UNIVERSITY OF CRAIOVA
ELECTRICAL ENGINEERING FACULTY

M.Sc. Alin-Iulian DOLAN

ABSTRACT OF PHD. THESIS

Contributions to modeling of the fields and of the transient regimes in electrical equipments

Scientific coordinator:
Prof. Grigore A. CVIDJIAN

CRAIOVA, 2009
ACKNOWLEDGEMENTS

I owe my deepest gratitude to scientific coordinator, Prof. Grigore A. Cividjian, for very meticulous guidance, scientific advices and critical comments, extremely valuable in accomplishing this work.

I’m honored by and I thank to Prof. Andrei Ţugulea, member of Romanian Academy, to Prof. Mihai Iordache, Prof. Dumitru Topan and Prof. Ioan Popa, for accepting to make the peer review of the thesis.

Thank once again to Prof. Dumitru Topan and to Prof. Ioan Popa, for the encouragements given at the appropriate time for undertaking steps in obtaining abroad internships, which have enriched my scientific and linguistic horizon.

Also thank to the University Agency for Francophonie, for the financial support to achieve the inter-university mobility and to Prof. Serge Monchaud from the National Institute of Applied Sciences in Rennes, for the careful coordination of its beginning in the Technical University of Sofia.

Thank to the French Institute in Sofia, for its hospitality and special support in rapid assimilation of the French language.

I want to thank Prof. Ivan Yatchev from Technical University of Sofia, for his great hospitality and assistance in using the ANSYS program, along the research internships undertaken at the Doctoral School from this university, making possible the extension of the numerical simulations related to Chapters III and IV.

Thank, by this way, to Prof. Leonardo-Geo Mănescu, for kindly helped to me in contacting the professors and specialists from Grenoble Electrical Engineering Laboratory, referring Prof. Gérard Meunier, Prof. Albert Foggia and Prof. Thierry Chevalier, whom I thank for their hospitality and support in using the FLUX program, along the research internship undertaken at this laboratory.

In the same time I thank to CEDRAT Company in Grenoble for the rights of personal use of the FLUX program, which had allowed the numerical simulation related to the chapters V and VI.

I want to thank all colleagues in the Department of Electrical apparatus and technologies, for many encouragements and very useful advices along this work.

I thank and am deeply grateful to my family for the moral support, the understanding and patience, constantly exhibited, helping me to finalize this thesis.
SUMMARY

Abbreviations list ................................................................................................................. 9 (5)

INTRODUCTION .................................................................................................................. 11 (6)

1 FINITE ELEMENT METHOD FORMULATIONS .................................................................... 13 (7)
   1.1 Introduction .................................................................................................................. 13
   1.2 Projective formulation ................................................................................................... 15 (7)
   1.2.1 Weighted residues method ....................................................................................... 17
   1.3 Variational formulation ................................................................................................. 18 (7)
   1.4 Unknown functions approximation ............................................................................. 19 (7)
   1.5 Finite element method formulations in Magneto statics ............................................. 22 (7)
   1.5.1 FEM in magnetic scalar potential formulation (MSP) ............................................. 23 (7)
       1.5.1.1 Reduced MSP formulation (MSPr) .................................................................. 23
       1.5.1.2 Total MSP formulation (MSPt) ...................................................................... 24
       1.5.1.3 Difference MSP formulation (MSPd) ............................................................. 24
       1.5.1.4 Generalized MSP formulation (MSPg) .......................................................... 25
       1.5.1.5 Edge MSP formulation (MSPe) ...................................................................... 26
   1.5.2 FEM in magnetic vector potential formulation (MVP) ............................................. 27 (7)
   1.5.3 FEM in edge element formulation (EE) .................................................................... 29 (8)
   1.6 Conclusions .................................................................................................................. 31

2 INDUCTANCE OF PLUNGER-TYPE ELECTROMAGNET .................................................. 33 (8)
   2.1 Introduction .................................................................................................................. 33 (8)
   2.2 Power approximation of boundary conditions method (PABCM) ............................ 33 (8)
   2.3 Utilization of PABCM to the inductance of plunger-type electromagnet computation .. 36 (9)
      2.3.1 Computation of \( F(a, z) \) function ....................................................................... 36
      2.3.2 Computation of intern inductance of plunger-type electromagnet 1 ............... 40 (9)
      2.3.3 Numerical solution and experimental verification .............................................. 43 (10)
      2.3.4 IPTM application ................................................................................................. 47
   2.4 Conclusions .................................................................................................................. 48

3 STATIC CHARACTERISTIC OF A PLUNGER-TYPE ELECTROMAGNET ................................ 49 (11)
   3.1 Introduction .................................................................................................................. 49
   3.2 Numerical computation of electromagnetic forces .................................................... 50 (11)
      3.2.1 Maxwell stress tensor method (MTM) ................................................................. 50 (11)
      3.2.2 Virtual work method (VWM) .............................................................................. 54 (11)
      3.2.3 Equivalent sources method (ESM) ..................................................................... 58
   3.3 Numerical determination of static characteristic of plunger-type electromagnet 2 and experimental verification ........................................................................................................ 60 (12)
   3.4 Theoretical determination of static characteristic of plunger-type electromagnet 2 .... 68 (13)
   3.5 Conclusions .................................................................................................................. 70

4 LEAKAGE MAGNETIC FIELD AND MODELING LIGHTNING SURGES IN POWER MULTI-WINDING AUTOTRANSFORMER ........................................................................... 71 (15)
   4.1 Introduction .................................................................................................................. 71
   4.2 Leakage reactance. Impedance voltage ..................................................................... 74
      4.2.2 No load test at rated voltage ............................................................................... 76
      4.2.3 Short-circuit test at reduced voltage and rated current ...................................... 77
   4.3 Impedance voltage of the power multi-winding autotransformer ......................... 79 (15)
      4.3.1 Primary-secondary windings pair ....................................................................... 80 (15)
      4.3.2 Tertiary-primary winding pair ............................................................................ 81
      4.3.3 Tertiary-secondary winding pair ....................................................................... 81
   4.4 Numerical evaluation of the magnetic field energy and of the short-circuit reactance with FEMM program .......................................................... 82 (16)
      4.4.1 2-D model and the boundary conditions ......................................................... 82 (16)
      4.4.2 2-D numerical results of short-circuit tests ....................................................... 85 (17)
   4.5 Numerical evaluation of the magnetic field energy and of the short-circuit reactance with ANSYS program .......................................................... 88 (17)
      4.5.1 3-D model and the boundary conditions ............................................................. 88
      4.5.2 3-D numerical results of short-circuit tests ....................................................... 89
      4.5.3 Optimization of 3-D simulations by memory management .............................. 92 (18)
   4.6 Modeling lightning surges in the power multi-winding autotransformer .............. 94 (18)
      4.6.1 Short-circuited tertiary winding influence ......................................................... 94
      4.6.2 Self and mutual inductances for short-circuited tertiary winding .................... 96 (18)
      4.6.3 Capacitance of a pair of interlinked winding disks ............................................ 98
      4.6.4 Simple model for lightning surges on free end of regulating winding .......... 99
   4.7 Conclusions .................................................................................................................. 101
5 NUMERICAL SIMULATION OF TRANSIENT ELECTRIC AND MAGNETIC FIELDS IN RECTANGULAR SOLID BUS BARS ............................................. 103 (20)

5.1 Introduction ............................................................................. 103
5.2 Analytical evaluation of magnetic field distribution ....................... 104 (20)
5.2.1 Exterior magnetic field distribution ........................................... 104
5.2.2 Distribution of electric and magnetic fields at step current injection .... 106 (20)
5.2.3 Distribution of electric and magnetic fields at step voltage application .... 107
5.3 Numerical simulation of transient electric and magnetic fields in the system of rectangular bus bars .......... 108 (21)
5.3.1 Solutions for open boundary problems ....................................... 108
5.3.2 Utilization of FLUX in simulation of electric and magnetic fields penetration in the system of rectangular solid bus bars .................. 109
5.3.3 Utilization of FEMM in initial magnetic field analyses in the system of rectangular solid bus bars .......... 110
5.3.4 Numerical evaluation of exterior magnetic field ......................... 111 (21)
5.3.5 Numerical evaluation of electric and magnetic fields distribution at step current injection .............. 117 (23)
5.3.6 Numerical evaluation of electric and magnetic fields distribution at step voltage application .......... 121
5.4 Conclusions ............................................................................. 126

6 NUMERICAL DETERMINATION OF TRANSIENT PARAMETERS OF A SYSTEM OF RECTANGULAR SOLID BUS BARS ............................................. 127 (25)

6.1 Transient parameters of the linear electrical circuits ....................... 127 (25)
6.1.1 Introduction ............................................................................. 127
6.1.2 Transient parameters problem ................................................ 127
6.1.3 Determination of electromagnetic field associated to a linear multipolar circuit element .......... 130
6.1.4 Transient parameters of a non-filliforme and with additional losses circuit element .................. 137 (25)
6.1.4.1 Introduction of transient parameters for dipolar circuit element .......... 137
6.1.4.2 Inductive dipolar circuit element in magnetic quasi-stationary regime ...... 139
6.1.4.3 Capacitive dipolar circuit element in electric quasi-stationary regime .... 140
6.1.4.4 Integral relationships between instantaneous values of currents and voltages .......... 141 (25)
6.1.4.5 Experimental determination of transient parameters .................. 143 (25)
6.1.5 Conclusions ............................................................................. 144
6.2 Utilization of FLUX program in determination of transient parameters of the system of rectangular solid bus bars ............................................. 146 (26)
6.2.1 Introduction ............................................................................. 146
6.2.2 Determination of transient resistance and inductance at step current injection .......... 148 (26)
6.2.3 Determination of transient resistance and inductance at ramp current injection ......... 150
6.2.4 Determination of transient conductance and capacitance at step voltage application .............. 152
6.2.5 Determination of transient conductance and capacitance at ramp voltage application ......... 154
6.2.6 Conclusions ............................................................................. 155

