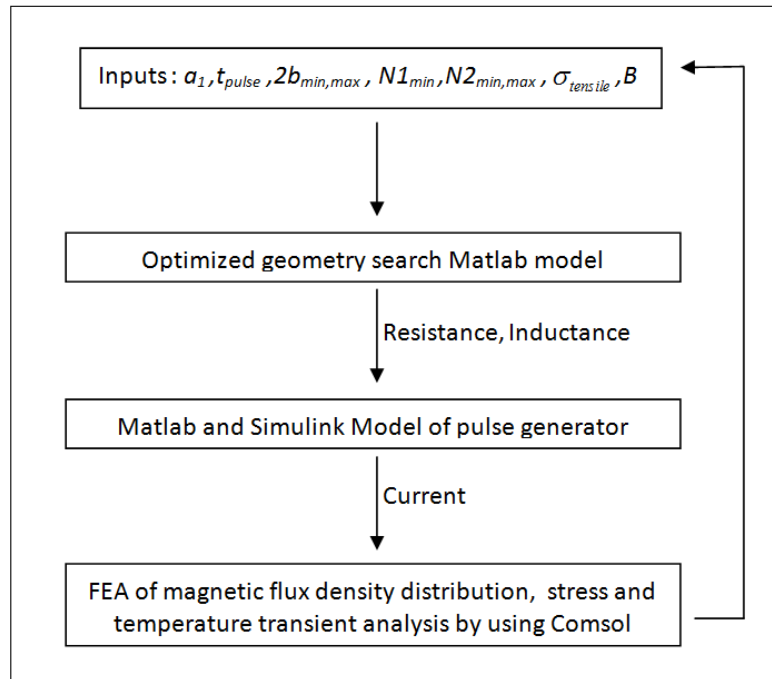


Fig. 42. Simplified scheme of inductor design algorithm

With the given process possible inductor geometry optimization to generate 40 T was done with different wire cross-sections. The result is with wire A non-destructive inductor operation can be obtained within the given limits of geometry and pulse duration. On the other hand, the inductor constructed with wire B experience the overheating which would damage the insulation and even wires and reinforcement. In the following of this chapter each step of the process will be studied to design two inductors with wire A and wire B. It will also be shown that inductor design with wire B experience overheating.

4.2.1 Determination of Inductor Geometry

First step of design includes determination of required inductance by using pulse duration equation. It was given before that pulse duration can be found approximately by equation (16). Actually it is better to use equation (39) since it gives better accuracy. However, the resistance value of inductor is unknown at this stage. For this reason equation (17) will be used. From this equation inductance can be represented as $L = \tau^2 / K^2 \pi^2 C$. Here as described before K is the constant dependent on circuit characteristic i.e. under-damped, over-damped or critically damped. Usually compact inductor designs have small resistance as the wire length is small. Therefore, we can assume that designed inductor will have small resistance and it means that circuit behaviour will be under-damped. In this case, constant K equals to 1. On the other hand, as energy storage 5.4 mF capacitor bank will be used. The pulse duration was chosen to be 0.8 ms which is within the required limits. As a result, the required inductance approximately equals to 12 μH . However, this equation neglects the resistance of inductor which exists in reality. Therefore, inductor that will include wire B will have considerably more resistance than inductor with wire A because of its smaller cross section and the effect of resistance on pulse duration will be bigger as well. As a result, it is expected that pulse duration will be more than 0.8 ms for inductor with wire B. Because of this reason inductance requirement for inductor B will be assumed few nH less than 12 μH . For instance, 11.5 μH .

$$\alpha = \frac{2\sqrt{\mu_0 \sigma_t}}{2\sqrt{\mu_0 \sigma_t} - B} \quad (47)$$

Equation (45) gives the inductor inductance dependent on inductor geometry. On the other hand, from the equation (47) ratio of outer diameter to inner diameter α as a function of maximum magnetic field to be generated and tensile strength of the wire material is obtained as a rough approximation [9]. In our case for maximum 40 T magnetic flux density using Cu-Nb wire that has 1.1 GPa tensile strength $\alpha = 2.16$. To ensure the non-destructive operation α will be chosen greater than 2.16. With the all the given information above optimal inductor dimensions will be determined by using equation (45) and (47). For this purpose a special optimization Matlab® code based on trial and error was used and the geometry parameters of two inductor with different wires is given in Table 9 and Table 10. The inductors including wire A and wire B are named inductor A and inductor B respectively.

