Multiphysics Approach to the Boundary Problems of Power Engineering and Their Application to the Analysis of Load-Carrying Capacity of Power Cable Line

Nikolay Korovkin, George Greshnyakov, and Simon Dubitsky, *Member*, *IEEE*

***Abstract*—Many electrical problems involve the simultaneous solution of equations from different physical domains, i.e. require multiphysics solution. Multiphysics problems are typical for many electrical applications. Most of difficulties arising here are subject of study and classification. For example, for multiphysics analysis is typical to combine several physical models with different level of details. Another complicating factor is multiscaling, i.e. significant difference in space or time scale between different physical domains. The numerical strategy for multiphysics problem depends heavily on the assumptions made and level of physical details taken into account.**

In the paper some features of multidisciplinary problems are considered, typical problems are classified, and an approach to the solution is outlined. As a typical multiphysics problem we consider the modelling of current carrying capacity of underground three-phase power cable line. Such analysis demands the solution of the electromagnetic field equations, Kirchhoff's equations for grounding circuitry, and the heat transfer equations coupled together. Each physical domain can be modeled with appropriate level of details. Several variants of geometric location of single-phase cables of three-phase are considered: in line, in triangle, and with separation of one phase from two others. One-sided and two-sided grounding of cable shield and armor is taken into account.

The conducted study validates a number of the engineering simplifications, which are typical for multiphysics problems in the electrical engineering.

Index Terms—Finite element analysis, multiphysic analysis, cable insulation, cable shielding, grounding.

I. Introduction

Increasing worldwide competition brings to the fore the quality and reliability of electrical components and systems. This goal may be achieved by thoroughly multilevel testing of the equipment prepared to the market. From the other side, shortening the time to market leaves less room for physical experiments during development cycle. Such circumstances dictates further expansion of employing CAE (Computer Aided Engineering) tools. Concerning electrical engineering, this means the multiphysics numerical modelling and simulation.

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II. Multiphysics Simulation

The particular feature of most electrical equipment is that the model unavoidable combines phenomena from different physical domains. The phenomena includes but not limited to electromagnetism, heat transfer, fluid dynamics, and structural mechanics. This is quite clear for devices converting electromagnetic energy to heat, as well as for such devices, where the main limitation is allowable temperature. In addition, multiphysics model is vital for high power pulse systems, where the limitation often arises from allowable level of electrodynamic forces.

In most cases the electromagnetic field equation desirable, and sometimes necessary to solve simultaneously with the circuit equations. We may refer to two main reasons:

- An electrical device usually operates as a part of more complex system. In some cases such device, eg. brushless DC motor, by its principle of operation is inseparable from an electronic control circuit. Therefore, the complete mathematical model of such device combines field and circuit equations.
- Equivalent electrical circuit provides simple and well-developed model for many sophisticated devices and phenomena. The substitution of a complex equation system by an appropriate equivalent circuit greatly reduces the dimension of the problem preserving the accuracy of result.

When solving a multiphysic problem couples the equations from different physical domains, one should not only choose the appropriate numerical scheme for each partial problem, but also establish effective interface between domains. The typical features of coupled problems is the space and time multiscale. It means that the characteristic dimensions and time constants for coupled sub-problems may differ in several orders in magnitude. Further, the need of exchange data between sub-problems requires the calculation of intermediate variables providing the coupling.

III. The Classification of Coupled Problems

The thorough attempt of classification of coupled problems was done in [1]. In this paper the coupled problems are treated broader than only those that combining equations from different physical domains. The authors refers as

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coupled also the problems that includes equation from the same physical nature, but:

- The equation is solved simultaneously in domains with significantly different material properties. It is assumed here that the difference is high enough to provide different constitutive equations.
- More than one mathematical model is used for the same physics. For instance, with heat transfer analysis of an electrical machine the 2D FEA(two-dimensional finite element analysis) model in the cross section can be combined with equivalent thermal circuit with lumped elements for the axial heat fluxes.
- Coupled physical domains have very different time constants that imply non-homogenies time discretization schemes in different domains. Another option is using quasi-transient analysis [2], where for the slowest process (heat transfer) the truly transient analysis is used, whereas the rapid process (electromagnetic) is modelled as a gradually varying steady-state solution.