7 ORIGINAL CONTRIBUTIONS AND CONCLUSIONS ............................................. 157 (27)

REFERENCES .................................................................................. 165 (33)

ANNEXES

A.1 Laplace transformation .............................................................. 179
A.2 ANSYS source program (parameter language APDL) for force computation of the plunger-type electromagnet 2, δ = 0.5 mm air gap, MVP-EE formulation ......................... 181
A.3 FEMM source program (parameter language LUA) for computation of short-circuit reactance of power multi-winding autotransformer 400/400/80 MVA, primary-secondary short-circuit test, plus tapping, MVP-EE formulation ......................... 189
A.4 ANSYS source program (parameter language APDL) for computation of short-circuit reactance of power multi-winding autotransformer 400/400/80 MVA, primary-secondary short-circuit test, plus tapping, MVP-EE formulation ......................... 195
Abbreviations list

AN – analytic solution;
ANSYS – 2-D and 3-D FEM modeling software;
APLD – ANSYS Parameter Design Language, used by ANSYS program;
ATP-EMTP – Alternative Transients Program - Electromagnetic Transients Program, modeling power systems components package;
NE – nodal elements;
EE – edge elements;
FEMM – Finite Element Method Magnetics, 2-D FEM modeling software;
FLUX – 2-D and 3-D FEM modeling software;
IPTM – DELPHI application for internal inductance determination of a plunger-type electromagnet;
LUA – parameter language, used by FEMM;
PABCM – power approximation of boundary conditions method;
EMCM – equivalent magnetization current method;
FDM – finite differences method;
FEM – finite element method;
BEM – boundary elements method;
VWM – virtual work method;
CVWM – Coulomb virtual work method;
ESM – equivalent sources method;
EMCM – equivalent magnetic charges method;
FVM – finite volume method;
CMM – conformal mapping method;
MTM – Maxwell stress tensor method;
NUM – numerical solution;
ESP – electric scalar potential;
MSP – magnetic scalar potential;
MSPd – difference magnetic scalar potential;
MSPg – generalized magnetic scalar potential;
MSPe – edge magnetic scalar potential;
MSPr – reduced magnetic scalar potential;
MSPt – total magnetic scalar potential;
MVP – magnetic vector potential;
QUICKFIELD – 2-D FEM modeling software;
SC – Schwartz-Christoffel module of MATLAB program (numerical conformal mapping);
TPTLEC – transient parameters theory of linear electric circuits;
FVT – final value theorem;
IVT – initial value theorem;
2-D – two-dimensional;
3-D – three-dimensional.
INTRODUCTION

The paper contains contributions in numerical modeling of electric and magnetic fields, established in electrical equipments or their accessories in normal operating and unexpected or controlled transient regimes.

The basic tool used in all numerical simulations is the finite element method (FEM) for which the author has done thorough research both theoretically, concerning the variety of formulations developed over time and obtaining competences in the use of specialized programs, commercial or noncommercial, in which the method is implemented: QUICKFIELD, FEMM, ANSYS, FLUX.

The thesis aims to validate analytical formulas deduced in approximate hypotheses and numerical computation of electric or magnetic, local or global quantities, experimentally obtained. In some cases, combined analytical-numerically solutions were proposed.

The variety of formulations of the FEM applied to concrete problems and the extraction techniques of local or global quantities from numerical field solution led to obtaining parallel results allowing a comparison between formulations and techniques in term of numerical resources and required time to solve the problems, pointing out the effectiveness of some of them.

The thesis is structured into seven chapters, beginning with fundamental description of the projective and variational formulations (Chapter 1). Since the method has targeted magneto static applications, starting from customizing the electromagnetic field equations for this regime, were presented its various formulations, sustained by an extensive review of recent literature.

The following chapters are two applications of 2-D and 3-D FEM: to calculate the inductance of plunger-type electromagnets (Chapter 2) and the magnetic force developed by such equipment (Chapter 3). The description of techniques for determining the global forces from field solution enjoys special attention, focusing important conclusions from published works in recent years.

The leakage flux in magnetic circuits has been studied for a power multi-winding, under load adjustable, autotransformer, for which 2-D and 3-D numerical models were created, that allowed, with a good precision, the short-circuit reactance computation (Chapter 4). Optimization of solutions in 3-D numerical simulations were searched to reduce the solving time and to increase the accuracy. The study concludes by analyzing the behavior of autotransformer at the application of lightning surges, using FEMM and ATP-EMTP programs, aiming the over voltages level on the no load tappings of regulating winding.

Chapters 5 and 6 concern the transient phenomena taking place in a system of parallel solid rectangular bars supplied with step and ramp signals of current and voltage. The results of numerical simulation of electric and magnetic fields penetration were compared with some analytical and combined with them to improve the effects of simplifying assumptions (Chapter 5). The transient parameters of the bar system were numerically determined and some of them were derived from some others, based on analytical relationships established by the theory of linear electric circuits transient parameters, making comments on certain irregularities found (Chapter 6).

In the last chapter (Chapter 7) the author's original contributions and conclusions are pointed out, structured in the chapters in which they appear, indicating the perspectives of their application.
Chapter I

FINITE ELEMENT METHOD FORMULATIONS

1.2 Projective formulation

FEM is one of the methods of continuous problems solutions representation by approximations on discretized domains [77]. The general method for approximating the sought function \( u(x) \) is its representation by the projection on a finite size subspace, whose base is defined by \( N+1 \) basic functions (projection functions, shape functions) \( \Phi_i(x) \):

\[
  u(x) \approx \sum_{i=0}^{N} q_i \Phi_i(x)
\]

(1.3)

1.3 Variational formulation

Many physical problems allow solutions approximation methods based on minimizing of functional corresponding usually to a type of energy. These are called variational formulations [21], [52], [168].

1.4 Unknown functions approximation

The approximate solution is sought as a linear combination of known basic functions [145], usually polynomial, linear or quadratic, set to take nonzero values only around certain particular points (interpolation points).

1.5 Finite element method formulations in Magneto statics

The solutions of the field problems are generally obtained using potential functions [3]. The magnetic scalar potential (MSP) or the magnetic vector potential (MVP) are often used for magnetic field.

1.5.1 FEM in magnetic scalar potential formulation (MSP)

MSP is of great importance in solving the 3-D magneto static problems because of its low cost of numerical calculation comparing to MVP consisting of three components and also without uniqueness problems [52], [82], [114]. There are different formulations (strategies) for obtaining the solution: reduced magnetic scalar potential formulation (MSPr), total magnetic scalar potential formulation (MSPt), difference magnetic scalar potential formulation (MSPd), generalized magnetic scalar potential formulation (MSPg), edge magnetic scalar potential formulation (MSPe).

1.5.2 FEM in magnetic vector potential formulation (MVP)

MVP is used in almost all magnetic field problems in which occur current densities. It is very popular for 2-D or axi-symmetric applications because in these cases has only one component, orthogonal to the plane of analysis. In 3-D, the calculation is tripled and uniqueness problems occur, making it less attractive than MSP.
1.5.3 FEM in edge element formulation (EE)

The classical formulations of FEM associate degrees of freedom to the nodes of the mesh, using nodal elements (NE). In another approach, the degrees of freedom associated to the elements edges, aiming determining the field line integral along them, based on edge elements (EE) [17]. Depending on the used potential and on the way of degrees of freedom association, there are different particular formulations: MSP-NE, MSP-EE, MVP-NE, MVP-EE.

Chapter II

INDUCTANCE OF PLUNGER-TYPE ELECTROMAGNET

2.1 Introduction

In the papers [32], [33], [35] is developing a new numerical method for power approximation of the boundary conditions (PABCM).

2.2 Power approximation of boundary conditions method (PABCM)

![Illustration of power approximation of boundary conditions method](image)

Fig. 2.1 - Illustration of power approximation of boundary conditions method

Analyzing the field in the vicinity of peak A with conformal mapping method, in the papers [32] and [33] is proposed to approximate tangential component of the magnetic field along the border AB, by the relationship (2.1), respecting the potential difference $U$ (electric or magnetic) between A and B:

$$H_y'(y) = H_\delta \left[ k_1 + \frac{k_2}{a\left(1 - \frac{y}{\delta}\right)}\right], \quad H_\delta = \frac{U}{\delta}, \quad a < 1, \quad \int_0^\delta H_y'(y)dy = U, \quad k_1 + k_2 = \frac{H_y'(0)}{H_\delta} = u_0 \quad (2.1)$$

$$u_0 = 0.831957 + 1.54394 \cdot 10^{-2} \left( \frac{\delta}{a}\right)^3 - 0.175235 \left( \frac{\delta}{a}\right)^2 + 7.66579 \cdot 10^{-2} \left( \frac{\delta}{a}\right) - 1.60908 \cdot 10^{-2} \left( \frac{\delta}{a}\right)^5 + 1.83817 \cdot 10^{-3} \left( \frac{\delta}{a}\right)^4 - 1.09529 \cdot 10^{-4} \left( \frac{\delta}{a}\right)^3 + 2.66537 \cdot 10^{-6} \left( \frac{\delta}{a}\right)^7 \quad (2.5)$$
2.3 Utilization of PABCM to the inductance of plunger-type electromagnet computation

In the paper [36] is derived a formula to calculate the internal inductance of a plunger-type magnet, using the power approximation of boundary conditions method in two-dimensional space. The proposed formula is difficult to apply because of function:

\[ F(\alpha, z) = \int_0^1 \frac{\cos[z(1-t)]}{t^\alpha} \, dt; \quad \alpha \in (0 ; 1) \]  

containing an improper integral. In this chapter is proposed a method ([40], [140]) for evaluating the function using MATHCAD software [178] and a numerical verification by finite element method (QUICKFIELD [179], [177] and FEMM [175]) of the inductance formula from the papers [36].

