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Magnetic field analysis of the Inductive Dynamic Drive

Abstract. *In this paper, the results of research about the Inductive Dynamic Drive are shown. This kind of drive is necessary component in the Ultra – Fast Hybrid Circuit Breakers, where it properly cooperates with a Vacuum Interrupter. This paper shows a result of electro – magnetic analysis using a 2D model of IDD in a Finite Element Method software. The article contains a description of laboratory stand where it is possible to check IDD's specification by using a high – speed camera.*

Streszczenie. *W artykule przedstawiono wybrane wyniki symulacji elektro – magnetycznej modelu 2D napędu indukcyjno – dynamicznego metodą elementu skończonego oraz badania dynamiki działania próżniowego członu zestykowego z napędem tego typu, stosowanym w ultraszybkich wyłącznikach prądu stałego. Do symulacji wykorzystano pakiet oprogramowania Ansoft Maxwell 2D, natomiast do badań dynamiki działania napędu zastosowano kamerę szybką Photron.* ***(Symulacja zmiennego pola magnetycznego w napędzie indukcyjno-dynamicznym)***

Keywords: Inductive Dynamic Drive, Thomson coil actuator, hybrid circuit breaker
Słowa kluczowe: Napęd indukcyjno-dynamiczny, ultraszybki wyłącznik próżniowy, łącznik prądu stałego, kamera szybka

Introduction

In the last few years the number of high power devices supplied by DC – current has raised. Manufactures are demanded to guarantee a high durability and reliability of their products. Conventional circuit breakers with magnetic blowout are able to extinguish electrical arc in several dozens of milliseconds. The result is a rise of short – circuit current close to prospective value. The main advantage of semiconductors is elimination of occurrence of electrical arc thus the switching off time is shorter. However, semiconductors bring high losses in conducting state. The hybrid circuit breaker is composed of semiconductor and mechanical switch. This solution eliminates drawbacks of these devices. The mechanical switch is responsible for conducting current in normal state and semiconductor takes part in turning off process. One of proposed solutions of hybrid circuit breakers is a switch based on forced commutation of current from mechanical switch to the branch with semiconductor.This type of switch is shown in figure 1. Application of inductive-dynamic drive (IDD) as propulsion for contacts limits the switching off time to less than 2 ms. In comparison to conventional circuit breakers this solution results in a decrease of maximal value of the turning-off short-circuit current. This kind of drive in cooperation with a vacuum interrupter guarantees opening time around hundreds of microseconds and acceleration around tens of thousands $\frac{m}{s^2}$ of movable contact. Thus, combination of inductive dynamic drive and vacuum interrupter is called Vacuum Switching Unit (VSU) which has been shown in figure 2. It is necessary to distinguish the rest of components in VSU such as a lock which is responsible for holding contacts in open position, sets of springs, an isolator, a driving rod and a bumper which is essential to absorb energy [1-4].

In figure 3 the 3D model of IDD has been shown. The propulsion consists on multi turn, flat, fixed, circular coil (2) and a copper disc (3) placed directly under the coil which operates as a shorted ring mounted to the base of disc (4). The driving rod connects movable contact with the disc. Drive is supplied from a capacitor charged by external power supply. A rapid discharge of energy stored in this capacitor gives a pulse of current which flows through a coil. This current generates strong magnetic field which induces in metal disc eddy currents. A large repulsion force which is generated due to interaction between these currents allows actuating one of the contacts. Maximal stroke of disc is limited by a vacuum interrupter and in typical developments it is not greater than 10 mm. The bumper is necessary to absorb all of the energy which can break vacuum interrupter. Next movable contact stops on a lock to satisfy insulation requirements.

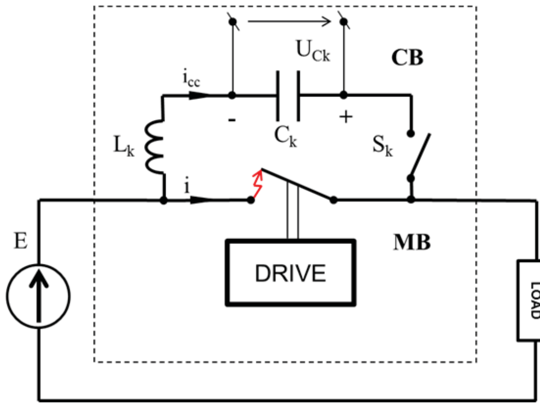

Fig. 1. Scheme of switch with force commutation . MB - main branch, CB - commutation branch

Small movements and high velocities make phenomena which occur in IDD complex. Hence, to analyse problem and find a solution it is necessary to use professional software based on Finite Element Method. In this case Ansoft Maxwell 2D has been used. To observe movements of components of IDD the ultra – fast camera Photron APX has been applied. The results from simulations and experiment have been compared.