Another coupled problem classification is based on the link type between tasks:

- When strong (or direct) link is used, the space and time discretization scheme combines equations from different physical domains into the single matrix for simultaneous solution.
- The weak (indirect) link involves separate solution of the sub-problems, e.g. electromagnetic and heat transfer formulations, which are linked together by interface variables. The density of ohmic loss provides the link from electromagnetic to heat transfer analysis, whereas the calculated temperature is transferred in opposite direction to take into account the temperature dependency of resistivity.

A. Numerical Difficulties

Many physical phenomena are represented by partial differential equations (PDE) of the same or very similar nature. Such similarity suggests that the numerical procedure of modelling different phenomena in the same geometry should be quite similar. It is not always true by the following reasons:

1. The speed of different processes may greatly differ. For example, the time constant of electromagnetic, mechanical and thermal processes may be in range of microseconds, seconds and hours respectively.
2. It is typical the great difference in material constants. As result, the geometric domains for the process of one physical nature may come apart in a different way than for another process. This is especially important if the problem includes thin layers of material, small air gaps, crack, and so on.
3. To achieve appropriate accuracy one should have more dense mesh where the field gradient is high. Conversely, for saving time and memory the mesh should be coarse where the field is uniform enough. When solving a multiphysics problem, the mesh density requirements may greatly differ for different physical phenomena in the same space area. This problem is well recognized as a multiscale modelling. There exist extensive research in multiscale numerical math, considering both theoretical and practical aspects [3], [4].

B. Numerical Schemes

The family of known numerical procedures for solving multiphysics problem do not yet formed some unifying mathematical framework. In contrast, many known approaches strongly reflects their origin problem domain [3]. It is still an actual scientific goal to form an unified multi domain and multiscale numerical framework. Achieving this goal will make the data transfer across physical domains of the multiphysics problem more smooth and predictable.

Depending on the physical nature of multiphysics problem and of the type of link between domains, the following kinds of multiphysics formulation are used:

- *Single Model, Uniformly Multiscale*. The single system of equation is discretized on the same mesh for all physical domains. The multiscale difficulties are overcome by using variable mesh resolution in both space and time, either manually or by adaptive mesh refining.
- *Single Model, Non-Uniformly Multiscale*. If the problem contains areas, which significantly differ by scale, separate discretization is used for the same equations in each area. The equations solved on each separately meshed area should be stitched together across the borders. One possible approach considers closure method, where one model of the main scale of interest is completed by one or more auxiliary models of significantly less scale. The last ones may be analytical, surrogate and so on.
- *Multiple Models, Non-Uniformly Multiscale*. This approach consider several coupled models differ in both discretization and governed equations. Data transfer across the model is maintained by crosslinking or collocation. The main problem arises there is resolving model mismatch.

A common promising technique for all approaches listed above is the model reducing by means of orthogonal decomposition, stochastic and surrogate models.

C. The Software

The basic numerical methods for solving PDE are well established. Those included finite difference method (FDM), finite element method (FEM), methods based on the discretization of integral equations (eg. MoM), method of finite integrals (FIT), etc. The pros and cons of each, as well as preferred area of application is also well known [18].

Among the numerical approaches there is one, the area of application of which is much broader that others – the finite element analysis (FEA). Despite the fact that there are number of areas in which FEA does not take the primary position (eg. fluid dynamics, high frequency electromagnetics), in many other areas FEA is number one in the number of solved problems and the software tools available [1]. The main reasons of FEA dominance are following:

- The conservative of numerical scheme, which means that the discretized equations preserves the energy conservation law, the charge conservation law, and other conservation laws inherent in the continuous equations [6];
- The absolute stability, i.e. the approximate solution depends continuously on the equation right-hand side, provided the discretization step tends to zero; The stability of FEA follows from the formulation and do not require a formal proof [7];

- The ability to use unstructured mesh [6];
- The relative simplicity of use various constitutive equations, including nonlinear ones.