Table 9. Proposed inductor dimensions for inductor A and B

Parameter	inductor A	inductor B
Inner radius (a_1 , mm)	7	6
Outer radius (a_2 , mm)	18.14	13
Length ($2b$, mm)	48	21.6
Number of turns on each layer (N_2)	10	9
Number of layers (N_1)	4	4

For calculation of inductor resistance equation (44) was used. Wire resistivity that is 65% IACS equals to, $\rho_{CuNb}(293K) = 2.723 \cdot 10^{-8} \Omega \cdot m$. Resistivity dependence on temperature should be considered. Resistivity of Cu-Nb wire was measured under 293 K and 77 K to find a ratio that is: $\rho_{CuNb}(293K) / \rho_{CuNb}(77K) = 4.5$. With the help of this coefficient the dependency of resistivity on temperature is found and given in equation (48) [92]. As temperature on calculation of resistance 293.15 K room temperature will be used.

$$\rho_{CuNb}(T) = -3.41 \cdot 10^{-9} + 7.2 \cdot 10^{-11} T(1.7973 - 0.001177T) \quad (48)$$

Table 10. Calculated inductor parameters for inductor A and B

Parameter	Inductor A	Inductor B
Total number of turns (N)	40	36
Geometry coefficients (α , β)	2.59, 3.42	2.17, 1.70
Filling factor (λ)	0.7276	0.3425
Total wire length (l_w , m)	3.3487	2.1488
Resistance ($R(273K)$, Ω)	0.0092	0.046
Inductance (L , μH)	12.13	11.64

4.2.2. Determination of Current

In the following resistance of inductors will be considered as 0.0190 Ω and 0.056 Ω since connections of inductor to the experimentation equipment increase resistance approximately 0.01 Ω . Following step is to find the current that is required to generate 40 T magnetic flux density in the center of inductor's bore. For this purpose equation (9) will be used. After rearranging equation (9), current value that is required to generate specific magnetic field density in the center of inductor can be found. This new equation is given below.

$$I = \frac{Ba_1}{\mu_0 N} \left[\frac{2\beta(\alpha-1)}{F(\alpha, \beta)} \right] = \frac{2Ba_1(\alpha-1)}{\mu_0 N} \ln^{-1} \left(\frac{\alpha + \sqrt{\alpha^2 + \beta^2}}{1 + \sqrt{1 + \beta^2}} \right) \quad (49)$$

After solving this equation for 40 T current value is found for inductor A and inductor B, $I_A = 43230A$, $I_B = 24569A$ respectively. To obtain voltage that capacitor has to be charged

to generate required currents equation (2) is used and it is found for inductor A and B, $U_{0A} = 2720V$ and $U_{0B} = 2295V$. Inductors were placed into the Matlab Simulink® model of pulse generator with 0.4Ω crowbar resistance. Crowbar resistance was chosen high to shorten the current tail. Obtained currents for both inductors are shown in Fig. 43. As can be seen the maximum current reaches 43090 A and 24560 A which insignificantly differs from calculated current to generate 40 T magnetic flux density.

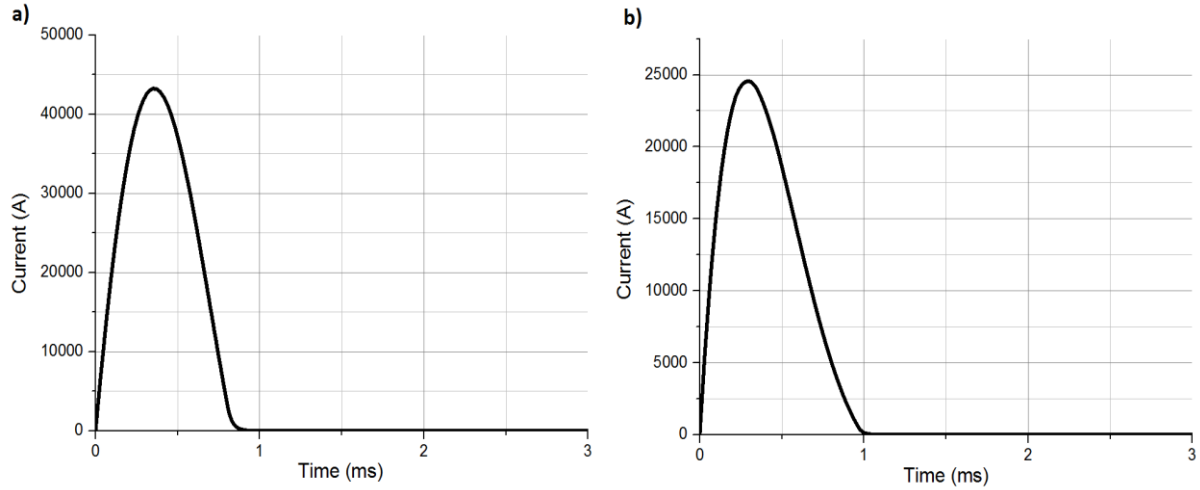


Fig. 43. Current pulses in the proposed inductors to generate 40T a) Inductor A, b) Inductor B

As expected pulse duration of inductor B shows error due to relatively high resistance. Pulse duration is slightly more than 1 ms that is the limit of pulse duration. However, the error is insignificant and it can be assumed that inductor operates in the required pulse duration interval.

