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Measurements of impulse magnetic fields

Abstract. The measurements of impulse magnetic fields using different methods were investigated. The main goal was the comparison of methods for measuring a strong magnetic fields. Method based on a Hall sensor was compared with the method using the measuring coil. In addition, the comparison of analog and numerical integration of the back electromotive force e(t) is presented. The paper shows waveforms of magnetic flux density and current recorded under investigation. The paper presents measurements of the magnetic induction up to 3 T. The main goal of investigations is development of precise methods and cheap devices for measurements of strong impulse magnetic fields.

*Streszczenie. W pracy przedstawiono pomiary impulsowych pól magnetycznych z wykorzystaniem różnych metod. Celem pracy było ich porównanie. Metoda bazująca na pomiarze za pomocą czujnika Halla została porównana z metodami bazującymi na pomiarze napięcia indukowanego w cewce pomiarowej. Dodatkowo, w pracy przedstawiono porównanie dwóch metod całkowania analogowego i cyfrowego siły elektromotorycznej e(t). W pracy przedstawiono przebiegi indukcji magnetycznej i prądu zarejestrowane w czasie badań. Pomiary indukcji magnetycznej prowadzono w zakresie do 3 T. Głównym celem badań jest opracowanie dokładnych metod i tanich urządzeń do pomiaru impulsowych pól magnetycznych. (**Pomiary impulsowych pól magnetycznych**).*

Keywords: measurements of a impulse magnetic field, a Hall sensor, a back electromotive force
Słowa kluczowe: pomiary pól impulsowych, czujnik Halla, siła elektromotoryczna

Introduction

High magnetic fields are applied in science, engineering and technology. Strong magnetic fields are used mainly for materials research and recently also for military applications. High magnetic fields are used e.g. in research of magnetization of crystals of materials [1,2], behavior of metallic melt under pulsed magnetic field [3], the thermodynamic properties of magneto-caloric materials [4], electromagnetic railgun RAFIRA [5]. In recent years in China is being build the main laboratory of high magnetic fields [6]. In these types of research measurements of high magnetic impulse fields are needed. Impulse magnetization of permanent magnets also uses high magnetic fields.

Impulse magnetization of hard magnetic materials is one of the most common way of final step in production permanent magnets. This method is applied especially for permanent magnets with high density of magnetic energy such as Nd-Fe-B and Sm-Co magnets. Impulse magnetization needs impulse magnetizer and magnetizing fixture. Impulse magnetizer is device equipped with high capacity and voltage capacitors. Inside magnetizing fixture is placed hard magnetic element. Magnetizing fixture dimensions, number and configuration of magnetic poles is determined by a permanent magnet application. For each kind of permanent magnet material is specified value of magnetic field that is needed for magnetization to saturation. The pulse of magnetic induction for impulse magnetization should have proper course in time and value. This is especially needed for magnetization of permanent magnets with low resistivity due to induced eddy currents in magnets. Eddy currents counteract of magnetization of an entire magnet.

During design process of magnetization fixtures the value of magnetic field is calculated analytically or using field analysis such as Finite Element Method. However after manufacturing of magnetizing fixture it is needed to measure real magnetic field. The basic cheapest teslameters can not measure impulse fields. It can be done using special teslameters or fluxmeters which are often expensive.

The main goal of investigations is development of precise methods and cheap devices for measurements of impulse magnetic fields.

Measurements of impulse magnetic fields

Measurements of impulse magnetic fields were done for a impulse magnetizer with a cylindrical coil. Impulse magnetizer was designed and manufactured in Tele and Radio Research Institute. The voltage is regulated and its maximum value is 5000 V and capacitance C=1 mF. As a magnetizing fixture it was used an air coil with 80 mm diameter and 193 mm in length for placing hard magnetic element. The coil has 440 turns of 3 mm diameter wire.
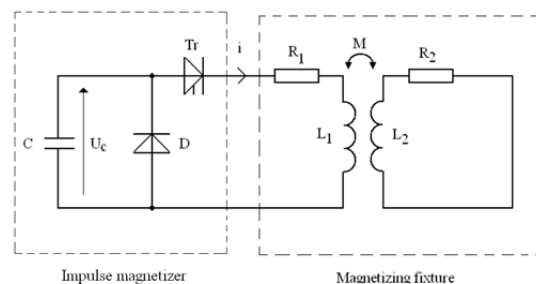Electric diagram of impulse magnetizer with magnetizing fixture is shown on fig. 1.