The particular feature of FEA is relative complexity of its software implementation. Strictly speaking, the complexity is not so much a feature of the method, but a consequence of the maturity of its commercial, public domain, and in-house implementations. It is an objective fact that the “price of entry” is relatively high because a list of components and numerical procedures that must be implemented. Those includes:

- Geometry editor for entering or importing a model geometry.
- The FEA mesh generator for chosen type of finite element. As N-dimensioned mesh generating requires first the meshing of all its borders of dimension N–1, it is a whole family of mesh generators on edges, faces and bodies.
- A database and user interface for setting and storing the material properties, border conditions and field sources of different physical nature.
- Generator of the FEA matrix consisting of FEA equation builder on the element level and assembling system. The resulting matrix is normally very large and sparse. It is practically impossible to store the matrix in memory wholly including zeroes. Therefore, any assembling and solving procedure is developed and assessed together with the storing scheme of the sparse matrix.
- The solver – a numerical procedure of matrix inversion, based on direct or iterative approach.
- Iterative procedure for solving the nonlinear problem.
- The postprocessor for the field visualization, extracting local and integral quantities.
- With multiphysics problem, it is necessary to identify and calculate interface variables for transferring to a coupled problem. Often the goal of simulation is not only the solving of a single problem, but also finding the optimal point or the trajectory in a space of input parameters. A comprehensive FEA software provides tools for optimization, sensitivity analysis, and solving inverse problem.

For multiphysics problems, especially those the software does not support directly, need extensive customizable tools for extracting and exchanging intermediate data between the sub-problems. In addition, it is quite necessary an embedded or external scripting language acting as a glue between the sub-problems and auxiliary calculations.

The technique of data exchange across the sub-problem is so important that it may be a good motivation for writing a new FEA software instead of a standard one solely in sake of convenient data exchange [8]. In the paper [9] is shown that the QuickField software is an appropriate choice for solving multiphysics problems thanks to the family of solvers for different physics, data transfer between problems, coupling to electric circuit, and extensive scripting support.

The rest of the paper demonstrates application of multiphysics approach to the problem of ampacity of the three-phase power cable line.

IV. Multiphysics Example: Power Cable Line Ampacity

Our subject is a three-phase power cable line formed by three single-phase cables. Each cable has the copper central conductor, the copper wire screen and aluminum strip armor. There are also semiconductive layers for electric field grading, but they do not play role in power ampacity. The sample is a buried line rated as 700 A, 35 kV.

The cable current carrying capacity is limited by maximal temperature of the cross-linked polyethylene insulation. The heat source is ohmic losses from the current in the central conductor as well as induced and circulating current in the screen and armor. The induced current depends on the cable internal geometry, insulation and soil thermal conductivity, mutual arrangement of the cables, and the grounding circuitry. We consider direct buried cable, but this approach also works for cables installed in air, in the thermal backfill, in the plastic pipe, and in a duct bank.

Without field simulation, the cable ampacity prediction is based on the IEC 60287 standard, summarizing the experience gained in many countries for decades. The IEC 287 standard relies on electrical and thermal equivalent circuit technique, developed for the power cabling in the 1950-th [11] and later generalized by J. G. Anders [12].

The FEA simulation of electromagnetic and temperature field promises to be more comprehensive and general, because do not rely on simplified field distribution. Early paper [13]–[15] considered the heat transfer simulation generated by a priory known field sources. Such approach is not able to take into account electromagnetics in full extent, namely the skin effect and proximity effect. In a later papers various approaches to the multiphysics problem were adopted. In [16] the electromagnetic part is modelled by means of equivalent circuit. In [17] FEA is used for both electromagnetic and thermal parts, but do not includes the grounding circuitry.

In comparison to equivalent circuit (IEC 287), the multiphysics FEA offers the following advantages:

- FEA can simulate both steady-state and transient operations, as well as emergency and asymmetric modes.
- FEA does not limit simulation the variety of real world cable installations – underground, in air, with thermal backfill, in duct and pipes and so on. The model may include several cable groups taking into account their electromagnetic and thermal mutual influence.
- The FEA model also predicts the magnetic field on the surface of the earth, which is limited in the habitable territory.

A. Problem Formulation

Generally, the problem includes the following physical domains:

1. Electromagnetic field produced by three-phase current system in central conductors taking into account induced currents in screen and armour.
2. Flow of the induced currents through the grounding system through the soil.
3. The heat transfer and dissipation from loaded conductors;
4. The fluid dynamics of the convective heat transfer above the ground surface.

Certainly, depending of the purpose of the simulation, some of above listed problems may be reduced. First, for many cable context the calculation of grounding current can be reduced to the equivalent circuit. Also in many common circumstances, the fluid dynamics equations can be substituted by the convective boundary condition. Actually, it means involving surrogate models. Setting the parameters of a surrogate model requires physical and numerical experiments and reach operating experience of cable lines.