2.3.2 Computation of internal inductance of plunger-type electromagnet 1

The geometry of plunger-type electromagnet 1, for which the inductance is computed, is presented in figure 2.5. The internal inductance per unit length (thickness) analytically computed \( L'_{\text{int,AN}} \), corresponding to the magnetic flux in electromagnet window (fig. 2.5) according to [36], can be written as:

\[ L'_{\text{int,AN}} = \int_0^1 \frac{\cos[z(1-t)]}{t^\alpha} \, dt; \quad \alpha \in (0 ; 1) \]  

![Fig. 2.5 - Geometry of plunger-type electromagnet 1](image1)

![Fig. 2.6 - Internal inductance per length unit, analytically computed by relationship (2.31) (line) and numerically by QUICKFIELD, FEMM (points)](image2)

![Fig. 2.7 - Numerical results (points), analytic-numerically (line) and experimentally (triangles) for total inductance](image3)
In formula (2.31) the cross section of the coil is considered having the window size: \( a_c \approx a, \ b_c \approx b \).

### 2.3.3 Numerical solution and experimental verification

In order to numerically verify the analytical expression of the internal inductance \( L_{\text{int,AN}} \) of plunger-type electromagnet 1 (Fig. 2.5), deduced by PABCM, was used 2-D FEM implemented in QUICKFIELD [179], [177] and FEMM [175] programs.

The internal inductance has been evaluated using the magnetic field energy corresponding to the interior domain (domain I, Fig. 2.5). The 2-D FEM analysis in MVP formulation was performed in magneto static regimes (1.42-1.45). In order to estimate the total inductance of the plunger-type electromagnet 1, the 2-D FEM analysis was extended to the outer magnetic core domain (domain II, Fig. 2.5) corresponding to frontal parts of the coil.

\[
L'_{\text{int,NUM}} = 2 \frac{W'_{\text{int}}}{I^2}, \quad L'_{\text{ext,NUM}} = 2 \frac{W'_{\text{ext}}}{I^2}, \quad I = J \frac{a_c b_c}{w} \quad (2.46)
\]

Using internal and external values of inductances per unit length, analytically or numerically computed, the total inductance of the plunger-type electromagnet 1 is determined considering for internal inductance, the thickness \( g \) of the core and for external inductance, the difference between half-length of average turn \( (l_m/2) \) and thickness \( g \) (Fig. 2.5).

\[
L'_{\text{tot}} = L'_{\text{int}} + L'_{\text{ext}} = g L'_{\text{int}} + \left( \frac{l_m}{2} - g \right) L'_{\text{ext}} \quad (2.48)
\]

**Fig. 2.8** - Distribution of magnetic field density in interior domain for \( \delta = 20 \) mm (QUICKFIELD, 103,954 nodes)  
**Fig. 2.9** - Distribution of magnetic field density in exterior domain \( \delta = 20 \) mm (QUICKFIELD, 56,217 nodes)
Chapter III

STATIC CHARACTERISTIC OF A PLUNGER-TYPE ELECTROMAGNET

3.2 Numerical computation of electromagnetic forces

3.2.1 Maxwell stress tensor method (MTM)

The electromagnetic field theory [119] establishes that the force \( F \) acting on a body placed in the magnetic field, results by integration on body volume, of magnetic force density \( f \), assumed known. An equivalent problem is considering a system of surface forces \( T_n \), called magnetic \((\text{Maxwell})\) stress, which, acting on a closed surface \( S \) around the body, produces the same resulting (Fig. 3.1):

\[
F = \int f \, dv = \int_{S} T_n \, ds = \int_{V} \text{div}[T] \, dv,
\]

\[
T_n = (Bn)H - \frac{1}{2}(BH)n
\]  

(3.1)

\( T_n \) is a vector quantity associated to external normal to surface \( S \), with outward unit \( n \), by a tensor \( [T] \), with symmetric second-order components matrix, called \( \text{Maxwell's tensor} \) (\( \text{Maxwell stress tensor} \)).

\[ B = \mu_0 H \]

\[ n = 2\alpha \]

\[ S \]

\[ V \]

\[ \mu \]

\[ \mu_0 \]

\[ \Phi \]

\[ \Phi_{\text{ct}} \]

\[ W_m \]

\[ W_m^* \]

\[ i \]

\[ s \]

\[ i_{\text{ct}} \]

\[ F_s \]

\[ \frac{\partial W_m}{\partial s} \]

\[ \frac{\partial W_m^*}{\partial s} \]

\[ F_s \]

\[ F_s = -\frac{\partial W_m}{\partial s} \bigg|_{\Phi_{\text{ct}}}. \]

(3.6)

\[ F_s = \frac{\partial W_m^*}{\partial s} \bigg|_{i_{\text{ct}}}. \]

(3.7)

3.2.2 Virtual work method (VWM)

Virtual work method (VWM) derived from the theorems of generalized forces in magnetic field, based on energy balance of an electromagnetic system. The electromagnetic field theory [119] establishes the expressions of generalized force \( F_s \) (force itself or torque) depending on the variation of magnetic energy \( (W_m) \) or complementary magnetic energy \( (W_m^*) \) of system with respect to generalized coordinate \( s \) (linear or angular displacement) in certain imposed mathematical conditions:

- constant magnetic flux \( \Phi \) in derivative process:

\[ F_s = -\frac{\partial W_m}{\partial s} \bigg|_{\Phi_{\text{ct}}}. \]

(3.6)

- constant current \( i \) in derivative process:

\[ F_s = \frac{\partial W_m^*}{\partial s} \bigg|_{i_{\text{ct}}}. \]

(3.7)
3.3 Numerical determination of static characteristic of plunger-type electromagnet 2 and experimental verification

To numerically determine the static magnetic field, the finite element method (FEM) implemented in 3-D ANSYS program was used, in magnetic scalar potential formulation (MSP) and magnetic vector potential with edge elements (MVP-EE). In the case of MSP formulation, the electromagnetic force was computed by Maxwell's stress tensor method (MTM) and by virtual work method (VWM) and in the case of MVP-EE, by VWM [61].

For automation of numerical computation, the classic work with menus was dropped, adopting the alternative of creation of command files using the parameter language APDL (ANSYS Parameter Design Language) used by program ANSYS.

The electromagnetic force was measured using a tens sensor [61], [64] (Fig. 3.7) and simple procedures [51] (Fig. 3.8) for magneto-motive force in the range $\theta = 345.0-575.0$ A.

This study points out the superiority of virtual work technique versus Maxwell stress tensor integration for electromagnetic force calculation from field solution obtained by finite element method.

![Fig. 3.6 - Geometry of the plunger-type electromagnet 2](image1)

![Fig. 3.7 - Measurement scheme for magnetic force using a tens sensor](image2)

![Fig. 3.8 - Measurement scheme for magnetic force, balanced by the gravity force](image3)

1 - micrometer;
2 - support;
3 - tens sensor;
4 - electromagnet;
5 - additional weight.
3.4 Theoretical determination of static characteristic of plunger-type electromagnet 2

Additional to numerical investigations on the evaluation of mechanical stress, analytical studies have been developed, providing sufficiently accurate solutions. Thus, the paper [51] recovered earlier theoretical research on the permeances computation using conformal mapping method [38], [37], [47], [50], providing 2-D simple and accurate analytical formulas for magnetic field computation and for force in various forms of electromagnetic devices. These formulas were applied to plunger type electromagnet 2 (Fig. 3.6), in 2-D system [51].

The ratio \( k \) between \( \lambda_1 \) permeance corresponding main air-gap \( \delta \) and \( \lambda_2 \) permeance of higher air-gap \( \delta_3 = \delta + \delta_2 \), can be expressed [51]:

\[
k = \frac{\lambda_1(\delta)}{\lambda_2(\delta)} \approx \frac{c + 0.88}{c + \frac{h_2}{\delta_1} + \frac{t}{\delta_3} + 1.76}
\]  

(3.17)

The equivalent permeance was computed considering a series reluctances connection:

\[
\lambda = \frac{\lambda_1 \lambda_2}{\lambda_1 + \lambda_2}
\]  

(3.22)

The electromagnetic force of plunger-type electromagnet 2 was derived:

\[
F(\delta) = \mu_0 \frac{\theta^2}{\left(1 + \lambda(\delta) \frac{L_{eq}}{\mu_0 c}\right)} g\lambda'(\delta)
\]  

(3.24)

The results are shown in Figure 3.11, compared with 3-D numerical solutions, which joined a 2-D solution by a FEM in MVP-EE formulation with MTM, observing the best matches on the whole range of analyzed air-gaps in comparison with the other methods.
Fig. 3.15 - Front perspective of the model with associated mesh - MVP-EE formulation [61]

Fig. 3.16 - Symmetry plane perspective of the model with associated mesh - MVP-EE formulation [61]

Fig. 3.17 - Magnetic flux density on the symmetry plane and lateral faces (0.5 mm, 575.0 A, MVP-EE formulation) [61]

Fig. 3.18 - Static electromagnetic force distribution (0.5 mm, 575.0 A, MVP-EE formulation) [61]
Chapter IV

LEAKAGE MAGNETIC FIELD AND MODELING LIGHTNING SURGES IN POWER MULTI-WINDING AUTOTRANSFORMER

4.3 Impedance voltage of the power multi-winding autotransformer

The power multi-winding three-phase autotransformer under investigation has rated powers of 400/400/80 MVA for voltage levels of 400/231/22 kV.

Let $w_1$, $w_2$, $w_3$ be the numbers of turns of the three principal windings of power autotransformer: primary, secondary and tertiary winding. The secondary winding is connected to the median (principal) tapping of the regulating winding, so that the phase secondary voltage for principal and marginal tappings is:

$$ U_{2ph} = U_{2phr} \cdot \frac{w_2 + \alpha \frac{w_R}{2}}{w_2}, \quad U_{2phr} = \frac{U_{lr}}{\sqrt{3}} \frac{w_2}{w_1 + w_2} $$

where $U_{lr}$ is the primary rating line voltage and $\alpha$ is a coefficient depending on the tapping position of regulating winding, $-1 \leq \alpha \leq 1$, being zero for principal tapping.