4.2.3. Testing Inductor Using FEA Software

In this section inductor with optimal geometry to fulfill requirements will be tested to check if it can withstand the aimed magnetic flux density without failure. To test the inductor FEA software Comsol Multiphysics® will be used. First step is to investigate magnetic flux distribution. Next step is to perform stress analysis and finally, temperature transient analysis.

4.2.3.1. Magnetic Flux Density Distribution Analysis

Next step is to analyse magnetic flux density distribution with using FEA software Comsol Multiphysics®. Inductors were modelled using 2D axis-symmetry geometry. They were placed in air environment while using infinite element domain for air. Magnetic fields and joule heating physics were added to analyse temperature transient later. As inductor domain multi-turn inductor domain was used. To obtain accurate results with using as less computational power as possible optimal meshing was chosen and meshed inductor models are shown in Fig. 44. Even better meshing can be used however the computation time would be longer while changes in results would remain insignificant.

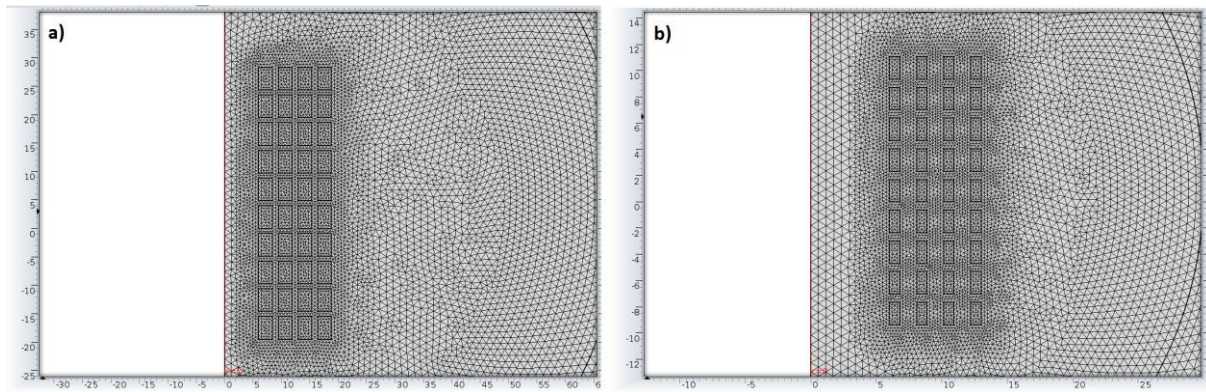