Modelling

Simple modelling and reduced computation time in 2D analysis software, encourages designing IDD faster and easier to proceed. Symmetry of IDD allows implementing model in cylindrical coordinate system $r\theta z$. The main assumptions have to be provided:

- all currents flow in the θ direction,
- the magnetic field has no θ component,
- all currents are sinusoids oscillating at the same frequency.

Simulation was made in Ansoft Maxwell 2D which conducts calculation based on Maxwell's equations (1-2):

$$(1) \qquad \bigtriangledown \times \frac{1}{\mu} \bigtriangledown \times A = (\sigma + \mathrm{j}\omega\varepsilon)(-\mathrm{j}\omega A - \bigtriangledown\phi)$$

$$(2) \qquad \int_{\omega} \frac{1}{\mu}(\sigma + \mathrm{j}\omega\varepsilon)(-\mathrm{j}\omega A - \bigtriangledown\phi)\,\mathrm{d}\omega = \mathrm{I_t}$$

where $\mathbf{A}$ is the magnetic vector potential, ϕ is the electric scalar potential, μ is the magnetic permeability, ω is the angular frequency at which all quantities are oscillating, σ is

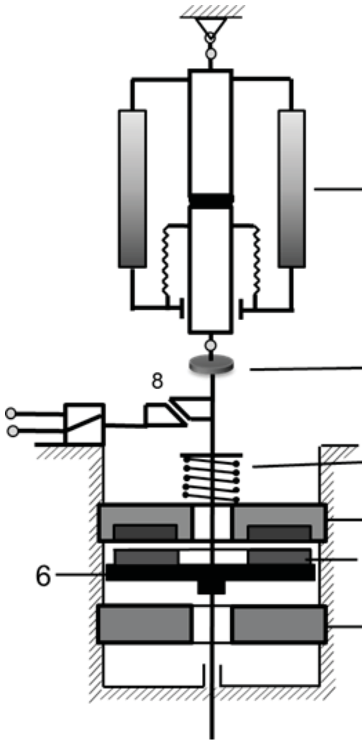

Fig. 2. Vacuum Switching Unit. 1 – vacuum interrupter, 2 – isolator, 3 – springs set, 4 – drive's coil, 5 – copper disc, 6 – base of disc, 7 –bumper, 8 - lock

conductivity, ε is the permittivity, $\mathrm{I_t}$ is the total current flowing in conductors. Hence, electro – dynamic force which has an effect on a disc along $\mathbf{z}$ axis was calculated (3-5):

(3) $$\mathrm{F_N = F_{AC} + F_{DC}}$$

(4) $$\mathrm{F_{DC}} = \frac{1}{2}\int \mathrm{Re}|\overline{\mathrm{J}} \times \overline{\mathrm{B}^{\circ}}|\,\mathrm{dV}$$

(5) $$\mathrm{F_{AC}} = \frac{1}{2}\int |\overline{\mathrm{J}} \times \overline{\mathrm{B}}|\,\mathrm{dV}$$

Next, using a propulsion force F_N and a mass of movable components of IDD the average velocity of disc was calculated (6):

(6) $$\overrightarrow{\mathrm{F_N}} \bigtriangledown \mathrm{t} = \mathrm{m}\overrightarrow{\mathrm{V}}$$

where: F_N – average value of force acting on a disc in interval of time, t – time interval of a force duration, m – mass of movable parts, V – average velocity.

In figure 3 the 2D model of IDD has been presented. The coil's armature is represented by a rectangle with define magnetomotive force θ. In this example a coil is made of 30 turns and a thickness of a copper disc is 3 mm. In this paper the results for three issues in IDD have been provided:

- the influence of a magnetomotive force in coil on a generated in a drive electromagnetic force;
- the influence of frequency of coil's current on maximal force;
- the difference in a force for disc made of aluminium and copper.

In the thirst part of conducted research frequencies of coil's current within the range 50 Hz - 2 kHz have been chosen.

