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MULTIPHYSICAL NUMERICAL ANALYSIS OF ELECTROMAGNETIC DEVICES: STATE-OF-THE-ART AND GENERALIZATION

У статті наведено аналіз стану проблеми та здійснено спробу узагальнення основних принципів комп'ютерного моделювання зв'язаних процесів у різноманітних електромагнітних пристроях (електричні машини, індукційні нагрівачі, актуатори, електрофізичне обладнання та ін.). Наведений аналіз побудовано на досвіді автора з розв'язання різноманітних прикладних задач стосовно проектування та експлуатації сучасних електричних машин і апаратів, а також на роботах інших дослідників.

В статье приведен анализ состояния вопроса и предпринята попытка обобщения основных принципов компьютерного моделирования связанных процессов в различных электромагнитных устройствах (электрические машины, индукционные нагреватели, актуаторы, электрофизическое оборудование и др.). Приведенный анализ основан на опыте автора по решению различных прикладных задач применительно к проектированию и эксплуатации современных электрических машин и аппаратов, а также на работах других исследователей.

I. INTRODUCTION

The design of rotation electrical machines and other electromagnetic devices (induction heaters, various actuators, electrophysical devices, etc.) presents one of the most challenging applied tasks since many different phenomena and their interaction have to be considered. To develop modern, effective and cheap design it is strongly recommended to carry out complex investigations of various physical processes and effects in the device under consideration taking into account their complicated interaction. Such research works can be done by means of relatively cheap computer simulation (in other words: "coupled" [1-3] or "multiphysical" [4] numerical analysis) instead of expensive full-scale experiments.

The operation principle of electrical machines and other electrical devices is based on electrical and magnetic fields, heating and the forces resulting from those fields. In the process of designing an electrical machine or another electrical device, one has to deal with electromagnetics, temperature distributions, structural mechanics, thermodynamics, fluid dynamics and their often complex interaction. Therefore, a reliable numerical simulation of electrical machines, devices and apparatuses – enable to tackle all aspects of the multiphysical approach as well as fabrication, design and material tolerances – is desirable and even mandatory in the frame of the design procedure and operation of the equipment.

Coupled field modelling [1-3] (in other words: "multiphysical" [4], "multi-field" [5], "multi equations" [6] or even "multi-nature" [7] simulation) of various electrical machines and other electrical devices is one of most complicated and, simultaneously, quickly developing areas of modern computational electromagnetics. In the author's opinion, multiphysical numerical analysis of electrical machines and other devices should be based on results of intensive pure research aimed to make a valuable contribution in the development of modern fundamental (theoretical) principles and basics of applied investigations in the field. Here, necessity to design, manufacture, operate, and, therefore, simulate new types of innovative electrical devices working on the base of new physical principles requires to generalize basic principles of the coupled (multiphysical) numerical analysis of electrical machines and other electromagnetic devices. The author proposes and elaborates in this paper two "directions" of generalization:

1 – determination of main interrelated multiphysical phenomena and effects occuring during the operation of electrical machines and devices as well as their representation in graphical and table forms, and

2 – determination of main parameters to be obtained as outcomes of the coupled computer simulation from practical point of view.

The author has wide experience of the various fundamental and practical problems solution regarding design and operation of the variety of innovative electromagnetic devices such as rotation electrical machines, actuators, induction heaters, devices for pulsed magnetic fields generation, resistance welding machines, etc. The analysis presented in this paper is based on the author's experience as well as on research works carried out by other researchers. In the author's opinion the proposed general view on the fundamentals basics of pure and applied research in the area of multiphysical numerical modelling will be useful for two main "target groups":

1 – "pure" researchers working in the field;

2 – designers, manufacturers and even industrial operating personnel as "users" of obtained numerical results and proposed practical recommendations.

II. INITIAL GENERAL CLASSIFICATIONS

A. Main multiphysical phenomena to be taken into account in numerical analysis

The author tries to propose a relatively "complete" list of interrelated physical phenomena and effects to be taken into account in numerical analysis of electrical machines and electrical devices. Of course, all readers working in the field of multiphysics are invited to take part in this investigation in order to extend the proposed list as well as to determine most important effects and effects to be neglected.