Fig. 44. Meshed inductors a) Inductor A, b) Inductor B

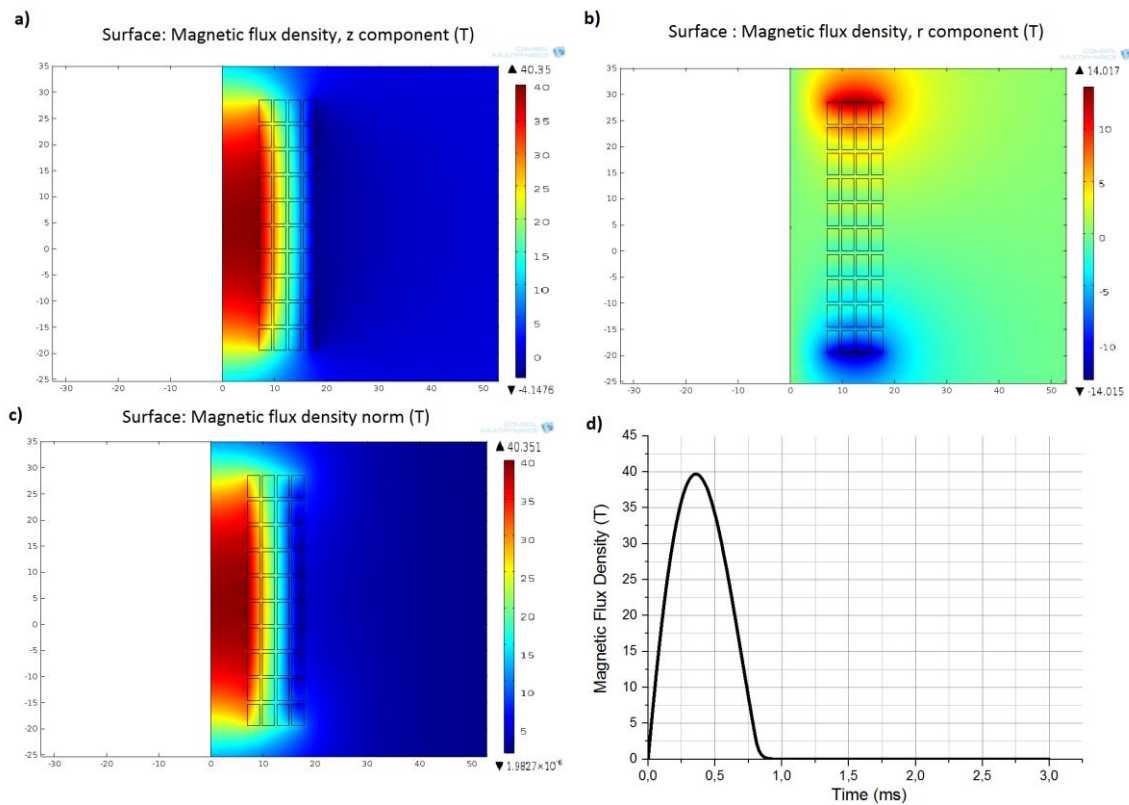


Fig. 45. Magnetic field density distribution in Inductor A a) Axial magnetic field density component, b) Radial magnetic field density component, c) Normalized magnetic field density, d) Magnetic flux density in the center of bore

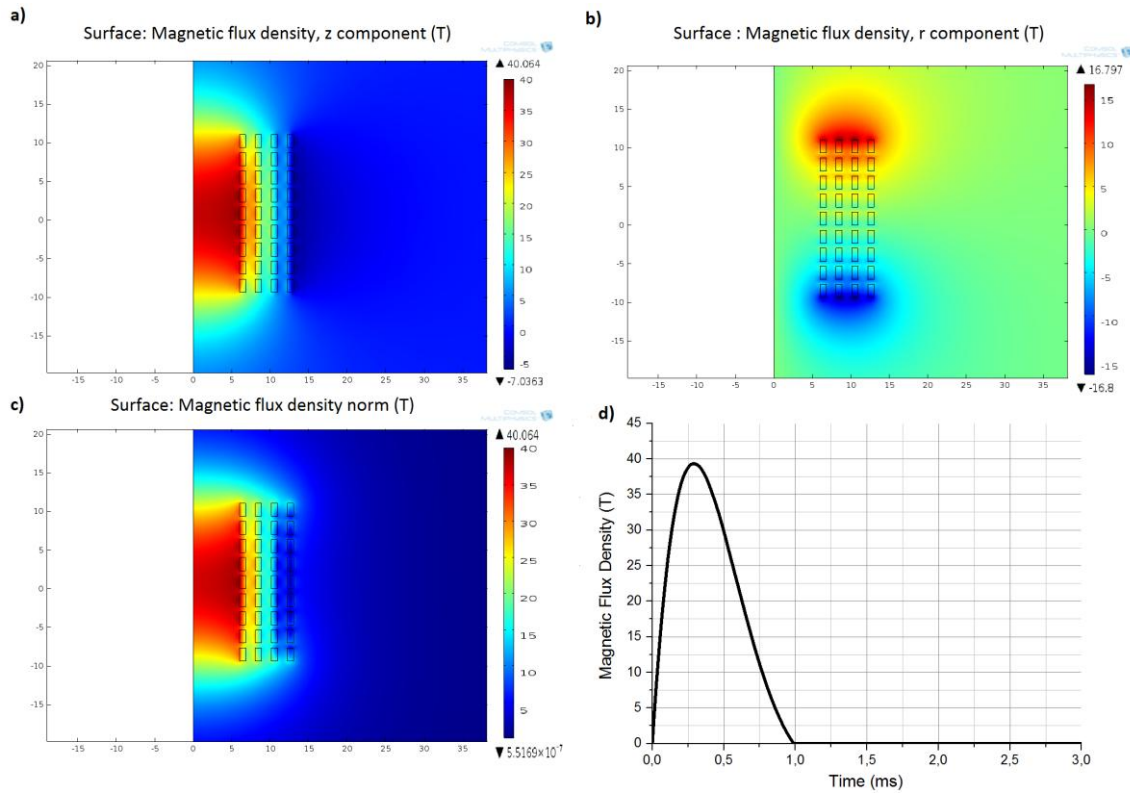


Fig. 46. Magnetic field density distribution in Inductor B a) Axial magnetic field density component, b) Radial magnetic field density component, c) Normalized magnetic field density, d) Magnetic flux density in the center of bore

Simulation was performed using time domain solver. In the figures above the resulting magnetic fields are shown for both inductors. As can be seen in Fig. 45 c) and Fig. 46 c) aimed magnetic flux density which was $40 \text{ T} \pm 1 \text{ T}$ in the inductor bore was achieved. It is also observable that the axial magnetic flux density is considerably higher than radial magnetic flux density component. Also the first layers of both inductors experience the highest magnetic flux density as expected. This will cause Lorentz forces on the first layers to be higher as well.