The above simplifications are not mandatory for successful simulation. It is always a matter of right balance between the modeling cost and the benefits derived from more complex model. The model of grounding current flow is substantially 3D complicated by the following factors: a big difference of typical size of grounding conductor and the whole area, and uncertainty of such parameters as soil conductivity and contact resistance. Engineering analysis allows reducing the 3D FEA model of grounding by an electric circuit without loss of accuracy, but only within a particular task.

Thus, the reduced multiphysics problem includes three interconnected models: the 2D electromagnetic FEA model, the circuit model of grounding circuitry, and 2D FEA model of heat transfer. The latest one may be either steady state (continuous load) or transient (emergency condition such as symmetric or single phase short-circuit).

According to the above classification of multiphysics problem, the electromagnetic FEA model is strongly coupled with a grounding circuit: the field and circuit equations produce the same matrix, so the equations are solved simultaneously. In turn, the electromagnetic problem is coupled with a heat transfer problem by a one-way weak link. The generated ohmic losses are transferred from the electromagnetic model to the thermal one. If needed, the link can be made two-way, for correcting of the conductivity by calculated temperature.

Further reducing of complexity is eliminating the fluid dynamics problem. Instead, we apply the convective boundary condition on the ground surface. Two parameters govern the boundary condition – the ambient air temperature and the convection coefficient. Both of them are known with some uncertainty. Worse, they are not quite constant across space and time. As usually, a lot of operational data and numerical experiments are necessary for estimating the appropriate values and their affect to the overall accuracy.

The further assumptions and complexity reducing are the following:

- The modelling area is two-dimensional. Any inhomogeneity along the cable not taken into account.
- We neglect the fact that the screen and the armor is not solid, but is formed from copper wires and aluminum strips. The solid metal layer with particular conductivity replaces both screen and armour. For sake of preserving integral thermal conductivity and dissipation, it is better to keep unchanged the real thickness of metal layer. Consequently, we should proportionally decrease the electric and thermal conductivity of the copper and aluminum, to preserve the integral thermal conductivity of the layer.
- For sake of brevity, we neglect the dependence of conductivity on temperature.

The 2D FEA problem is solved in the domain shown in the Fig. 1.

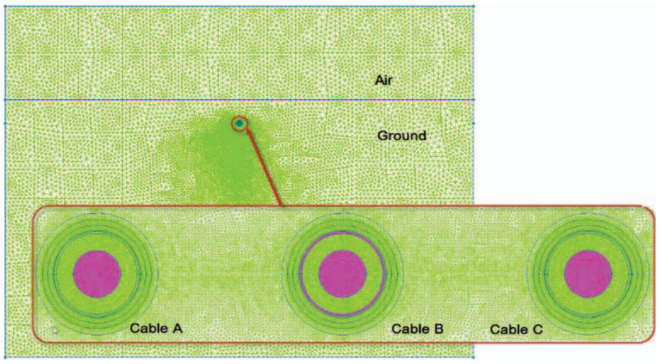


Fig. 1. The meshed 2D computational domain.

The electromagnetic and thermal problems has different requirements to the mesh density. The eddy current calculation in the thin solid screen requires several layers of finite elements across the screen thickness, whereas for heat transfer calculation a single layer is quite enough. Avoiding interpolation of interface variables from one mesh to another gives a good reason for using the same mesh for both problems, until the computational time increases inacceptable.

The electromagnetic problem is formulated with respect to the magnetic vector potential in frequency domain:

$$\nabla\left(\frac{1}{\mu}\nabla \mathbf{A}\right) = -j_{ext} + i\omega\sigma\mathbf{A} \qquad (1)$$

where μ – is permeability, (H/m), σ – specific conductivity (Sm/m), ω – the cyclic frequency (rad/s), **A** – complex magnetic vector potential (Wb/m), $\boldsymbol{j}_{ext}$ – density of external (source) current (A/m^2).

The field equation (1) is coupled with electric circuit equation needed for taking into account the grounding circuitry. The equation of a circuit branch associated with a solid conductor in the magnetic field is:

$$I = \frac{U}{R} - \sigma\int_{\Omega} i\omega\mathbf{A}\cdot ds \qquad (2)$$

where U is the voltage applied to the conductor's terminals, (V), R – the DC conduction of the conductor (Ohm). Integration is performed over the cross sectional area of solid conductor Ω.