4.3.1 Primary-secondary windings pair

To determine the short-circuit parameters of each pair of windings, the magnetic energy evaluation method was adopted. For primary-secondary windings pair, the magnetic field energy can be calculated for any arbitrary value of the primary line current $I_{1e}$ (usually close to the primary rated current $I_{1r}$).

For star connection, the phase current will be the same (fig. 4.4) and the corresponding secondary tapping currents ($I_{2c}$) result from the equality of the primary and secondary magneto motive forces:

$$ I_{2c} = I_{lep} \cdot \frac{w_1}{w_2 + \alpha \frac{w_R}{2}}, \quad I_{lep} = I_{le} = I_{IN} $$

If $W_{12}$ denotes the magnetic field mean energy per phase, produced by the currents $I_{1e}$ and $I_{2c}$, the referred to primary winding short-circuit reactance $X_{k12}$ can be expressed in absolute values or in percentage of equivalent primary impedance $Z_{IN}$, as:

$$ X_{k12} = \omega \cdot \frac{2W_{12}}{I_{1e}^2} [\Omega], \quad X_{k12\%} = 100 \cdot \frac{X_{k12}}{Z_{IN}} [%], \quad Z_{IN} = \frac{U_{IN}}{\sqrt{3} I_{IN}} $$
4.4 Numerical evaluation of the magnetic field energy and of the short-circuit reactance with FEMM program

4.4.1 2-D model and the boundary conditions

In the autotransformer window (Fig. 4.5), three ferromagnetic borders with zero tangential component of the magnetic field were considered. For the frontal part of the coils, the vertical border can be considered as zero potential magnetic line \((A = 0)\). To study the approximation \((A = 0)\) for symmetry axis \((a - b)\), a harmonic analysis at commercial frequency was performed.

![Fig. 4.5 - Magnetic field pattern in autotransformer window with two phases, at minus tapping for \(i_R = \text{max}\)](image)

![Tab. 4.1 - Current densities corresponding to R and S phases, at minus tapping for \(i_R = \text{max}\)](image)

<table>
<thead>
<tr>
<th>Phase</th>
<th>R</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>(J_1 [A/mm^2])</td>
<td>0.799 - 0.400 - j0.692</td>
<td>-0.400 - j0.692</td>
</tr>
<tr>
<td>(J_2 [A/mm^2])</td>
<td>-1.198 0.599 + j1.038</td>
<td>0.599 + j1.038</td>
</tr>
<tr>
<td>(J_R [A/mm^2])</td>
<td>1.392 - 0.696 - j1.206</td>
<td>-0.696 - j1.206</td>
</tr>
</tbody>
</table>

The analysis shows that the approximation \((A = 0)\) can be enough well applied to the symmetry axis \((a - b)\) of the autotransformer window (Fig. 4.5). If the current in T phase reaches its peak, the currents in R and S phases have equal values and the field distribution is completely symmetrical.

![Fig. 4.6 - Distribution of MVP along the symmetry axis \((a - b)\) of autotransformer window, at minus tapping for \(i_R = \text{max}\)](image)

![Fig. 4.7 - Distribution of MVP along the bottom border \((c - d)\) of autotransformer window, at minus tapping for \(i_R = \text{max}\)](image)

As it can be seen in Figures 4.6 and 4.7, the lowest value of potential module is obtained along the axis \((a - b)\). The introduction of this border has the advantage of the possibility to apply a cylindrical model and of two times reduction of the nodes number.
4.4.2 2-D numerical results of short-circuit tests

![Magnetic field pattern in inferior half autotransformer window for primary-secondary windings pair short-circuit test](image1)

4.4 Numerical evaluation of the magnetic field energy and of the short-circuit reactance with ANSYS program

The analysis of the magnetic field in autotransformer has continued in the papers [65], [67] using 3-D FEM implemented in ANSYS program. Three formulations were used in the magneto static regime, MVP-EE [65], MVP-NE) [67] and MSP [67].

![3-D model perspective with associated mesh](image2)

![3-D magnetic field pattern in MVP-EE formulation, for primary-secondary windings pair short-circuit test, at plus tapping](image3)

<table>
<thead>
<tr>
<th>Pair</th>
<th>Tapp.</th>
<th>Exp</th>
<th>2D</th>
<th>3D</th>
<th>2D</th>
<th>3D</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>MVP-NE</td>
<td>MSP-NE</td>
<td>MVP-EE</td>
<td>MVP-NE</td>
</tr>
<tr>
<td>1-2</td>
<td>0</td>
<td></td>
<td>40.41</td>
<td>41.03</td>
<td>37.79</td>
<td>40.76</td>
</tr>
<tr>
<td></td>
<td>+</td>
<td>29.56</td>
<td>28.87</td>
<td>27.64</td>
<td>29.11</td>
<td>27.35</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>82.68</td>
<td>82.84</td>
<td>75.25</td>
<td>80.70</td>
<td>75.19</td>
</tr>
</tbody>
</table>

Tab. 4.7 - Short-circuit reactance corresponding to short-circuit test for primary-secondary windings pair
4.5.3 Optimization of 3-D simulations by memory management

The memory management has direct implications on solving time \( t_s \). When the complexity of the model requires, the operating system supplements the internal memory (physical, RAM) of PC with additional memory, allocated from virtual memory, located on the hard disk. This strongly affects the speed performance of the solving algorithm. So, just a minimum necessary amount of additional memory must be allocated [3].

<table>
<thead>
<tr>
<th>Physical memory 1.5 GB</th>
<th>No additional memory</th>
<th>Maximum PC capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor frequency 1.83 GHz</td>
<td>MSP-NE</td>
<td>MVP-EE</td>
</tr>
<tr>
<td>Nodes</td>
<td>20,089</td>
<td>152,316</td>
</tr>
<tr>
<td>Elements</td>
<td>109,294</td>
<td>109,294</td>
</tr>
<tr>
<td>Equations</td>
<td>18,813</td>
<td>109,383</td>
</tr>
<tr>
<td>Additional memory</td>
<td>0 GB</td>
<td>0 GB</td>
</tr>
<tr>
<td>( t_{s,\text{real}} ) [sec]</td>
<td>183</td>
<td>238</td>
</tr>
</tbody>
</table>

Tab. 4.9 - Solving time \( t_s \) for “1-2 plus” short-circuit test

A limitation of solving time and a good precision were obtained by a different allocation of additional memory over the phases of pre-processing, processing, post-processing via a configuration file specific to ANSYS. The results presented in Table 4.9 show that utilization of additional memory in the range (1.5-3.0) GB, increases the solving time (10-24) times compared to the case of an unlimited internal memory.

4.6 Modeling lightning surges in the power multi-winding autotransformer

Both to the application of impulse voltages as well as of high frequency oscillating voltages, on the tapping of regulating winding and on the terminals, important over-voltages can appear, whose maximum values can exceed the maximum amount of applied voltages. The LC model study for the processes taking place in autotransformer windings during impulse voltage testing offers the opportunity to identify the constructive parameters influence on the level of the voltage impulse generated stress.

4.6.2 Self and mutual inductances for short-circuited tertiary winding

The self and mutual inductances were determined using the magnetic field in the autotransformer window for short-circuited and grounded tertiary winding. The field calculation was performed using the FEMM program [175]. The inductances are given by the expressions:

\[
L_i = \frac{\int \int \int A J_1 \, dV}{I_1^2}, \quad M_{12} = w_2' \frac{\int \int \int A \, dV}{I_1} \tag{4.39}
\]

where \( A \) represents magnetic vector potential, \( I_1 \) and \( j_1 \), the current and density current in the coil 1 (HV) with the cross-section \( S_1 \) and \( w_2' \) and \( S_2 \), the turns density and the cross-section of the coil 2 (LV).
Abstract of PhD. Thesis

Fig. 4.18 - Magnetic field pattern for current injected in upper half of regulating winding

Tab. 4.12 - Computed parameters and their values for current injected in upper half of regulating winding

Fig. 4.21 - Wires capacitances for n = 14

Fig. 4.22 - Simplified scheme of autotransformer windings

Fig. 4.23 - Lightning surges in free end of regulating winding and in the common terminal A2

(u2 point and respectively u1 point from simplified scheme)
Chapter V

NUMERICAL SIMULATION OF TRANSIENT ELECTRIC AND MAGNETIC FIELDS IN RECTANGULAR SOLID BUS BARS

5.2 Analytical evaluation of magnetic field distribution

5.2.2 Distribution of electric and magnetic fields at step current injection

In the case of current step injection \( i(t) = I_0 \cdot 1(t) \) in a two bars system, short-circuited at the opposite end - equivalent to a sudden short-circuit apparition or to a direct current interruption - the magnetic and electric fields expressions in central part of bars \((y = 0)\) are:

\[
H_y(\xi, \theta) = H_{yA} \left[ \xi (1 + \eta) - 1 + \frac{1}{\pi} \sum_{k=1}^{\infty} (-1)^k \eta \sin(k \pi \xi) - \sin\left( k \pi \left( 1 - \frac{\xi}{\theta} \right) \right) e^{-\xi \pi^2 \theta} \right], \quad \theta = \frac{t}{\tau} \tag{5.15}
\]

\[
E_z(\xi, \theta) = \frac{E_0}{1 + \eta} \left[ 1 + \eta + 2 \sum_{k=1}^{\infty} (-1)^k \left[ \eta \cos(k \pi \xi) + \cos\left( k \pi \left( 1 - \frac{\xi}{\theta} \right) \right) \right] e^{-\xi \pi^2 \theta} \right] \tag{5.16}
\]

where

\[
E_0 = \frac{I_0}{\sigma b h} \approx \frac{1 + \eta}{\sigma b} H_{yA} \tag{5.17}
\]

is the electric field in conductor in stationary regime [41].