4.2.3.2. Stress Distribution Analysis

By using equation (47) geometry coefficient α was obtained approximately so that they would withstand the mechanical stresses caused by Lorentz forces. However, to ensure that inductors will not fail under generated mechanical stresses detailed analysis must be done. As stated before radial mechanical stresses are caused by axial magnetic flux density, they act as inductor's expanding forces towards outer reinforcement cylinder. On the other hand, axial stresses are caused by radial magnetic field and act as inductor's compressive force along inductor's bore axis. After analysis of Lorentz force distribution hoop and finally von Mises stresses will be obtained. By placing Lorentz force integrations as given in equations (18) and (19) into Comsol Multiphysics® inductor models axial and radial stresses will be found. Next step is to calculate hoop stress by using magnetic field density in the inductor bore and layers by using the equation (20). Final step is to calculate von Mises stress distribution with equation (21) to investigate whether inductor failure occurs.

If radial stress is transmitted between layers that are strongly bonded (e.g. by epoxy) there is steep increase of hoop stress towards the inner radius of inductor. Therefore, this can be

visualized by considering that the outer layers have a tendency to expand more and thus pull the inner layers outwards. In reality it is derivative of the radial stress that causes this effect. Thus, a relatively small radial stress can cause a large increase of hoop stress. Strong outer reinforcement by thick steel shells are used in pulsed magnetic field generation to contain radial expansion [92].

The resulting radial, axial, hoop and von Mises stress distributions of both inductors are given in Fig. 47 and Fig. 48. It was proven that maximum sum stresses in inductor did not exceed the Yield strength (see Table 11.) of any material which was used to construct inductors and was responsible for inductor's operation. The maximum von Mises stress in the inner layers did not exceed 850 MPa that is the Yield strength of Cu-Nb wire. It means that all the construction parts including Cu-Nb wire, would overcome only elastic deformations. For other parts, like Zylon or SF glass fiber reinforcement layers stresses are 3-4 times weaker than their Yield strength. Steel shell in the bore of the inductor and on the sides of it is also deformed only elastically because magnetic forces are directly acting only on the first windings towards outer inductor layers and the middle plane.

Table 11. Material properties for structural analysis

Material	Yield Strength (MPa)	Tensile Strength (MPa)
Cu-Nb wire	850	1100
Zylon	3200	4500
Epoxy	42	70
S2 GF	2600	3660
Kapton	69	252
Steel Shell	200	520