Why the author says: "A relatively "complete" list?" The answers are the following:

1 – at the first stage of the proposed wide discussion it is intended to consider only electromagnetic, thermal and mechanical (structural) phenomena. The author supposes this is enough to start our analysis. Effects of fluid dynamics nature should be examined later.

2 – we suppose (from the point of view of classification

of physical phenomena) acoustic that deals with the study of mechanical waves represents a "branch" of mechanics of solids [8], [9] and/or fluid mechanics [10]. Therefore, here we do not consider acoustics as a separate physical effect (despite of increased interest to simulate noise and vibrations of electrical machines as well as important numerical results obtained [11]).

3 – naturally, the author is unable to find and describe <u>all</u> existing multiphysical electromagnetic, thermal and mechanical phenomena. Therefore, in this paper we propose the "open" list of such effects and ask our colleagues to answer together the following questions: how many multiphysical phenomena do you know? who knows more? which effects are important? which ones can be neglected? In this connection we divide all variety of known physical effects into two groups:

• well-known phenomena to be currently taken into account in numerical simulation of an electromagnetic device or machine under research depending on its operation principle;

• phenomena which currently look like to be neglected or even "exotic" ones. But modern science and technology develop so fast. And ho knows? May be, in a few years some "exotic" physical effects will lie in the base of the operational principle of innovative machines, devices and technological processes.

B. Main parameters to be obtained as outcomes of the coupled computer simulation

Besides, the author elaborates a list of main parameters to be recommended as outcomes of the multiphysical numerical simulation of different electromagnetic devices from practical points of view. Here this is useful to divide the parameters of electromagnetic devices into a few groups describing their practical utilization. It seems to us it is possible to determine three main groups of parameters:

1 – electrical parameters describing the devices' operation from "point of view" of external electrical circuits. This group includes such quantities as voltage, current, frequency, inductances, resistances, etc.

2 – operational or technological parameters describing main characteristics of the devices' operation including technical data of technological equipment and processes. This group includes torques, forces, temperatures, operating duration, main temporal operation parameters of electromagnetic devices and technologies, and so on.

3 – structural parameters describing main designers' solutions such as windings' number of turns, air gaps, utilization of ferromagnetic structural parts, design and parameters of cooling system, etc.

Asserting the great importance of financial considerations in the process of the design, production and operation of various electromagnetic devices, the author currently does not analyse financial aspects of some designers' solutions and changes in technological parameters.

III. GRAPHICAL REPRESENTATION OF COUPLING

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 [5] 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). Drawing the diagram the author did not take the effects of fluid dynamics nature into account and did not consider acoustics as a separate physical effect (see section II). The diagram (see Fig. 1) consists of three connected main elements (or "physical domains" as put forward in [5]) representing electromagnetic, thermal and mechanical phenomena. The numbers near the lines with arrows depict physical processes and effects listed below (see section IV). 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.

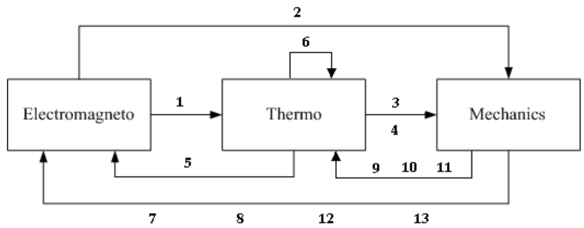

Fig. 1. Main "physical domains" of multi-physical simulations and their interactions

IV. A LIST OF MULTIPHYSICAL PHENOMENA

On the base of generalization of the author's experience as well as of intensive analysis of research works carried out by other researchers, we propose the author's vision of the "initial version" of the list of multiphysical phenomena (Table I) to be considered in building the mathematical model of an electrical machine or device. As it was mentioned in section II, we consider well-known physical effects as well as "exotic" ones. The numbers of items in Table I correspond to the ones in Fig. 1.