If a step voltage \( u(t) = U_0 \cdot 1(t) \) is applied, the magnetic and electric fields expressions in central part of bars \((y = 0)\) can be written [41]:

\[
H_y(\xi, \theta) = H_0 \left[ \xi - \frac{1}{1 + \eta} - 2m \sum_{k=1}^{\infty} \frac{\eta \sin(v_k \xi) - \sin(v_k (1 - \xi))}{v_k^2 ((m + 1) \sin(v_k) + v_k \cos(v_k))} e^{-v_k^2 \theta} \right] \tag{5.24}
\]

\[
E_z(\xi, \theta) = E_0 \left[ 1 - 2m \sum_{k=1}^{\infty} \frac{\eta \cos(v_k \xi) + \cos(v_k (1 - \xi))}{v_k ((m + 1) \sin(v_k) + v_k \cos(v_k))} e^{-v_k^2 \theta} \right] \tag{5.25}
\]

where \( v_k \) are solutions of the equation [41]:

\[
m(\eta + \cos \nu) = \nu \sin \nu \tag{5.26}
\]
5.3 Numerical simulation of transient electric and magnetic fields in the system of rectangular bus bars

For numerical simulation of the process of penetration of electric and magnetic fields in the system of parallel rectangular solid bars forming a circuit loop, was used 2-D finite element method implemented in FLUX [172] and FEMM [175] programs. The transient process itself and the stationary regime were investigated by FLUX 2D and the initial moment was analyzed using FEMM. The expulsion of the field lines from the conductor domain at analyzed moment was obtained by a trick involving the approximate cancellation of its relative permeability.

![Fig. 5.3 - Studied domain with associated mesh in FLUX 2D (stationary regime)](image1)

![Fig. 5.5 - Studied domain with associated mesh in FEMM (initial moment)](image2)

5.3.4 Numerical evaluation of exterior magnetic field

FEMM investigation for very thin bars \((b/a = 0.01)\) validates enough well the results of paper [48] in which the \(\eta\) ratio at initial moment \((\eta_0)\) is computed by conformal mapping method (CMM), for configuration \(b/a = 0\).

![Fig. 5.6 - \(\eta_0\) ratio computed by different methods](image3)
The transient magnetic field depends essentially on the initial field on the surface of conductors. In the paper [49] continue the analysis of this field started in [48] at current step injection in the bar system in Fig. 5.2. For the exact formulas obtained in [48] for infinitely small thickness bars, simple approximations are proposed, containing the factor used by Dwight to determine the electrodynamic forces between the bars (5.27), thus extending the applicability domain to small thickness bars:

$$\eta_{0}(x) = \left| \frac{H_{yB}}{H_{yA}} \right| = \frac{\pi}{2} \frac{-\arctg \left( \frac{x}{2} \right)}{\pi + \arctg \left( \frac{x}{2} \right)}, \quad x = \frac{h+b}{a}, \quad b < h \quad (5.27)$$

The problem is also solved by numerical conformal mapping, using Schwartz-Christoffel module (SC) of the MATLAB program.

Similarly to the ratio $\eta$ of the tangential components of magnetic field on the lateral sides, is defined the ratio $\eta_{b}$ of tangential components of the points C and A (Fig. 5.2) for whose average is proposed the formula:

$$\eta_{b_{med}}(\frac{b}{a}) = \left| \frac{H_{yc}}{H_{yA}} \right| = \frac{\pi - 4\arctg \left( \frac{b}{2a+b} \right)}{\pi + 4\arctg \left( \frac{h}{2a+3b} \right)} \left[ 1 + \frac{h}{100a} + \frac{b}{a} \left( 0.03 + \frac{h}{2000a} \right) \right] \quad (5.29)$$

**Fig. 5.11** - Influence of bars system geometry ($h/a$, $b/a$) on $\eta_{0}$ ratio - numerical (SC, FEMM) and analytical (5.27) results -

**Fig. 5.14** - Influence of bars system geometry ($h/a$, $b/a$) on $\eta_{b}$ ratio - numerical (SC, FEMM) and analytical (5.29) results -
5.3.5 Numerical evaluation of electric and magnetic fields distribution at step current injection

In the paper [41] the tangential component of the magnetic field and longitudinal electric field component were computed based on analytical equations (5.22), (5.23) using the same value of $\eta_{st}$ ratio for all analyzed moments. In this paper is proposed a mixed analytic-numerical solution (Fig. 5.17 and 5.19), based on the same equations, but using a variable $\eta$ ratio, resulting from FLUX 2D numerical simulation (Fig. 5.15).

---

**Fig. 5.15 - Evolution of ratio $\eta$ along the transient process at current step injection**

---

**Fig. 5.16 - Numerical and analytical results for transient magnetic field in conductor 1 at current step injection, for $h/b = 30$ and $a/b = 2$**

---

**Fig. 5.17 - Numerical and analytic-numerical results for transient magnetic field in conductor 1 at current step injection, for $h/b = 30$ and $a/b = 2$**
Fig. 5.29 - Distribution of magnetic field (left) and of current density (right) for $\theta = 10^{-2}$, $\theta = 10^{-1}$, $\theta = 10$, at step current (FLUX 2D)
Chapter VI

NUMERICAL DETERMINATION OF TRANSIENT PARAMETERS OF A SYSTEM OF RECTANGULAR SOLID BUS BARS

6.1 Transient parameters of the linear electrical circuits

6.1.4 Transient parameters of a non-filiforme and with additional losses circuit element

6.1.4.4 Integral relationships between instantaneous values of currents and voltages

The integral equations of current and voltage ($\varepsilon > 0$, arbitrary little) for the non-filiforme circuit elements and with additional losses are respectively:

$$
u(t) = l(0_+) \frac{di}{dt} + \frac{d}{dt} \int_{0^-}^{t} r(t-\xi) i(\xi) d\xi + u_0(t) = r_0 i + l(0_+) \frac{di}{dt} + \frac{d}{dt} \int_{0^-}^{t} (t-\xi) i(\xi) d\xi + u_0(t) \quad (6.70)$$

$$i(t) = c(0_+) \frac{du}{dt} + \frac{d}{dt} \int_{0^-}^{t} g(t-\xi) u(\xi) d\xi + i_0(t) = g_0 u + c(0_+) \frac{du}{dt} + \frac{d}{dt} \int_{0^-}^{t} (t-\xi) u(\xi) d\xi + i_0(t) \quad (6.71)$$

6.1.4.5 Experimental determination of transient parameters

At current step injection $i(t) = 1(t)$, respectively, at voltage step application $u(t) = 1(t)$, the relationships (6.70), (6.71) become:

$$u(t) = l(0_+) \delta(t) + r(t) = r_0 \cdot 1(t) + \frac{dl(t)}{dt}, \quad \int_{0^-}^{t} u(t) dt = r_0 t + l(t) \quad (6.80)$$

$$i(t) = c(0_+) \delta(t) + g(t) = g_0 \cdot 1(t) + \frac{dc(t)}{dt}, \quad \int_{0^-}^{t} i(t) dt = g_0 t + c(t) \quad (6.81)$$

At current ramp injection $i(t) = t \cdot 1(t)$, respectively, at voltage ramp application $u(t) = t \cdot 1(t)$, the relationships (6.70), (6.71) become:

$$u(t) = l(0_+) \cdot 1(t) + \int_{0^-}^{t} r(t) dt = r_0 \cdot t + l(t), \quad \frac{du(t)}{dt} = l(0_+) \cdot \delta(t) + r(t) \quad (6.84)$$

$$i(t) = c(0_+) \cdot 1(t) + \int_{0^-}^{t} c(t) dt = g_0 \cdot t + c(t), \quad \frac{di(t)}{dt} = c(0_+) \cdot \delta(t) + g(t) \quad (6.85)$$

The determination of transient resistance and conductance can be convenient in experimental conditions of step signals application, when, for a capacitive element ($l(0_+) = 0$) or inductive element ($c(0_+) = 0$), these parameters are identified with the applied signals:

$$r(t) = u(t) - l(0_+) \delta(t) \bigg|_{i(t)=1(t)} = u(t) \bigg|_{i(t)=1(t), \ t>0} \quad (6.92)$$

$$g(t) = i(t) - l(0_+) \delta(t) \bigg|_{u(t)=1(t)} = i(t) \bigg|_{u(t)=1(t), \ t>0} \quad (6.93)$$
6.2 Utilization of FLUX program in determination of transient parameters of the system of rectangular solid bus bars

6.2.2 Determination of transient resistance and inductance at step current injection

At current step injection \( i(t) = I_0 \cdot 1(t) \), for \( t \geq 0 \), the relationship (6.80) [140] links the transient resistance and the transient inductance:

\[
\begin{align*}
\mathbf{u}(t) &= \mathbf{I}_0 \left[ \mathbf{l}(0_+) \mathbf{d}(t) + \mathbf{r}(t) \right] = I_0 \left[ r_0 \cdot 1(t) + \frac{dl(t)}{dt} \right], \quad t \geq 0 \\
\end{align*}
\]

(6.99)

Using directly the numerical value of voltage at step current \( u_{\text{step,ctr,NUM}}(t) \), from the first equality and for \( t > 0 \), results the transient resistance at step current, from voltage \( r_{\text{step,ctr,U}}(t) \).

\[
r_{\text{step,ctr,U}}(t) = \frac{u_{\text{step,ctr,NUM}}(t)}{I_0} \left|_{t > 0} \right. 
\]

(6.100)

The second equality in (6.99) suggests another way to obtain transient resistance using the numerical value of the transient inductance at step current \( l_{\text{step,ctr,NUM}}(t) \) given by FLUX (total inductance). The result was suggestively called transient resistance at step current from inductance \( r_{\text{step,ctr,L}}(t) \).

\[
r_{\text{step,ctr,L}}(t) = r_0 + \frac{dl_{\text{step,ctr,NUM}}(t)}{dt} 
\]

(6.101)

Mutually, from the second equality can be approximately deduced the transient inductance from transient resistance, using the numerical value of inductance in stationary regime for its limit at infinity \( L_\infty \) and the value \( r_{\text{step,ctr,U}}(t) \) for transient resistance \( r(t) \):

\[
l(t) = L_\infty - \int_{t}^{\infty} \left( r(t) - r_0 \right) dt = L_{\text{sl}} - \int_{t}^{10^7} \left( r_{\text{step,ctr,U}}(t) - r_0 \right) dt = l_{\text{step,ctr,R}}(t) 
\]

(6.103)

The result was generically called transient inductivity at step current from resistance \( l_{\text{step,ctr,R}}(t) \).