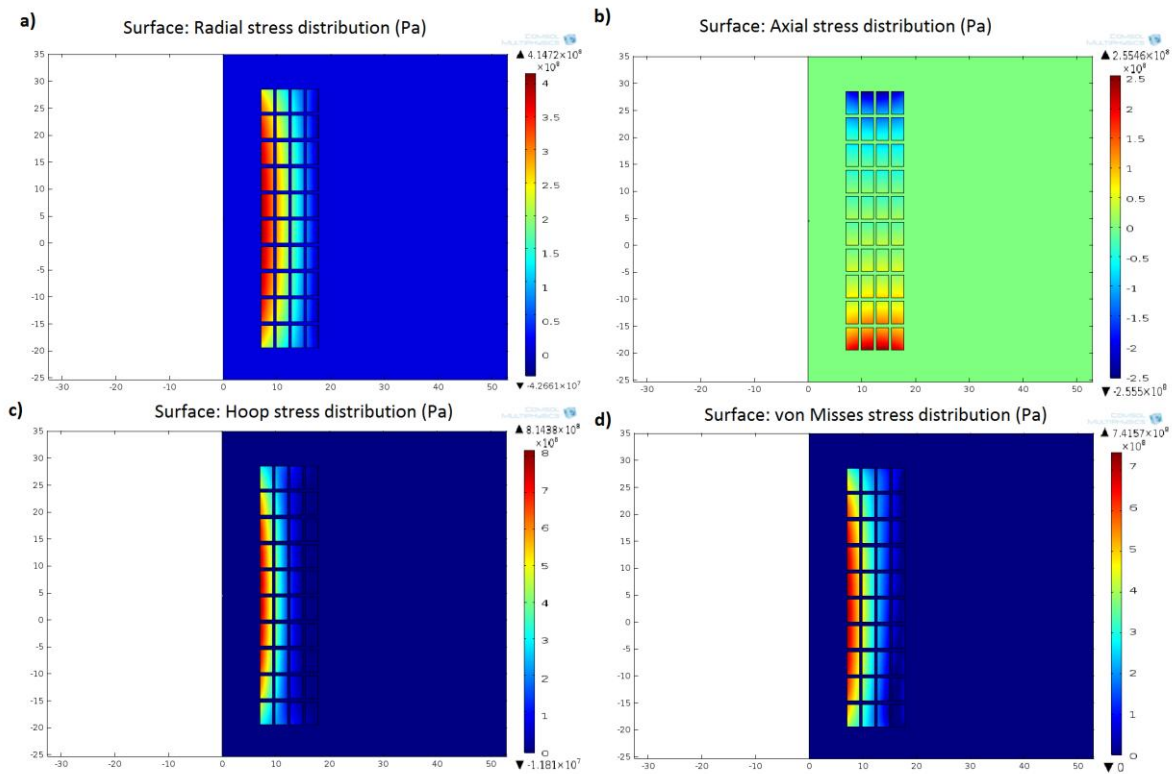


Fig. 47. Stress distribution in Inductor A a) Radial stress distribution, b) Axial stress distribution, c) Hoop stress distribution, c) Von Mises stress distribution

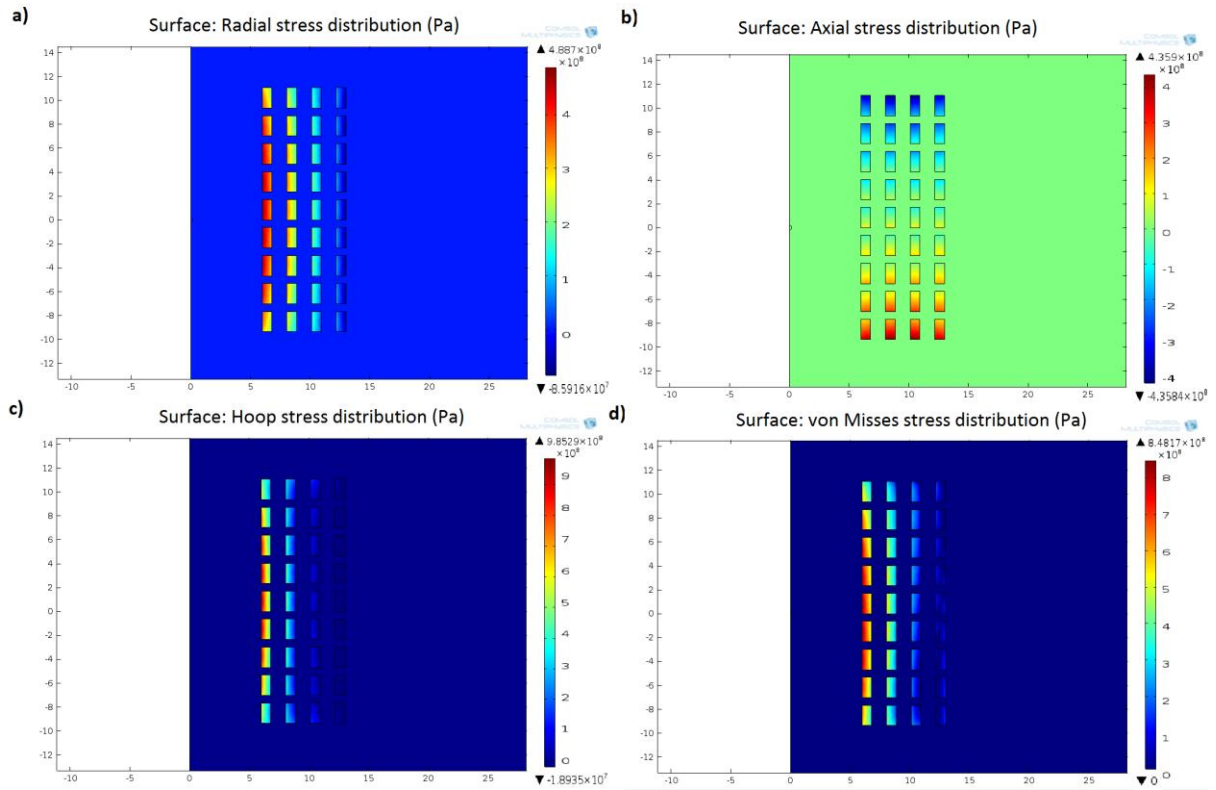


Fig. 48. Stress distribution in Inductor B a) Radial stress distribution, b) Axial stress distribution, c) Hoop stress distribution, c) Von Misses stress distribution

Taking into consideration the von Misses stress distribution in inductor B the magnitude of stresses in the inner layers reaches beyond 840 MPa. That means inductor B withstands the 40 T however, the inductor current and therefore capacitor voltage must be carefully controlled not to exceed the magnetic flux density limit to avoid inductor failure. Also probability of failure is high after several pulses. Reinforcement amount might be increased in inductor B to increase strength however, before doing it thermodynamic analysis should be performed to see whether inductors experience over-heating.