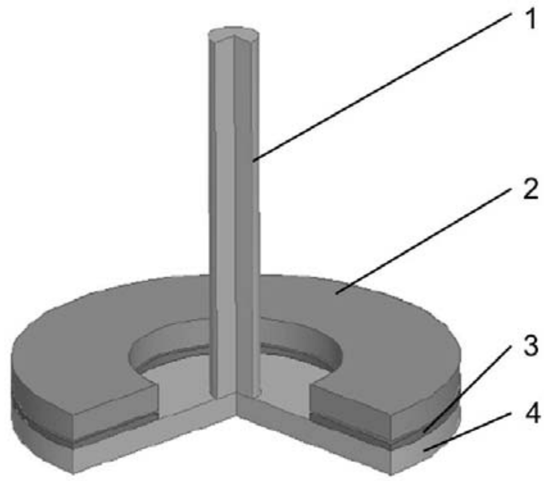

Fig. 3. Cross – section of 3D model of IDD. 1 – driving rod connecting movable contact with disc, 2 – drive's coil, 3 – disc, 4 – base of disc

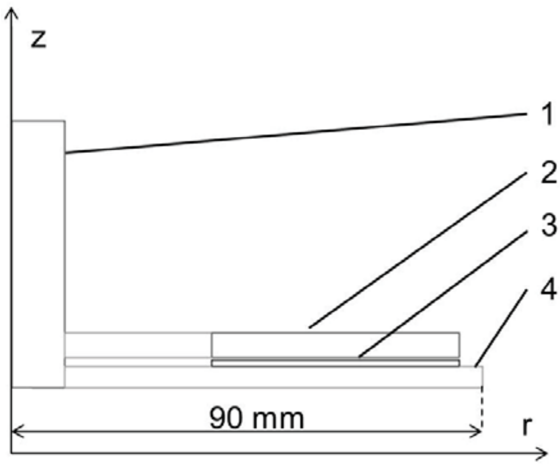

Fig. 4. 2D model of IDD defined in Ansoft Maxwell 2D. 1 – vacuum interrupter, 2 – isolator, 3 – springs set, 4 – drive's coil, 5 – copper disc, 6 – base of disc, 7 –bumper

For computation the constant flow θ equal 90000 At has been defined. The results are shown in figure 6.

The maximal force increases from 50 to 300 Hz very rapidly to become almost constant above 300 Hz. It is due to skin effect depth of copper disc. If the density of magnetic field in a disc is greater, eddy currents in a disc will increase and the maximal force of drive will be higher. For this case the increase of frequency above 300 Hz is groundless from maximal generated force point of view. However, it is important when the opening time is being considered. The faster current reaches its maximal value the faster maximal repulsion force occurs. This is the first step to choose proper parameters of coil's inductance and value of capacitor.

In the second part of research the influence of various numbers of ampere-turns has been analyses. Computation has been conducted for ampere-turns within the range from 15000 At to 220000 At. It has been assumed that a frequency of coil's current is equal to 1000 Hz. The results of this simulation are shown in a figure 7. The force is rising from 620 N up to 160 kN due to a growth of a coil's current. It useful to select a satisfactory magnetomotive force in a coil, to achieve a sufficient insulation gap between contacts of vacuum interrupter in an assumed time.

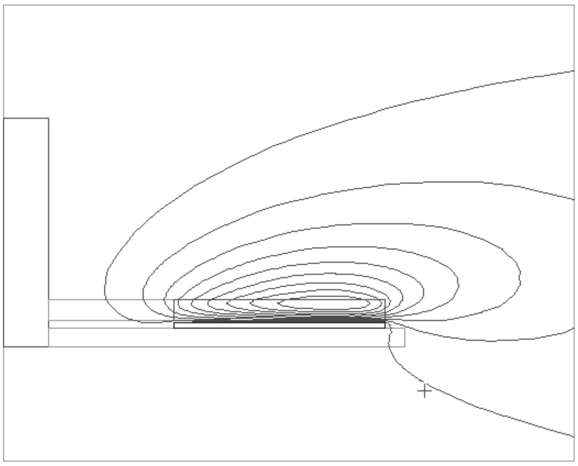

Fig. 5. Magnetic field distribution for frequency of coil's current equal to f = 2000 Hz