Fig. 1. Electric diagram of impulse magnetizer with a magnetizing fixture

The thyristor *Tr* is needed for a trigger of impulse current *i*. Magnetizing fixture is composed of a cylindrical coil inside and an aluminum coat outside. R_1 and L_1 represents resistance and self-inductance of a coil respectively. R_2 and L_2 represents resistance and self-inductance of an aluminum coat. Magnetic coupling between a coil and an aluminum coat is represented by mutual inductance M. Measures resistance of a coil R_1=0.38 Ω, calculated analytically: inductance L_1=5.52 mH, resistance R_2=17.1 $\mu\Omega$ and inductance L_2=73.22 nH. Calculated mutual inductance M=11.4 μH. U_c represents a voltage on a capacitor's bank. Diode D and thyristor Tr are high voltage and current elements manufactured by Westcode company. Impulse magnetizer is supplied from AC 230 V voltage.

The Hall sensor produced by Toshiba model THS 119 with supply circuit was used for measurements of impulse field in a cylindrical coil [7]. This measuring device was designed by Wroclaw University of Technology and manufactured in Tele and Radio Research Institute. Hall sensor is supplied from current source based on a 3 terminal positive regulator. Hall sensor device was calibrated in constant field of an electromagnet in comparison with F.W. Bell gaussmeter 5070 model.

For comparison purpose it was manufactured measuring coil with a passive analogue integrator based on a resistor and a capacitor. The measuring coil has 26 turns with diameter of 10.9 mm. As an integrator it was used an electric circuit consisted of a resistor R=217 kΩ and capacitor C=1.04 μF. Time constant is equal τ=R·C=0.23 s. In addition, recorded waveforms of electromotive force $e(t)$ were also integrated using Simpson's rule in Scilab 5.5.0 software.

Measurements of current in a supplying coil, electromotive force in measuring coil and magnetic induction by Hall sensor are convenient for analyses because in this case whole time courses are recorded and available for analyses.

Measurements of current were carried out using Tektronix TDS 210 oscilloscope with a current probe Tektronix A621 (AC Current Probe). Measurements of induced voltage in a coil and on capacitor from analogue integrator were also measured with Tektronix TDS 210 oscilloscope with a voltage probe Tektronix P2100.

Results of measurements
The current flowing through the coil reached the maximum value of 1.20 kA after the time 2.16 ms (fig. 2) for capacitor voltage U_c=3200 V.
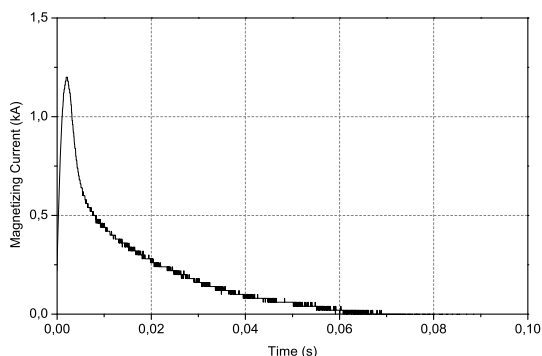

Fig. 2. Current waveform in a coil at the supply voltage of 3200 V.

Current "i" has aperiodical course. Rising slope of current flows from capacitor C, through thyristor Tr, resistance R_1 and inductance L_1. Falling slope of current "i" flows from inductance L_1, through diode D_1 thyristor Tr and resistance R_1.

Figure 3 depicts the magnetic induction waveforms that were recorded and calculated at supply voltage of 3200 V.

It is worth noting that the fall time of current is significantly shorter in comparison to the extinction of the magnetic field. This fact is related to the occurrence of eddy currents in the outer aluminum conductive shell of coil which prevent the disappearance of the magnetic flux inside the coil. These eddy currents in aluminum shell causes decrease of magnetic induction inside a coil.

Measurements of magnetic induction in a coil showed that ascending part of course of magnetic induction and its maximum value in three methods of measurements are comparable. The magnetic induction was measured and is equal 2.28 T at 3 ms in a case of Hall sensor measurements, 2.38 T at analog integration and 2.07 T at digital integration. The main differences are in descending part of course of magnetic induction. The differences are between measurements of induction with Hall sensor and induction obtained from integrations of electromotive forces. The main error that comes from digital integration is caused by ideal case of integration and neglecting discharge process of capacitor in real integration. Courses of

magnetic induction, obtained from electromotive forces, are derived from voltage drop on a capacitor. After impulse a capacitor is still charged and it is discharged in a circuit with 217 kΩ resistance and a few ohms resistance of measuring coil with time constant τ=0.23 s. Voltage on a capacitor decreases to practically to zero after 0.8 s which is after 3.5 time constants.
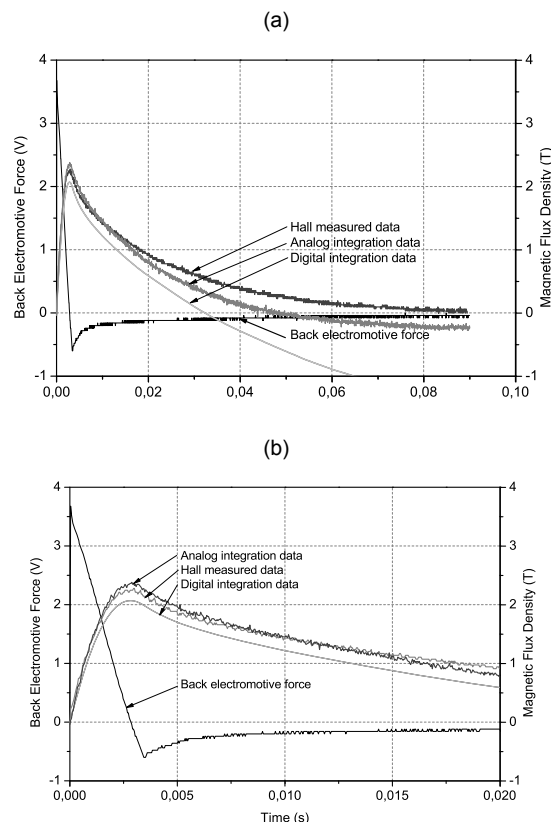
(a)

(b)

Fig. 3. Back electromotive force and magnetic flux density (a) at maximum time 0.1 s, (b) at maximum time 0.02 s, at the supply voltage of 3200 V.

Dependencies between the peak induction B_{peak} (measured by Hall sensor) vs. the supply voltage U_c is depicted in Figure 4. The study shows as would be expected that the relationship $B_{peak}(U)$ is linear. According to results of the regression analyze, the simple equation that describe the relationship $B_{peak}(U_c)$ may be drawn as $B_{peak} = (664\pm4)\cdot10^{-6}\cdot U$.
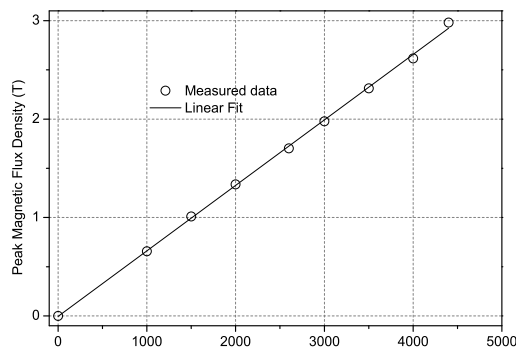

Fig. 4. Relationship between the peak magnetic induction and capacitor voltage measured by Hall sensor.

Summary

In the paper measurements of the impulse magnetic field have been investigated. Results of study indicate that it is possible to apply a Hall sensor and a measuring coil for measuring impulse magnetic fields over a range of magnetic fields up to 3 T. The prices of device with Hall sensor and measuring coil are comparatively very low to advanced measuring fluxmeters and gaussmeters.

Differences between measured and calculated courses are caused by ideal numerical calculations of integration in Simpsons' method and real measurements and analogue integration of electric signals.

Methods of measurements of magnetic flux density can be applied not only in impulse magnetization of magnets but also in e.g. devices with impulse magnetic fields for physicist.

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