4.2.3.3. Temperature Transient Analysis

Fig. 49 and Fig. 50 show that both inductors generated $40 \text{ T} \pm 1 \text{ T}$. However, the question is will they experience overheating due to Joule heating. To answer these question joule heating analysis must be performed.

Before starting simulation of joule heating some parameters, i.e. heat capacity at constant pressure, thermal conductivity and density that belong to Cu-Nb which was used in inductor design as wires should be determined. First of all these parameters for pure Cu will be defined and a coefficient will be included to equations to obtain the equations for Cu-Nb considering the percentage of materials. Equation (50) shows the heat capacity of Cu at constant pressure dependent on temperature [9].

$$c_{Cu}(T) = 834 - 4007y + 4066y^2 - 1463y^3 + 179.7y^4 \quad J / (kg \cdot K), \quad y = \log_{10} T \quad (50)$$

Considering that $c_{Nb}(300K) = 256 \quad J / (kg \cdot K)$ and material includes 18% of Nb and 82% of Cu the heat capacity at constant pressure for Cu-Nb composition is estimated as:

$$c_{CuNb}(T) = c_{Cu}(T) \cdot 0.94 \quad J / (kg \cdot K) \quad (51)$$

Other parameter that is thermal conductivity for pure Cu dependent on temperature is given below.

$$k_{Cu}(T) = 0.43(T - 273) + 400 \text{ W / (m} \cdot \text{K)} \quad (52)$$

Considering thermal conductivity of Nb at 300 K that is $k_{Nb}(300K) = 53.7 \text{ W / (m} \cdot \text{K)}$ and composition rates of material is thermal conductivity for Cu-Nb dependent on temperature is estimated as in equation (53):

$$k_{CuNb}(T) = k_{Cu}(T) \cdot 0.84 \text{ W / (m} \cdot \text{K)} \quad (53)$$

Density of Cu and Nb at the room temperature is 8910 kg / m^3 and 8570 kg / m^3 respectively. Considering the percentage of Cu and Nb in the wire composition the density is found as following:

$$\rho_{CuNb} = 8849 \text{ kg / m}^3 \quad (54)$$

The given material parameters were added to Comsol Multiphysics® joule heating model of designed inductors. To have realistic results natural convective cooling was also added to both models. After proper meshing the simulation were performed and obtained temperature transient in the center of first layer of inductor A and inductor B is shown in Fig. 49. The reason why only first layer was analysed is that due to the magnetoresistance and skin effect the inner layer is heated to the highest temperature.

As can be seen in the Fig. 49 inductor B is heated significantly more than inductor A and heat dissipation due to convective cooling is insignificant. The reason of this big difference is that cross section of wire B is considerably smaller than that of wire A and therefore, the resistance of wire B is higher than resistance of wire A. Also convective cooling is less effective on inductor B because of the smaller surface area of wire B. The temperature limit for insulation material used in both inductors was 600 K and it is exceeded in inductor B during the operation which means insulation material would be damaged in addition to possible damage on wire material. However, in inductor A the maximum temperature would not cause overheating and damaging effects on inductor's material. As a result from temperature analysis point of view inductor B cannot be used to generate the required 40 T magnetic flux density but inductor A seems to operate without experiencing any damages due to temperature transients while carrying the required current to generate 40 T.