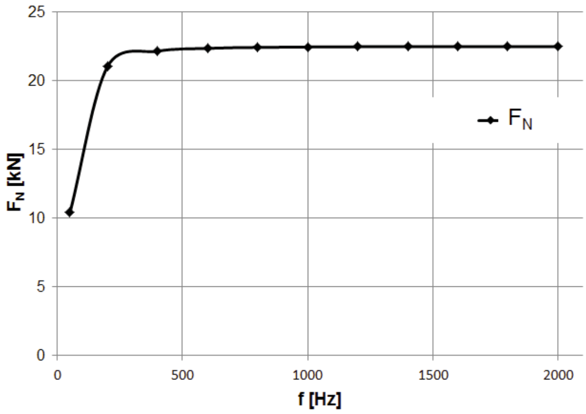

Fig. 6. The influence of frequency of coil's current f on repulsive force F_N

The parameter which has an effect on a maximum acceleration of movable parts of drive is their mass. In this part the disc made of aluminium and copper has been considered. The electrical conductivity of a copper is equal to σ = 58,6 * 10^6 $\frac{S}{m}$ and is greater than aluminium (σ = 36,6 * 10^6 $\frac{S}{m}$) However the drawback of copper is higher density. To find a solution a model from fig. 2 has been used. The results are shown in a table 1.

Due to lower conductivity of an aluminium disc the maximal generated forces in a drive are roughly the same. This conclusion due to lower cost and mass of movable parts is useful for the future projects.

Experimental tests and model verification

In figure 9 the scheme of main circuit for checking VSU placed in TUL Department of Electrical Apparatus is shown. Laboratory allows providing data about opening times and a the displacement of movable parts on which force acts. The capacitor C which is an energy store is charged to voltage U_C within the range (0,6 $\div$ 2) kV by autotransformer and rectifier. When controller of thyristor is triggering the capacitor discharges through propulsion's coil generating a one pulse

Table 1. The results for influence of disc material on generated in a disc repulsive force F_N

Type of disc	Magnetomotive force	Frequency f	Repulsive force F_N
	At	Hz	kN
copper	150000	1000	62,5
aluminium	150000	1000	62

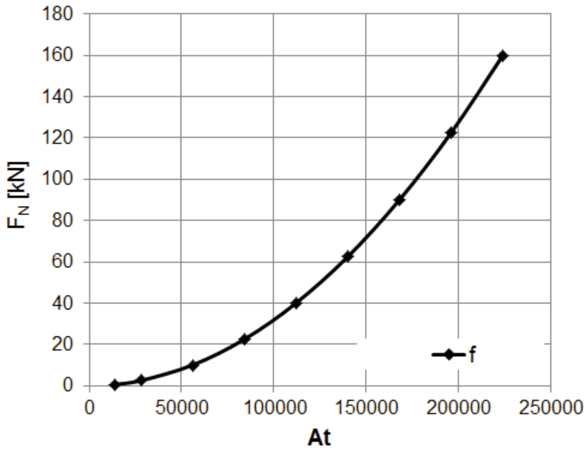

Fig. 7. The influence of a number of Ampere-turns on a maximal value of a repulsive force F_N

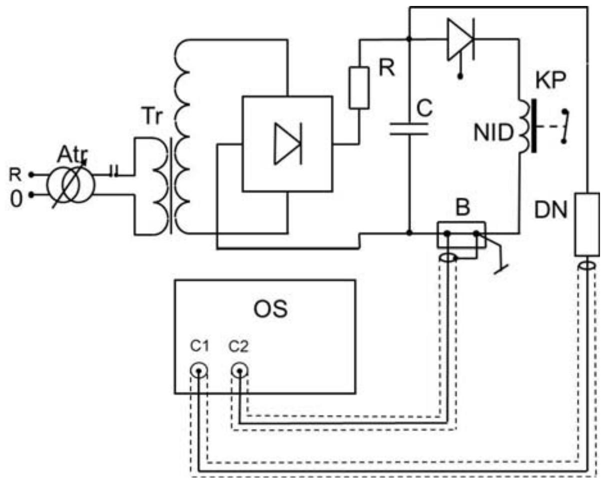

Fig. 8. Scheme of laboratory stand for Vacuum Switching Unit checking. NID - Inductive Dynamic Drive, KP - vacuum interrupter, OS - oscilloscope, B - Shunt, DN - voltage probe, C - capacitors, Atr - autotransformer, Tr - transformer, Pr - rectifier

current with frequency which depends on LC parameters.