The solution of (1) and (2) is the current density in each conductive media (the conductor, the screen, the armour). Calculated ohmic loss density is transferred to the heat transfer problem.

Then the heat transfer equation is solved on the same mesh:

$$\nabla\left(\lambda\cdot\nabla T\right) = -q - c\rho\frac{\partial T}{\partial t} \qquad (3)$$

where T – temperature (K), t – time (s), λ – thermal conductivity (W/(m·K)), c – specific heat capacity (J/(kg·K)), and ρ – mass density (kg/m^3).

The (3) is solved with the convection boundary condition on the earth surface. It is also possible to take into account the ambient solar radiation.

B. *Electromagnetic Analysis*

In practice, the cable line screen can be grounded with one side or both sides of the line. When the cable is equipped with an armour (Fig. 2), the last is always electrically connected with the screen on both sides of the line.

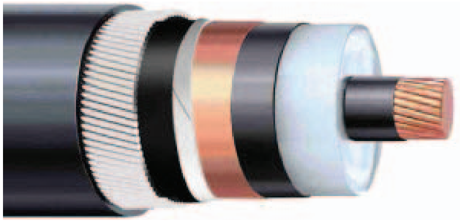
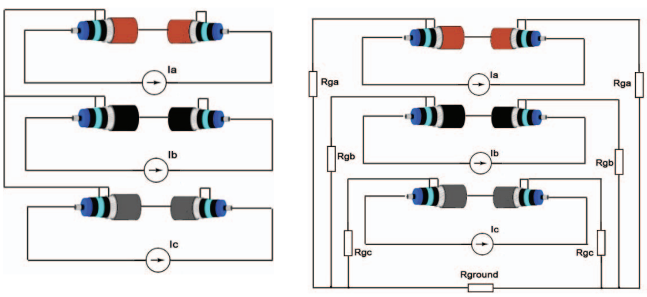


Fig. 2. The cable with the polyethylene insulation, copper screen and the armor of aluminum wires.

The grounding circuit is a reduced (surrogate) model with respect to the real grounding system that includes grounding conductors, surrounding soil and so on. As any surrogate model, it needs to be configured and assessed. Taking into account the resistance of grounding conductor is unavoidable, because it is a few Ohms, which is considerably greater than the resistance of 1 km length of a cable. We also include to the circuit the equivalent resistance of the ground between cable terminals (R_{ground} on the Fig. 3). We made numerical experiments varying with ground resistances in a wide range. The experiment shows that the grounding resistance cannot be neglected, but its value can be freely selected in the range from one to ten Ohms with no effect on the calculated power losses.

The wiring diagram with grounding is show on the Fig. 3. When the screen of the cable line is grounded at both ends of the line, the circuit included also grounding resistors and the resistance of the soil (Fig. 3b).

The example of calculated magnetic field shown on the Fig. 4. Sometimes there may be situations where, for various reasons cables are laid with a deviation from the project. In this case is necessary to estimate effect of the deviation on the ampacity. For example, on the Fig. 5 the magnetic field with one phase routed away from two others.



a) b)

Fig. 3. Wiring diagram with one-side (a) and two-side (b) grounding.

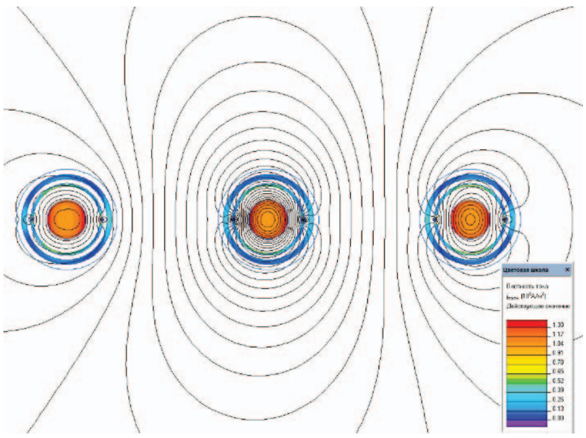


Fig. 4. Magnetic field lines and the current density with phase layout in line.