Fig. 6.8 - Transient resistance at step current: solid line (6.100), dot line (6.101)

Fig. 6.9 - Transient inductance at step current: solid line (FLUX), dot line (6.103), initial inductance: point (6.109)
Chapter VII

ORIGINAL CONTRIBUTIONS AND CONCLUSIONS

Author's original contributions to modeling the fields and transient regimes in electrical equipments are structured on the chapters.

In Chapter II is proposed an experimental and numerical verification of power approximation of boundary conditions method (PABCM) developed in [32], [33], [35] in the evaluation of total inductance of a plunger-type electromagnet (Fig. 2.5). The author's contributions in this verification follow:

- Based on PABCM, in the paper [36], in the assumption of fitting coil dimensions with electromagnet window, was derived an analytical expression of the internal inductance per unit length $L_{\text{int,AN}}$ (2.31) (domain I, corresponding to the magnetic core with thickness $g$, Fig. 2.5) for 2-D case, which is difficult to apply because it contains an improper integral $F(\alpha, z)$ (2.21). The author proposes its computation using MATHCAD program [178];

- To evaluate the total inductance of the electromagnet $L_{\text{tot}}$ were taken into account two components: internal inductance $L_{\text{int}}$ (domain I, Fig. 2.5) obtained by multiplying the internal inductance per unit length $L_{\text{int}}$ by the thickness $g$ of magnetic core and external inductance $L_{\text{ext}}$ (domain II, outer magnetic core domain, corresponding to frontal parts of the coil, Fig. 2.5) obtained by multiplying the external inductance per unit length $L_{\text{ext}}$ by difference between half-length of average turn ($l_m/2$) and the thickness $g$ (Fig. 2.5).

- The two components were numerically evaluated based on magnetic energy stored in corresponding domains, determined by FEM in magneto static regime implemented in QUICKFIELD [179] [177] and FEMM [175] programs. The average relative error of numerical solution versus analytical solution for the internal inductance per unit length $L_{\text{int}}$ is 2.47%, validating the analytical formula (2.31) to calculate the internal inductance.

- The analytical and numerical evaluation of internal inductance and numerical evaluation of the external inductance by two programs for 2-D FEM analysis led to two solutions for the total inductance, one purely numerical with presents very small average deviations versus experimental data (0.78%) and another solution, analytical-numerical, with errors of 1.67%. The accuracy of the results containing the analytical formula (2.31) once again confirms its accuracy.

- It were justified some results errors being made useful recommendations. The large differences between experimental data and those calculated for small air-gaps can be explained by distorted form of the plunger, whose sides are not flat as in Figure 2.5. Another possible errors source can be the simplified geometry of "I" form of plunger versus "T" real form (Fig. 2.5). The analytical and numerical solutions accuracy can be improved by removing the simplified geometric assumptions and, concerning only numerical solution, by 3-D approach for exact geometric configuration description.

Chapter III presents the results of theoretical and experimental investigations on a plunger-type electromagnet to test the effectiveness of analytical and numerical methods for calculating the developed force.

Earlier theoretical research [38], [37], [47], [50] using conformal mapping method (CMM) provided simple and precise analytical formulas for 2-D permeances calculation, useful for obtaining of an analytical expression for the electromagnetic force (3.19). The author has created 3-D numerical models of a plunger-type electromagnet (Fig. 3.6) and
experimental determinations were performed to validate the own results and the analytical ones. The contributions in these investigations are presented below:

- The numerical method used for analysis is the finite element method (FEM), which is most suitable for the techniques of determining the force. Two formulations of 3-D FEM in magneto static regime were adopted: the magnetic scalar potential formulation with nodal elements (MSP-NE) and the magnetic vector potential formulation with edge elements (MVP-EE). Two classical techniques to obtain the global force from the field solution were chosen: the Maxwell stress tensor method (MTM) and the virtual work method (VWM). The adopted formulations in conjunction with one or both techniques, implemented in the ANSYS program [171] led to obtain three numerical solutions for static characteristic of plunger-type electromagnet: MSP-NE MTM, MSP-NE VWM and MVP-EE VWM.

- To automate the calculation, the classic work with menus was dropped, adopting the alternative of creation of command files using the parameter language APDL of ANSYS program and to reduce the execution time of these files the batch mode was adopted minimizing the required hardware resources.

- The electromagnetic force was experimentally determined for a particular range of air-gap, using a tens sensor for smaller air-gaps and simple procedures of gravity plunger determination, applied to higher air-gaps, when the saturation effect is negligible.

- The obtaining of parallel results (Fig. 3.9) allowed the comparison of the methods based on measurements. Average relative error of analysis versus experimental data shows that the most accurate solution is given by MSP VWM, with 0.08%, followed by MVP-EE VWM formulation with 6.17%, the least precise formulation being obtained by MSP MTM, with 20.27% (Fig. 3.10). This study pointed out the superiority of virtual work technique compared to Maxwell stress tensor integration for electromagnetic force calculation from 3-D FEM field solution. The magnetic vector potential formulation with nodal elements (MVP-NE) was also used in conjunction with both techniques MTM and VWM, but the results have proved wrong. However, its 2-D implementation in FEMM program [175] in conjunction with MTM is in good agreement with experimental data (Fig. 3.9) (average relative error of 4.00%). Also, the average relative error of the force obtained with the analytical formula (3.24) compared to measurements is of 3.89%, which is its validation (Fig. 3.9).

- Another criterion of comparison between methods was the solution convergence versus the number of used finite elements and the size of elements in air-gap that have great influence on force accuracy. The results show a faster convergence of VWM compared to MTM requiring a finer mesh.

In Chapter IV has been studied the leakage magnetic flux in a three phase power autotransformer 400/400/80 MVA, 400/231/22 kV, with primary, secondary, tertiary and regulating windings, with multiple tappings, resulting 2-D and 3-D numerical models.

The autotransformer behavior at the application of lightning surges was also analyzed, aiming the over voltages level on the tappings of regulating winding. The considerable size of 3-D numerical simulations led to investigations for their optimization, concerning the solving time reduction and accuracy increasing, up to hardware resources. The author's contributions in these studies are pointed out below:

- Since the impedance voltage for secondary tapping of regulating winding can not be evaluated using simple formulas, derived under the assumption of straight lines of magnetic flux, the author has considered the real pattern of magnetic field obtained by FEM. Thus, two numerical models were obtained, a 2-D model using FEMM program [175] and a 3-D one using ANSYS program [171], assuming a static magnetic regime which
approximates enough well the regime of commercial frequency, taking into account the small sections of the conductors.

- To obtain the 2-D model, a preliminary study for necessary boundary conditions was performed. For the frontal part of the coils, on the vertical border, a small skin depth should be considered, due to aluminum or copper screen of the autotransformer tank. However, at commercial frequency, the magnetic field determined in these conditions is practically identical to the static field corresponding to zero frequency and the vertical frontal border can be considered as a zero magnetic potential line ($A = 0$).

- For the other borders, a FEMM analysis was performed in harmonic regime at commercial frequency, at two moments delayed by a quarter of period, aiming the magnetic vector potential (MVP) values along the symmetry line of the autotransformer window, compared to its values on the bottom border of the window (Fig. 4.5, 4.10). The results had showed extremely low values (Fig. 4.6-4.9), suggesting consideration of symmetry lines of the windows as zero potential magnetic flux lines.

- The last approximation is also sustained by the equality of magnetic field energies per unit length, calculated at the two moments.

- Another confirmation is given by the recalculation of the energy, applying the approximation to the symmetry axis, which proved to be only 0.50% lower.

- Considering the symmetry lines of the autotransformer windows as zero magnetic potential flux lines, like the flux lines from the frontal parts of windings, in the vicinity of the screened tank, has allowed the use of a cylindrical model, very economical in terms of numerical computation. The FEMM axi-symmetric solution in magneto static regime for the short-circuit reactance corresponding to principal and marginal tappings of regulating winding, agree with the experimental data with errors less than 3.00% (Table 4.8).

- The field problem was solved in 3-D using three formulations of FEM: MVP-EE, MVP-NE and MSP-NE, implemented in ANSYS for magneto static regime that led to results that deviate on average 1.00%, 5.83% and 8.34% from experimental values. Despite of simplifying assumptions, the 2-D axisymmetric solution in MVP-NE formulation, with an average relative error of 0.11%, ranks first in terms of accuracy (Table 4.8).

- Again, to automate the calculation, the work with commands files was adopted, using the parameter language APDL.

- Using ATP-EMTP software package [173], [174] and FEMM, the power multi-winding autotransformer behavior was studied at lightning surges application, considering a L-C simplified model of the windings, with short-circuited tertiary winding, aiming the level of over voltages that appear on the free end of regulating winding.

- The self and mutual inductances were determined with FEMM program in axisymmetric approach for short-circuited and grounded tertiary winding. Have been neglected the mutual inductances between the regulating and low voltage windings, because of its relatively low value, facilitated by the screen effect of the high voltage winding, located between them. Have been also neglected the mutual inductance between the high and low voltage windings. The distributed nature of the windings was taken into account by dividing them into four sections (two sections per window). The characteristic length of grouped elements required for analysis is about 20 to 50 cm.

- The capacities were analytically evaluated, taking into account the adjacent conductors dispositions and neglecting the capacitances of conductors located in different disks.

- The modeling results show some differences versus the measured values in the laboratory test (Table 4.16), which can be attributed to the simplifying assumptions and to the axisymmetric modeling.
• The simplified scheme ATP-EMTP can be used to identify the influence of autotransformer constructive parameters at a certain level and form of applied lightning surges.

