Coupled Magneto-Thermo-Mechanical Phenomena in Electromagnetic Devices: Main Interactions and their Graphical Representation

Michael G. Pantelyat
Department for Electrical Apparatuses,
National Technical University "Kharkov Polytechnic Institute",
Kharkov, Ukraine
E-mail: m150462@yahoo.com

***Abstract*—A list of main coupled electromagnetic, thermal and mechanical phenomena to be taken into account in numerical analysis of electrical machines and other electromagnetic devices is proposed. A number of well-known and "exotic" physical effects are listed and briefly analyzed. A detailed diagram depicting multiphysical processes is presented. An example devoted to illustration of the presented analysis utilization is considered.**

***Keywords*—electromagnetic devices; coupled phenomena; numerical simulation.**

I. Introduction

The operation principle of various electromagnetic devices (rotating electrical machines, transformers, actuators, induction heaters, magnetic resonance imaging scanners, etc.) is based on electrical and magnetic fields, heating and the forces resulting from those fields. To develop modern, effective and cheap innovative design it is strongly recommended to carry out complex numerical investigations of various physical processes and effects in the device under consideration taking into account their complicated interaction. Coupled (multiphysical) numerical analysis of electrical machines and other devices [1], [2] should be based on results of basic research aimed to make a valuable contribution in the development of modern fundamental (theoretical) principles as well as approaches for applied investigations in the field. Here, necessity to design and, therefore, simulate new types of innovative electromagnetic devices working on the base of new physical principles requires at first to determine a list of most important phenomena and effects of various physical natures to be taken into account during coupled interdisciplinary numerical simulation.

This paper represents an author's attempt to analyze and generalize all variety of multiphysical phenomena occuring during the operation of electrical machines and devices. A number of well-known and "exotic" physical effects to be taken into account in present and in further numerical investigations are listed and shortly described. To make the variety of known multiphysical electromagnetic, thermal and mechanical processes clear, an improved graphical representation of coupling is proposed.

II. Graphical Representation of Coupled Phenomena in Electromagnetic Devices

A graphical form is extremely useful to clarify complicated interactions of coupled phenomena and fields of various physical natures. As an example we refer to [3] where a general representation of coupled problems is presented.

In this paper, a more detailed diagram including a variety of known multiphysical electromagnetic, thermal and mechanical processes is proposed (Fig. 1). The diagram (see Fig. 1) consists of three connected main elements (or "physical domains" as put forward in [3]) representing electromagnetic, thermal and mechanical phenomena. The numbers near the lines with arrows depict physical processes and effects listed in section III. Naturally, the directions of the arrows demonstrate which main physical domain influences each of the others "by using" corresponding phenomena and effects of various physical natures.

III. Well-Known and "Exotic" Physical Effects: Which Ones Are Important/Neglected?

In this section we describe the author's vision of the "initial version" of the list of main multiphysical phenomena to be considered in building the mathematical model of an electrical machine or electromagnetic device. The numbers of the items correspond to the ones in Fig. 1.

In Fig. 1 the following well-known and "exotic" coupled physical effects acting in electrical machines and electromagnetic devices are shown:

1 – Joule losses; 2 – electromagnetic forces and torque; 3 – the temperature distribution which alters the mechanical state of the structure; 4 – mechanical properties depending on temperature; 5 – electromagnetic properties depending on temperature; 6 – temperature properties depending on temperature, too; 7 – new geometry of the structure which influences the electromagnetic field distribution; 8 – velocity of movement (deformations); 9 – heat generation due to plastic mechanical deformations of metals; 10 – heat generation due to friction; 11 – contact phenomena (contact thermal resistance); 12 – contact phenomena (contact electrical resistance); 13 – coercive force dependence on the state of mechanical stress. Besides, it is necessary to

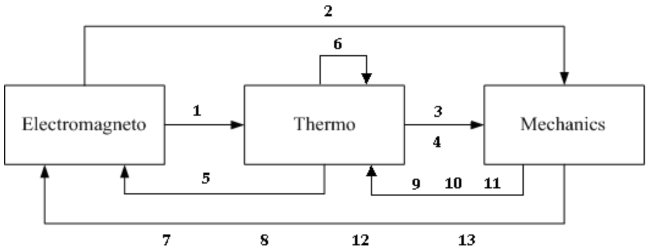

Fig. 1. Main multiphysical phenomena in electromagnetic devices.

consider the following “additional” phenomena of various physical natures: – first of all, magnetostriction; – magnetization losses; – dependence of magnetic properties on steel heat treatment regimen (steel microstructure). The author considers the presented list as a first attempt to determine the most important effects to be taken into account in the numerical analysis of electrical machines and electromagnetic devices as well as to find phenomena which can be neglected.

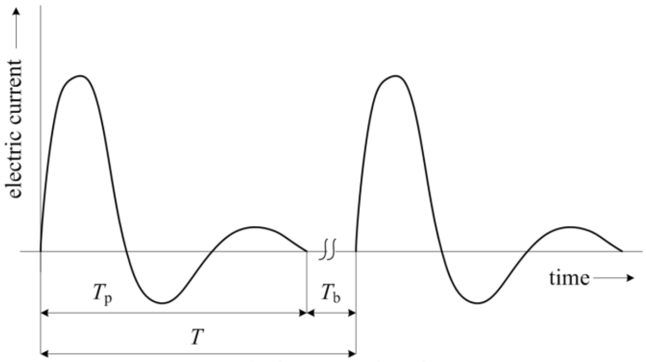

Fig. 2. Pulsed current in the inductor.

Finally, the author invites all colleagues working in the field of multiphysics to discuss and extend the proposed list.

To illustrate the presented analysis utilization, a novel technological process – so-called multi-impulse induction heating [4] – is considered. This type of fast high-temperature metal treatment with final temperature of 800–1000 ^{0}C and even more can be used to carry out such technological operations as hardening, mechanical processing, assembly, disassembly, and welding of metal parts. Heating of the workpiece is carried out during a few seconds by means of 100–1000 powerful repeated impulses of electromagnetic fields depicted in Fig. 2. The obtained numerical results demonstrate the necessity of considering the temperature dependences of the material properties and nonlinear magnetic properties of soft ferromagnetic materials for numerical simulation of coupled electromagnetic and thermal fields in high-temperature induction heating devices.

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