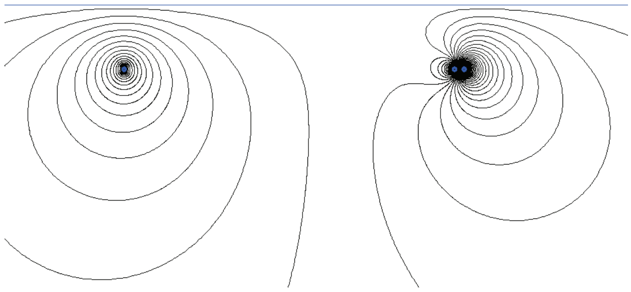


Fig. 5. The magnetic field when one phase is laid away from two others.

C. Heat Transfer Analysis

The interface variables that transferred from the electromagnetic analysis to the heat transfer are ohmic loss density, which are calculated taking into account the skin and proximity effects. Because we decide to forego the fluid dynamics analysis, we have to evaluate the convection coefficient. Empirical criteria equation gives the convection coefficient in range 1.7–6.3 W/(K·m^2) depending of the surface characteristic length. The numerical experiment shows that the middle value of this range can be selected with no risk for inaccuracy of the average temperature of the most heated conductor.

The temperature field patterns with cables laid out in line grounded at both ends of the line are shown on the Fig. 6.

The average conductor temperature of the cable laid away from others is by 8 deg. less than two others. The later in turn are by 6 deg. colder than those laid out in a normal way.

The difference of the average conductor temperature appears considerable enough to create an interphase asymmetry of resistances. The inductances of the phases as well as screen currents (or screen overvoltage when the screens are grounded at one side of the line) also differs. Such asymmetry should be assessed and taken into account.

We did a few comparative calculations of the ampacity of various power cable lines using both IEC 60287 and multiphysics FEA. The comparison shows that for many standard cable line configurations the FEA calculation gives the ampacity a bit more (in 8–12%) than IEC 60287. This trend persist with more complicated line configuration. Such phenomena still needs more detailed explanation, but we can guess that the main reason of difference is that electromagnetic FEA modeling gives more accurate heat calculation due to skin and proximity effects.

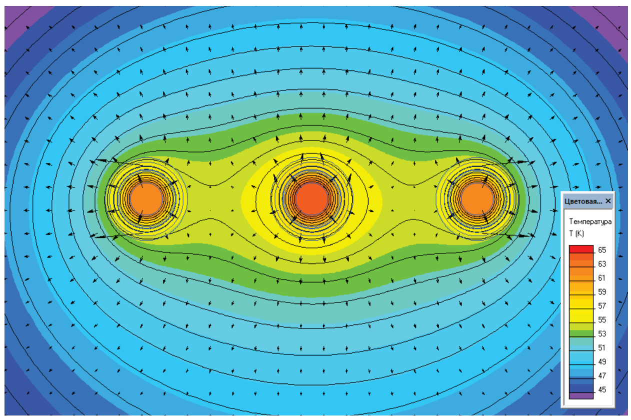


Fig. 6. The temperature field around cables laid out in line.

V. Conclusion

We have discussed a few different approaches of the using of multiphysics FEA to the modelling of electrical products. The classification of the multiphysics problem is given. Also we tried to discuss the potential difficulties and ways to overcome them.

The multiphysics FEA modelling is implemented for the ampacity prediction of the buried power cable line. Assumptions are discussed and the consequent numerical technique of the link between physical domains. The proposed approach takes into full account both electromagnetics and thermal interference cables to each other even with a non-standard layout of cables. This approach is also applicable to transient ampacity with a symmetrical and asymmetrical short-circuit.

In addition to the previous works the coupled field-circuit analysis is used for accurately account the screen grounding at one end and at both ends of the line.

The discussed approach is also applicable for transient analysis of cable lines in emergency conditions. The difficulty may arise here is the significant difference of electromagnetic and thermal time constants.

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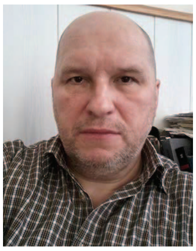

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Simon D. Dubitsky is currently with Tor Ltd, St. Petersburg. He receives MsC degrees in electrical engineering in 1983 and in computer science in 2003 both from SPbSPU. His main area of activity is development of QuickField FEA software in cooperation with Tera Analysis company locates in Svendborg, Denmark. Main research interest is implementing FEA as a handy tool for everyday engineering practice, advanced postprocessing of electromagnetic field solution, multiphysics FEA analysis coupled with circuit equations and surrogate models.