Table 1

Multiphysical phenomena in electromagnetic devices

Well-known phenomena	"Exotic" effects
1 – Joule losses [1, 3, 12-17]	9 – heat generation due to plastic mechanical deformations of metals [32]
2 – electromagnetic forces and torque [1, 3, 16, 18-24, 27]	10 – heat generation due to friction [33]
3 – the temperature distribution which alters the mechanical state of the structure [14, 25-28]	11 – contact phenomena (contact thermal resistance) [34, 35]
4 – mechanical properties depending on temperature [14, 26]	12 – contact phenomena (contact electrical resistance) [36]
5 – electromagnetic properties depending on temperature [14, 26, 29]	13 – coercive force dependence on the state of mechanical stress [37]
6 – temperature properties depending on temperature [14, 26]	
7 – new geometry of the structure which influences the electromagnetic field distribution [27]	
8 – velocity of movement (deformations) [3, 17, 26, 30, 31]	

So, at present we consider 13 multiphysical phenomena of various physical natures (electromagnetic, thermal and mechanical ones): 8 of them are well-known or "main" effects and 5 ones are "exotic". However, in some selected applications regarding innovative electromagnetic devices it can be necessary to take into account one or even more of last ones. This is a subject of further discussions.

Besides, in addition to phenomena listed in Table 1 it is necessary to consider the following phenomena of various physical natures:
– first of all, magnetostriction [38-40]
– magnetization losses [17, 41-46]
– dependence of magnetic properties on steel heat treatment regimen (steel microstructure) [31, 47-49].

The author considers the presented list (see Table I and Fig. 1) 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. The author invites all colleagues working in the field of multiphysics to discuss and extend the proposed list.

IV. A LIST OF PARAMETRS TO BE DETERMINED

Electromagnetic, thermal, mechanical, fluid dynamical processes and fields in electromagnetic devices are described in general by corresponding equations of mathematical physics [50]. Solving them by using various numerical methods [51] we obtain temporal and spatial distributions of electromagnetic fields, current densities, losses, temperatures, mechanical stresses and deformations, and so on. However, it is obvious that from practical point of view it is not enough to have only the mentioned "pure" solutions of corresponding equations. The reason is clear: distributions of various physical fields and related quantities (such as losses) do not directly permit to design and produce highly effective constructions of electromagnetic devices as well as to propose their optimal operation modes. From industrial and technological viewpoint the final goal of applied research is to determine recommended rational structural and operational conditions and parameters of designed equipment by using intensive multiphysical computer simulation of the phenomena in the device under consideration.

In Table II the proposed list of main parameters to be recommended as outcomes of the coupled numerical simulation of various electromagnetic devices from practical points of view is presented. To carry out such an analysis a lot of publications have been analyzed and generalized (some of them are cited by the author). As it was mentioned in section II all the variety of parameters is divided into three groups (electrical parameters, operational or technological ones, and structural or "pure" designer's solutions).

We analyze most widely used types of electromagnetic and other electrical engineering devices (see Table II):
1 – rotation electrical machines (an example of the structure under consideration: a synchronous turbogenerator rotor [53] presented in Fig. 2);
2 – induction heaters (see, for instance, Fig. 3 [86]);
3 – actuators (Fig. 4 [25]);
4 – electrophysical equipment for high pulsed magnetic fields generation (for pure scientific and technological purposes);
5 – selected electronic elements (an example is presented in Fig. 5 [81]);
6 – resistance welding machines.

Naturally, electronic components (such as thermistors and thyristors) and resistance welding technological equipment are formally not "electromagnetic devices" but the author decided to include them into the presented analysis because of their importance and wide utilization in modern industry and technology.

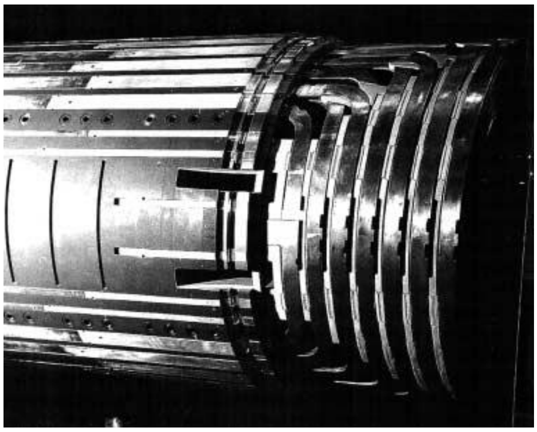

Fig. 2. A synchronous turbogenerator rotor [53]

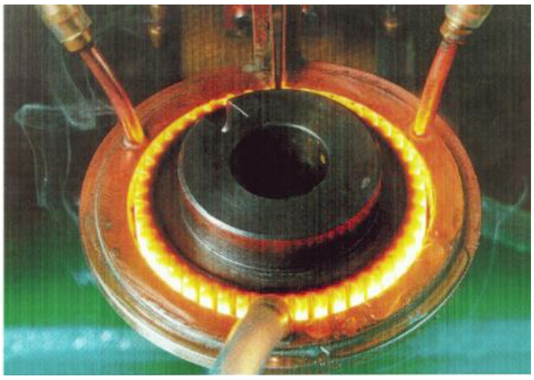

Fig. 3. Induction heating at Steremat Elektrowärme GmbH & Co. KG, Berlin, Germany [86]

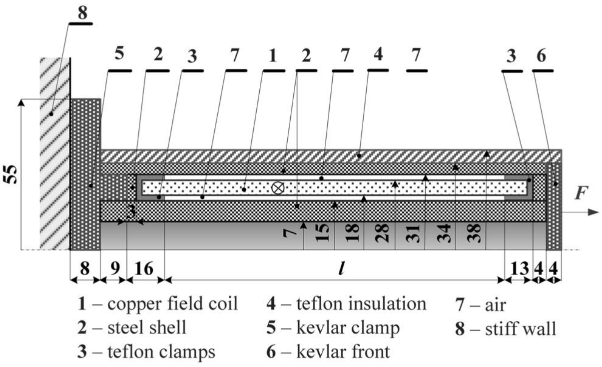

Fig. 4. Arrangement of a thermoelastic actuator [25]

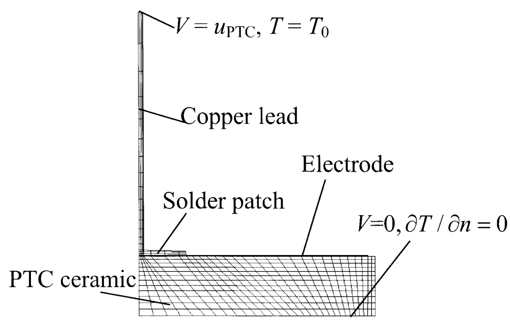

Fig. 5. One half of the axisymmetric model of the PTC thermistor [81]

In the author's opinion a list of electromagnetic and other devices under consideration included in Table II could be extended. We invite all colleagues working in the field of applied electromagnetics to take part in such the analysis. And, of course, we will be grateful for all colleagues' proposals regarding inclusion of additional parameters to be determined as outcomes of multiphysical numerical simulation.

V. SUMMARY AND CONCLUSIONS

In this paper[1] the author's view on the possibility to compile a relatively "complete" list of coupled multiphysical electromagnetic, thermal and mechanical phenomena to be taken into account in numerical analysis of electrical machines and other electrical devices is presented. The improved graphical representation of coupling is proposed. A number of well-known and "exotic" effects are listed and shortly described. Besides, the author proposes a list of main parameters to be recommended as results of the coupled (multiphysical) numerical simulation of various electromagnetic devices from practical points of view. Electrical, operational and structural parameters of electrical machines, induction heaters, actuators and other devices are listed. And, finally, the author invites all colleagues working in the field of multiphysics to discuss and extend the proposed lists.

VI. ACKNOWLEDGEMENT

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[1]The short version of this paper is published in [87].

Table 2

A list of main parameters to be recommended as outcomes of electromagnetic devices numerical simulation from practical points of view