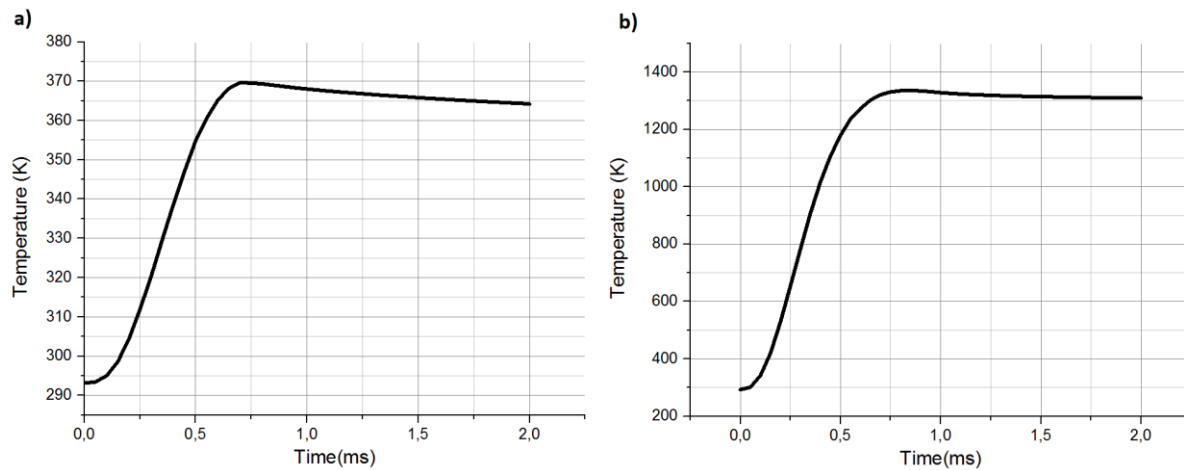


Fig. 49. Temperature transients in a) Inductor A, b) Inductor B

4.3. Conclusions of Chapter 4

In this chapter design algorithm based on trial and error method for designing pulsed magnetic field inductors were developed in order to propose 40 T inductor design for CMR based sensor testing purpose. First of all materials that are suitable in high pulsed magnetic field inductors manufacturing were studied. It was decided to use Epoxy impregnated Zylon as internal reinforcement, S2 glass fiber and Kapton as insulation material in the inductor design. As wire of inductors there were two possible wires at the High Magnetic Field Center of Vilnius that could be used. Both having rectangular cross section with $4.2 \times 2.37 \text{ mm}^2$ and $1.7 \times 0.8 \text{ mm}^2$ dimensions, respectively. Wire materials consist of 18% Nb and 82% Cu with 65% IACS and 1.1 GPa tensile strength. Reference insulation amount were used using previous experiments to provide inputs for inductor design algorithm together with given requirements and various calculations. After running the algorithm it was found that both inductors withstand the mechanical forces during pulse generation caused by Lorentz forces however, inductor including smaller cross section wire experience over-heating due to Joule heating. In the following of this chapter, each step of algorithm which consists of three main steps were explained. First step is Matlab® optimal geometry search sub-algorithm. Next step is to determine current to generate required peak field. Final step is to perform FEA analysis in Comsol Multiphysics® to analyse magnetic flux density distribution, mechanical analysis and thermodynamic analysis. It was shown that algorithm needs various inputs such as limits of inductor geometry, pulse duration limits, reference insulation amount, reinforcement amount, wire dimensions, material types and peak field.

General Conclusions

1. Simulation results of pulsed magnetic field generator without and with crowbar circuit modeled using Matlab Simulink® are reliable for determination of current waveforms in inductors of this generator since errors between simulation results and experimental results are up to 3% considering peak current value and 2.5% considering pulse duration.
2. Analysis of influence of crowbar circuit on current waveform using Matlab Simulink® model of pulse generator reveals that lower crowbar resistance values provide longer pulse duration and lower recharging (opposite polarity) voltage value of capacitor bank. This extends life-time of the capacitor bank.
3. Developed computer based models using Matlab® and Comsol Multiphysics® are reliable for the analysis of magnetic flux density in the inductor bore. Comparison of experimental and simulation results demonstrated that maximum errors are 5% considering the peak field and 4% considering pulse duration meaning that these models can be used for magnetic flux density analysis prior to experiments.
4. It was shown that to achieve high peak fields with smaller current values while sacrificing from longer pulse durations compact inductors are better choices. On the other hand, if long pulse duration is required inductors of larger volume are preferred.
5. Algorithm based on trial and error method was proven to be useful for non-destructive inductor design. In order to propose a design for 40 T inductor, this algorithm needs input parameters such as wire dimensions, insulation amounts, information on material that is intended to be used, required peak field, limits of pulse duration and inductor geometry.
6. Two inductor design proposals were given using the design algorithm and two type of wires made of the same material but having different cross-sections, i.e. $4.2 \times 2.37 \text{ mm}^2$ and $1.7 \times 0.8 \text{ mm}^2$ were used in simulations. It was found that both inductors with proper inner reinforcement were able to withstand mechanical stresses caused by high magnetic fields, however, inductor with smaller cross section wire experienced over-heating due to Joule heating. It was concluded that cross section of wires is important for inductor design and only inductor with larger cross section ($4.2 \times 2.37 \text{ mm}^2$) is suitable for generating 40 T non-destructively.

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