• Optimization of solutions in 3-D numerical simulations were searched to reduce the solving time and to increase the accuracy. It's known that, if necessary, the computer's operating system supplements the random access memory (RAM, physical memory) by additional memory located on hard disk, which drastically slows down the program running. Consequently, the author has taken over the PC memory management through a configuration file, specific to ANSYS. Thus, the amount of additional memory could be minimized by its differentiated allocation along the phases of pre-processing, processing and post-processing.

• Also, based on nodes number used by each formulation, the solving time could be evaluated under assumptions of an unlimited physical memory. The results presented in Table 4.9 show that using additional memory in the range (1.5-3.0) GB, increases the solving time of (10-24) times compared to the ideal case.

• The large multiple numerical simulations have confirmed that the solutions are faster obtained, as the computer physical memory is more important, which minimizes the amount of additional memory required from the hard disk.

Chapter V concerns transient phenomena taking place in a system of two solid rectangular parallel bus bars, to the step signals application of current and voltage. The transient magnetic field problem for infinitely high bars is completely analytically solved [161], considering a zero magnetic field on the outer surfaces of both bars. New analytical results [41] were obtained for finite height but large enough bars, maintaining the assumption of one-dimensional magnetic field inside the bars, constantly distributed on the height, but considering a nonzero magnetic field on the outer sides. The ratio \( \eta \), of the fields in the middle of the two sides of the high bar, was also held constant.

The author has numerically simulated the penetration process of electric and magnetic fields into the system bar (Fig. 5.2) using 2-D FEM. The simulation results were compared with analytical ones and combined with them to improve the effects of simplified assumptions. The contributions to the study of this transient phenomenon are given below:

• The transient regimes established in the system of two solid rectangular parallel very high bars \((h/b = 30)\) (Fig. 5.2), to the step signal application of current and voltage, was simulated using 2-D FLUX [172] and FEMM [175] programs. Being an open boundary problem, the FLUX facilities were used for this purpose, by bordering the bars system with so-called infinite box, respectively, by asymptotic boundary conditions available in FEMM.

• To increase the accuracy, the spatial and temporal mesh have been refined in areas with large quantities variations, i.e. along the edges of the bars and especially around the peaks and to towards the beginning of the transient process. A major influence has a rate of change of elements size in the mesh. Thus, the step time was increased in steps, keeping it constant on small time intervals, aiming to have jumps no more than 2-2.5 times to junctions of uniform intervals.

• The evolution of the ratio \( \eta \) along the transient process was numerically determined using FLUX to the step signal application of current and voltage. In both cases there was observed a negative slope of the numerical curves on the first two decades (Fig. 5.15, 5.22), explained by inevitably rough temporal mesh on these sections.

• To investigate the value of \( \eta \) ratio at absolute initial moment \((t = 0)\) \((\eta_0)\), static simulations were performed in FEMM program. The expulsion effect of the field lines from
conductor domain in this moment was obtained by a trick involving the approximate cancellation of its relative permeability.

- The FEMM numerical simulations at the moment \( t = 0 \) led to values very close to the minimum of numerical curves obtained by FLUX, indicating the moments from when the transient simulation in the FLUX can be taken into account.
- The FEMM investigation for extremely thin bars \( (b/a = 0.01) \) (Fig. 5.2) validates enough well the results for \( \eta_0 \) obtained by conformal mapping method (CMM) [48] for \( b/a = 0 \) configuration.
- Large differences were found compared to analytical values of \( \eta_0 \) [41] (Fig. 5.6, 5.15, 5.22) indicating that the assumptions under which the ratio was analytically derived at time \( t = 0 \), are very approximate.
- However, in the stationary regime, the numerical simulations lead to the same results as the analytical calculations, based on testing of a large variety of geometric configurations (Fig. 5.7, 5.8).
- The analytical determination of the tangential and longitudinal components of magnetic field [41] was based on the use of a constant ratio \( \eta \) equal to its value in stationary regime \( \eta_{st} \). Even under this assumption, the comparison between numerical and analytical curves for different moments of the transient process shows good agreement, excepting the external sides of the bars (Fig. 5.16, 5.18, 5.23, 5.25).
- The time variation of electric and magnetic fields on the periphery of the bar, numerically determined (points A and B, Fig. 5.1) confirms the agreements with analytical results, excepting the first decades, where the errors of numerical method are visible (Fig. 5.20, 5.21, 5.27, 5.28).
- The author has proposed a mixed analytical-numerical solution (Fig. 5.17, 5.19, 5.24, 5.26) based on analytical equations [41] with the use of a variable ratio \( \eta \), given by the numerical simulation in FLUX (Fig. 5.15, 5.22).
- The numerical simulations in FEMM had continued at \( t = 0 \) moment, for different geometric configurations, validating results of numerical conformal mapping method [49] using the Schwartz-Christoffel (SC) module of MATLAB software and also validating new very simple analytical formulas for \( \eta_0 \) ratio (5.27) and for its average (5.28) [49], for small thickness bars, using the coefficient \((b+h)/a\) used by Dwight for determining the electrodynamics forces between the bars.
- The average of ratio \( \eta_0 \) of tangential components of magnetic fields at points C and A (\( \eta_{\text{med}} \)) (Fig. 5.2) was subject of the same type of numerical investigations. It was validated the SC evaluation and analytical expression (5.29) [49], observing a low dependence of the ratio \( h/a \).
- Automation of calculation in FEMM program was obtained by running the command files (scripting files), created using parametric language LUA [176] for pre-processing, processing and post-processing, which does not exclude the interactive work.

In Chapter VI were numerically determined by 2-D FEM the transient parameters of the system of solid rectangular parallel very high bars \((h/b = 30)\) (Fig. 5.2) and based on analytical relationships between them, established by the theory of transient parameters of linear electric circuits (TPTLEC) [140], the ones of them were derived from the others, making comments on certain founded irregularities. The author's contributions in transient parameters evaluation are listed below:

- The 2D simulations using the FLUX program described in chapter V on the transient process of the bars system at the application of step or ramp signals of current and voltage, had allowed the determination of three transient parameters: transient resistance,
directly deduced from the numerical value of the applied voltage (6.100), (6.105), transient conductance, directly deduced from the numerical value of the injected current (6.100), (6105) and transient inductance, directly offered by FLUX, based on the classical definition of total magnetic flux (6.96) (6.97) (6.98).

• The analytical relationships between the parameters established by TPTLEC [140] had allowed the calculation of transient inductance from transient resistance (6.103), (6.107) containing in its expression the inductance in stationary regime \(L_{st}\) and the calculation of transient capacitance from transient conductance, containing in its expression the capacitance in stationary regime \(C_{st}\) (6.115) or initial capacitance \(C_{in}\) (6.120).

• The determination of initial capacitance \(C_{in}\) was made in the particular feeding regime of ramp voltage application, for which the TPTLEC [140] provides a relationship that contains the current and its derivative with respect the time (6.118), (6.117). Given that \(C_{in}\) is a constant quantity, its value should result the same, no matter of the moment of its evaluation. The author has proposed a formula for \(C_{in}\) (6.119) that makes the average of 234 values, corresponding to the moments describing the analyzed transient process, covering ten decades.

• The stationary capacitance \(C_{st}\) was considered equal to the transient capacitance at ramp voltage application, calculated at the last moment, corresponding of ten time constants.

• The stationary inductance \(L_{st}\) was evaluated in magneto static regime, verifying very well the numerical value of transient inductance, directly given by FLUX and calculated at the last moment.

• Mutually, based on analytical formulas of TPTLEC [140], from numerical value of the transient inductance, directly offered by FLUX (total inductance), was calculated transient resistance (6.101), (6.105).

• Following the same methodology as for \(C_{in}\), the initial inductance \(L_{in}\) was also determined in particular feeding regime of ramp current injection, for which the TPTLEC [140] provides a relationship that contains the voltage and its derivative with respect the time (6.108), (6.105). Given that \(L_{in}\) is a constant quantity, its value should result the same, no matter of the moment of its evaluation. The author has proposed a formula for \(L_{in}\) (6.109) that makes the average of 234 values, corresponding to the moments describing the analyzed transient process. The \(L_{in}\) value was very precisely validated by FEMM static simulation (Chapter V).

• The comparisons between the numerical and analytical-numerical results of the transient parameters point out some differences that may have several causes. Thus, the numerical simulation of the beginning of transient regime is strongly affected by the temporal mesh inevitably rough in the first decades. The errors in the middle decades can be attributed to the different ways of definition of transient inductance. The FLUX program [172] evaluate this parameter by the classical definition using the total magnetic flux (6.96), (6.97), while TPTLEC [140] uses an equivalent flux, linked to inductance by a convolution product (6.78). Other sources of error may also be application of derivative operators on interpolated numerical signal. A more fine mesh could improve the accuracy of the results.

• The features of the solid conductor versus the ideal filiform conductor were pointed out by comparing the evolutions of terminals quantities in feeding regime of ramp signals of current and voltage.