	Type of electromagnetic devices					
Type of parameters ↓	Rotation electrical machines	Induction heaters	Actuators	Electrophysical devices for high pulsed magnetic fields generation and technological applications	Electronic component s (thermistors, thyristors, thermoelectric generators)	Resistance welding machines
Electrical	• voltage and current in the machine's windings (for motors and generators) [13, 16, 52-57] • machines' electrical parameters (e.g. resistances, inductances) [13,57-60] • machines' lumped thermal model parameters (e.g. thermal contact resistances, thermal conductivities) [61] • efficiency [62] • losses and their minimization [63-67]	• operating voltage or current in the inductor [14, 27, 72-74] • frequency of electromagnetic oscillations in the inductor [27, 30, 74] • power and efficiency [27, 30]	• operating voltage or current in the field coil [25, 34] • frequency of electromagnetic oscillations in the field coil [25]	• amplitude value of operating voltage or current in the inductor (coil) [14, 27, 76] • energy stored in the capacitors [27, 77] • frequency of electromagnetic oscillations in the inductor (coil) [78]	• applied voltage [79-82] and its time evolution [82] • current flowing through the element [79-82] and its time evolution [82] • frequency of the pulses [82] • efficiency [80]	• voltage on electrodes [83, 84] • type of power supply (DC, AC, frequency) [85]
Operational and technological	• torque and forces [3, 11, 20, 22, 52, 65, 69] • temperature distribution (don't exceed permitted working temperature of the insulation) [63-65, 68] • level of noise and vibrations [11, 69, 70] • in-service time of electrical machines at some operating conditions (for example, at the turbo-generator line-to-line short circuit) [16, 63]	• temperature distribution in treated workpiece [14, 27, 28, 30, 72, 73, 75] • duration of heating and cooling of treated workpieces [14, 27, 28, 30, 31, 49, 72, 73, 75] • required (from technological point of view) velocity of heating and/or cooling [14, 31, 49] • velocity of movement of the treated workpiece or inductor [17, 30, 31] • mechanical stresses and deformations of treated workpiece and inductor, including absence or presence of plastic ones [14, 28, 30, 72, 73, 75] • temperature distribution in the inductor (coil) to use appropriate insulating materials [27]	• operation duration [25, 34] • forces and/or torque values [25, 34] • mechanical stresses and deformations of structural parts [25, 34] • temperature distribution in structural parts [25, 34] • duration of heating and cooling of the working part [25, 34] • velocity of heating and/or cooling [25, 34] • velocity of movement of structural parts [26]	• operation duration [14, 27, 76] • temperature distribution in the inductor (coil) and treated workpieces [14, 27, 76] • mechanical stresses and deformations of the inductor (coil) and treated workpieces [14, 27, 76]	• temperature distribution (don't exceed permitted working temperature of the element) [79-82] • mechanical stresses and deformations (to prevent fracture) [79, 80]	• temperature distribution [83, 84] • duration of welding [83, 84] • duration of cooling of welded parts [85] • pressure on electrodes [83, 84] • mechanical stresses and deformations of welded pieces to prevent fracture [84, 85] • mechanical stresses and deformations of electrodes [84]

Continue of Table 2

Type of parameters ↓	Type of electromagnetic devices					
	Rotation electrical machines	Induction heaters	Actuators	Electrophysical devices for high pulsed magnetic fields generation and technological applications	Electronic component s (thermistors, thyristors, thermoelectric generators)	Resistance welding machines
Structural (for designers)	• parameters and design of air, water or hydrogen cooling systems of stator and rotor of various electrical machines [16, 71] • geometry of some structural parts (e.g. turbogenerator damper system, rotor slot wedges [13, 16]) • rational choice of materials for some structural parts (e.g. turbogenerator slot wedges in rotor and stator [66])	• number of turns of inductor and its design [27, 30, 72, 74, 75] • air gap value and geometry [27, 30, 75] • type of quenching media or coolants (air, water, oil, water-polymer liquids) [31, 49] • velocity of quenching media or coolants [31, 49] • utilization of ferromagnetic cores [27, 30, 75]	• number of turns of field coil and its design [25, 34] • rational choice of materials for some structural parts [25, 34] • type of quenching media or coolants (air, water, oil) [25, 34] • velocity of quenching media or coolants [25, 34] • utilization of ferromagnetic structural parts [26]	• number of turns of inductor (coil) and its design [27, 76] • air gap value [27] • type of quenching media or coolants (air, water, oil) [76] • velocity of quenching media or coolants [76] • utilization of ferromagnetic cores [27]	• geometrical parameters of the element [79, 80, 82] • ventilation parameters [80, 82] • utilization of casing [80]	• geometrical parameters of electrodes [83, 84] • type of quenching media or coolants (air, water, oil) [85] • velocity of quenching media or coolants [85]

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Pantelyat M.G.
Multiphysical numerical analysis of electromagnetic devices: state-of-the-art and generalization.
In this paper, an analysis of state-of-the-art and an attempt to generalize the basic principles of multiphysical (coupled) computer simulation of various electromagnetic devices (electrical machines, induction heaters, actuators, electrophysical devices, etc.) are presented. The analysis is based on the author's wide experience in solving various practical problems regarding design and operation of a variety of innovative machines and devices as well as on studies carried out by other researchers.
Key words – **electromagnetic devices, multiphysics, computer simulation.**