The movable components of VCU's drive were observed by high-speed camera Photron APX which allows users to record films up to 350000 frames per second. In this case the films were made at 20000 fps what is sufficient to observe all components of drive. Two chosen frames were presented in figure 10. The displacement starts from closing position which is shown in figure 10a. After the force occurrence, the copper disc hits into the bumper and stops on a lock (figure 10b) to guarantee a proper insulation gap between the contacts. In the result of a lack of disc's stiffness the isolator was observed. The motion tracking is used to give information about full displacement in time of movable parts of VCU's. Based on this data an average acceleration and then average velocity of disc has been calculated. From equation 6 an average velocity of disc has been determined by using a force from simulation. These two values are compared in table 2.

Table 2. A comparison of the average velocity V_{AV} from simulation and from experiment, for three chosen voltage of capacitor U_C

Voltage U_C	V_{AV} from simulations	V_{AV} from experiment
$[V]$	$\frac{m}{s}$	$\frac{m}{s}$
800	1,28	1,48
1200	2,67	3,22
1600	4,47	5,03

Average velocities coming from simulation and experiment are rising with the increase of coil's current. The difference between them which is the greatest for the third case is due to insufficient stiffness of a VCU. The deformation of a disc will have the biggest impact on average velocity and the opening time for higher coil's current. These observations were useful to design a completely new VCU which is able to eliminate problems mentioned above and bring better stiffness.

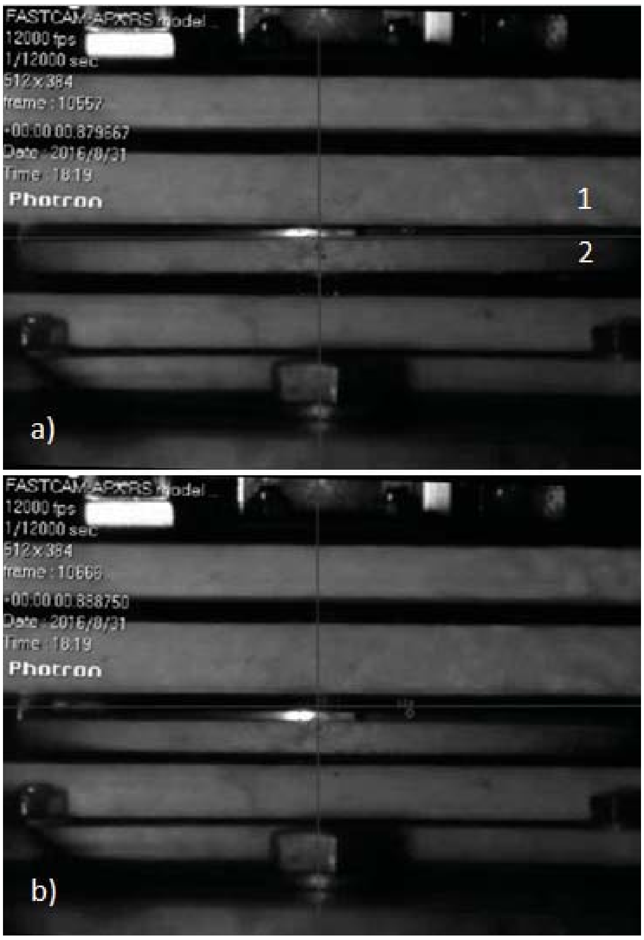

Fig. 9. Chosen frames from high-speed camera: a) Closed state, b) Opened state; 1 - coil, 2 - disc

Conclusion

Professional analysis software Ansoft Maxwell 2D dedicated to computation and solving problems in many industries branches has turned out to be very useful for modelling and designing of IDD. The influence of electrical and mechanical parameters of IDD on generated electromagnetic force was calculated. The results of simulations were verified in an experiment. The ability to calculate the maximal force which acts on movable parts can be very useful in future designs of VCU. The ultra-fast AC or DC high power switches are expected to guarantee a big spring's force to reduce power losses in normal conducting state. For this issue the required acceleration and velocity of IDD have to be delivered.

High-speed camera is useful to observe displacements of a movable contact and deformations of all components. This solution gives a possibility to increase a reliability of a VCU.

This procedure has been introduced in the current agreement with CERN (European Organization for Nuclear Research) concerning the compilation of ultra-fast vacuum switches protecting the superconducting magnets in Large Hadron Collider (LHC).

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