• The author has built a graphic animation that simulates the penetration of electric and magnetic fields into the rectangular bars system at current step injection.
REFERENCES

[20] Champaney, L., Méthodes d’Approximation de Solution pour les Problèmes de Physique, Course, University of Versailles St-Quentin in Yvelines, 2005;
[27] Cividjian, G., Degeratu, P., Cernian, O., Dimensionarea electromagnetilor cu armatură în T, (Dimensioning the T-armature electromagnets), The XIIth Technical Scientific Session of ICPE, reff. 152/G, pp. 3-20, November 4-6, Bucureşti, 1976;
[28] Cividjian, G., Radulian, G., Inductanta electromagnetilor cu armatură în T, (Inductance of the T-armature electromagnets), The XIIth Technical Scientific Session of ICPE, ref. 185/A, pp. 1-10, November 4-6, Bucureşti, 1976;
Abstract of PhD. Thesis


Cividjian, G.A., Initial magnetic field distribution around high rectangular busbars, Simpozionul Național de Electrotehnică Teoretică - SNET '07, October 12-14, București, 2007 (Unpublished);


Contribute modeling of the fields and of the transient regimes in electrical equipments


Démidovitch, B., Maron, I., *Éléments de calcul numérique*, Mir Publishing House, Moscow, 1979;


Dolán, A., *Softiri comerciale pentru modelarea câmpurilor și a regimurilor tranzitorii*, PhD Report, University of Craiova, May 2006;


Dolán, A., *Simulation de dispositifs électrotechniques par FLUX 2D-3D - Transformateur triphasé*, Stage Report, Grenoble Electrical Engineering Laboratory (G2Elab), French, March 2007;


Dufour, F., *Développement de la méthode des éléments finis avec des points d’intégration lagrngiens: application à la géomécanique*, PhD. Thesis, Centrale School of Nantes & University of Nantes, 2002;


Flux 9.3.2, *Guide d’utilisation*, 2006;

Freeman, E.H., Ashen, E.M., *Force calculation in magnetic field problems using virtual work with only one solution*, Sixth International Conference on Electrical Machines and Drives, September 8-10, 1993, pp. 318-322;


Hebrin, R., Cours d’analyse numérique 2004-2005, Course, Master in Mathématiques, University of Aix Marseille 1, 2004;


International Compumag Society (ICS), Testing Electromagnetic Analysis Methods (TEAM), Problem 13;

International Compumag Society (ICS), Testing Electromagnetic Analysis Methods (TEAM), Problem 20;

Ioan, D., Munteanu, Irina, Ionescu, B., Popescu, M., Popa, R., Lazarescu, M., Ciuprina, Gabriela, Metode numerice în ingineria electrică, Matrix Rom Publishing House, București, 1998;


Joan, M., Modélisations des paramètres R et L de matériels électriques bobinés par la méthode des éléments finis 3D, PhD. Thesis, Institut National Polytechnique de Grenoble (INPG), Laboratoire d’Electrotechnique de Grenoble (LEG), 2004;


Karsay, K., Kerenyi, D., Kiss, L., Large Power Transformers, Akademiai Kiado, Budapest, 1987;


Kostensko, M., Piotrovski, L., Electrical machines (In French), Mir, Moscow, 1976;


Lefevre, M., Contributions à la modélisation électrique, électromagnétique et thermique des transformateurs - Application à l’étude de l’échauffement sur charges non linéaires, PhD. Thesis, University of Nantes, 2006;


Marinescu, A., Transformer behaviour at switching overvoltages (In romanian), Tehnica Publishing House, București, 1988;

Marinescu, A., Călin, Gh., HV Power Auto-Transformers Protected for Internal Overvoltages, Proceedings of the 8-th International Conference on Optimization of Electrical and Electronic Equipments, May 16-17, Brașov, 2002;


Abstract of PhD. Thesis 36


Mocanu, C.I., Teoria câmpului electromagnetic, EDP, București, 1981;

Morega, M., A., Elemente de modelare numerică pentru probleme la limită, Polytechnic Institute of Bucharest Publishing House, 1997;


Nens, E., Contribution à la modélisation des structures symétriques en électromagnétisme, PhD. Thesis, Institut National Polytechnique de Grenoble (INPG), Laboratoire d’Electrotechnique de Grenoble (LEG), Faculté Polytechnique de Mons, 2002;


Ngneu, T., Contribution à la modélisation mathématique et informatique des pertes supplémentaires dans les transformateurs de puissance de type cuirasse, PhD. Thesis, Institut National Polytechnique de Grenoble (INPG), Laboratoire d’Electrotechnique de Grenoble (LEG), 1989;


Petrov, G.N., Электрические машины ч. 1, Трансформаторы, ГЭИ, Москва, 1956;

Popa, I., Modélisation numérique du transfert thermique - Méthode des volumes finis, Universitaria Publishing House, Craiova, 2002;

Prasad, K.M., Davey, K.R., A boundary element analysis of Team Problem no. 20: Static force calculation, 4th International TEAM Workshop, November 1993;

Preda, M, Markovici, J., Topan, D, Asupra imitanțelor parametrilor tranzitorii pentru circuitele nefiliforme, a relațiilor dintre parametrii re greg nesinusoial, EEA – Electrotehnica, Year 23, No. 1, pp. 15-22, 1975;

Preda, M., ș.a., Bazele electrotehnicii, Vol. I, EDP, București, 1980;


Prikler, L., Hoidalen, H., K., ATP DRAW ver. 3.5 for Windows, Preliminary Release no. 1, August, 2002;


Alin-Iulian DOLAN – Contributions to modeling of the fields and of the transient regimes in electrical equipments


[150] Șora, C., Bazele electrotehnicii, EDP, București, 1982;


[153] Yatchev, I., Modélisation numérique par la méthode des éléments finis, Seminar, University of Craiova, 2002;


[155] Tihomirov, P.M., Расчет трансформаторов, Энергоатомиздат, Москва, 1986;


[165] Yatchev, I., Modélisation numérique par la méthode des éléments finis, Seminar, University of Craiova, 2002;


http://www.acad.ro;
http://www.ansys.com/;
http://www.cedrat.com/;
http://www.ceeug.org;
http://www.cemtp.org/;
http://leemm.foster-miller.net;
http://www.lua.org/;
http://www.oscimize.com/fr/quickfield.htm;
http://www.ptc.com/;
http://www.quickfield.com/.
CURRICULUM VITAE

Full name: DOLAN Alin-Iulian

Nationality: Romanian
Date of birth, place: July 1st, 1971, Craiova, ROMÂNIA
Marital status: Single
Home address: Dr. Victor Papilian Str., No. 1, Bl. A3, Appt. 20
CRAIOVA, 200323, DOLJ, ROMÂNIA

Personal phone: + 40 351 426 259 (home)
+ 40 721 902 301 (mobil)

E-mail: adolan@elth.ucv.ro, alin_dolan@yahoo.com

Profession: Engineer, electrical domain
Place of work: University of Craiova, Electrical Engineering Faculty, ROMANIA
Function: Lecturer
Professional address: Electrical Engineering Faculty, Decebal Bd., No. 107, CRAIOVA, 200440, DOLJ, ROMANIA
Tel. / Fax: + 40 251 436 447
Office phone: + 40 251 435 724 / 127

Studies

<table>
<thead>
<tr>
<th>Type of diploma</th>
<th>Institution</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Certificate of linguistic training</td>
<td>French Institute of Sofia</td>
<td>2005</td>
</tr>
<tr>
<td>General French (378 hours) - level 7/12, level B1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scientific and Technical French (108 hours)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Certificate of Teachers Forming Department</td>
<td>University of Craiova</td>
<td>2002</td>
</tr>
<tr>
<td>Master Degree in Electrical Engineering, Ecological Technologies Specialization</td>
<td>Electrical Engineering Faculty, University of Craiova</td>
<td>1996</td>
</tr>
<tr>
<td>Degree in Electrical Engineering, General Electrical Engineering Specialization</td>
<td>Electrical Engineering Faculty, University of Craiova</td>
<td>1995</td>
</tr>
<tr>
<td>Baccalaureate Diploma in Electronics</td>
<td>High School Mathematics and Physics Nicolae Bălcescu, Craiova</td>
<td>1990</td>
</tr>
</tbody>
</table>

Professional experience

<table>
<thead>
<tr>
<th>Function</th>
<th>Institution</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lecturer</td>
<td>Electrical Engineering Faculty, University of Craiova</td>
<td>23.02.2009 - present</td>
</tr>
<tr>
<td>University assistant</td>
<td>Electrical Engineering Faculty, University of Craiova</td>
<td>25.02.2002 - 22.02.2009</td>
</tr>
<tr>
<td>Junior assistant</td>
<td>Electrical Engineering Faculty, University of Craiova</td>
<td>01.03.1999 - 24.02.2002</td>
</tr>
<tr>
<td>Teacher</td>
<td>Pop Service Electronic HQ, Craiova</td>
<td>01.04.1998 - 31.05.1998</td>
</tr>
</tbody>
</table>

Abstract of PhD. Thesis
Abroad stages

<table>
<thead>
<tr>
<th>Stage type</th>
<th>Institution</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>PhD. Training - University Agency for Francophonie (AUF)</td>
<td>International Engineering Doctoral School, Francophone Department, Technical University of Sofia Scientific coordinator: Prof. Ivan YATCHEV</td>
<td>31.03.2007 - 01.08.2007</td>
</tr>
<tr>
<td></td>
<td>National Polytechnic Institute of Grenoble, Electrical Engineering Laboratory of Grenoble Scientific coordinators: Prof. Gérard MEUNIER Prof. Albert FOGGIA</td>
<td>02.10.2006 - 30.03.2007</td>
</tr>
<tr>
<td>PhD. Training - University Agency for Francophonie (AUF)</td>
<td>International Doctoral School in Engineering, Francophone Department, Technical University of Sofia, Regional Network Engineering for Development (RESED) Scientific coordinator: Prof. Ivan YATCHEV</td>
<td>02.08.2007 - 01.09.2007</td>
</tr>
<tr>
<td>Program no. 5 - Scientific and institutional reinforcement of universities</td>
<td>French Institute of Sofia</td>
<td>01.10.2004 - 22.12.2005</td>
</tr>
</tbody>
</table>

Scientific experience

- 5 research contracts
- 15 scientific papers

Informatics competences

- MICROSOFT OFFICE, TURBOPASCAL, FORTRAN, C++, MATHCAD, MATLAB, QUICKFIELD, FEMM (LUASCRIPT), ANSYS (APDL), ATP-EMTP, FLUX

Teaching fields

- Electrical apparatus - applications
- Electrical equipments - applications
- CAD of Electrical Equipments - applications
- High Voltage Engineering - applications
- Theoretical Electrical Engineering - applications
- Computer programming and programming languages - applications
- Statistical Models and Reliability - course
- Reliability - course

Foreign languages:

- French: read, speak, write
- English: read, speak, write

13.11.2009        Signature: