Electromagnetic field of the large power cables and impact on the human health

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Abstract: – In this work we survey our research on domain decomposition and related algorithms for large power electric cables and the impact on the human health. The equations that describe the behaviour of the fields in electromagnetic devices are coupled because most of the material properties are temperature dependent and may depend on temperature in a nonlinear way. More, any power loss is transformed in local heating so that the heat source in the thermal model is the Joule-Lenz effect of the electrical current. Here we assume that the sources of the magnetic field have sinusoidal time dependence and we neglect the effects due to the displacement currents.

The target example is from the electric engineering. It is a large power cable in a free space. General symmetry of the device can be used for efficient software. The algorithms for analysis are presented in the context of the finite element method. The results can be extended for simulation of distributed-parameter systems described by elliptic and parabolic equations.

The domain decomposition at the level of the problem is used. In this way the coupled magneto-thermal problem can be analyzed by a reduction of the computational effort.

Key Words – Electrical cables; Coupled fields; Finite element method; Bioheat equation.

1 Introduction

The physical systems have the energy distributed spatially. An accurate mathematical model for a given physical system is an equation or a set of equations with partial derivatives [1]. In some assumptions we model the real systems by ordinary differential equations where the theory and numerical algorithms are well developed. Generally, we speak about distributed parameter systems (DPS) where the mathematical models are partial derivative equations. The variety of the actual DPS and their mathematical models results in significant difficulties in analytical solutions so that the numerical models represent the basis of computer modelling [2].

Our work will concentrate on a large class of DPS from the engineering, called elliptic and/or parabolic systems. This class includes a lot of systems from the electrical engineering and mechanics described by elliptic and/or parabolic partial derivatives equations. Such systems are the electromagnetic devices where the mathematical models are very complex because of the natural interaction between more physical fields. Although the field quantities are vectorial variables, a scalar model is obtained for each component of the vectorial equation, or, by the potential formulation the field equations can be simplified.

Many physical systems with the energy distributed spatially in a domain Ω, are described by scalar or vectorial equation in the form ([4], [5]):

$$\frac{\partial u(t,x)}{\partial t} = \sum_{i,j=1}^{2} \frac{\partial}{\partial x_j}(a_{ij}\frac{\partial u}{\partial x_i}) + f(u) \qquad (1)$$
$$(x,t) \in \Omega \times (0,t_f]$$

where Ω is a bounded domain in R^2 with boundary C, and u is an unknown function. In Eqn. (1) variable x represents the spatial co-ordinates of a point from analysis domain, t is the time, and t_f is the final time of the time interval for analysis or control. Eqn. (1) is solved with a given initial condition and specified boundary conditions.

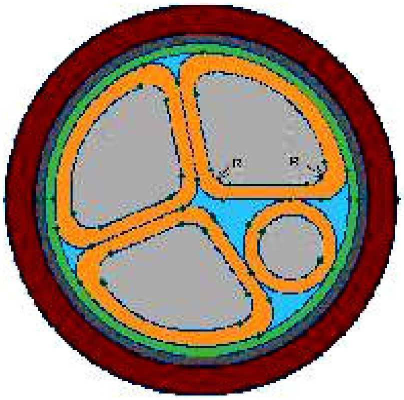
The time dependent electromagnetic field problems are usually solved using differential models of diffusion type. Many practical problems of great interest in electromagnetics involve time-harmonic fields and this case will be considered in this work.

In electrical power transmission and distribution, insulated power cables are widely used. The performance on power carrying capacity is determined by the heat dissipation.

Our target example is a large power cable where more physical fields interact so that we can not ignore the natural coupling of these fields [2]. Practically, an electromagnetic device is the house of electromagnetic, thermal and mechanical fields. An accurate model involves a coupled model and the development of the numerical algorithms for coupled problems. In some engineering application of the electrical cables, these operate with high power and high frequency currents. Under these conditions the current density is not unvarying in a cross section of the cables, but increases powerfully towards the periphery (skin effect). These aspects must be considered in an accurate analysis of the cables, especially in a dangerous environment without sufficient cooling. From a practical viewpoint of view the skin effect does not cause overheating locally, but it is important in the selection of the conductor material and the solution for the cooling.

2. A coupled magneto-thermal model

In the alternating current, the skin effect appears but in the most practical systems the conductor is stranded (that is made up several tightly wound strands of conductor insulated from each other) so as to force the currents to flow through the entire cross section of the conductor and thereby utilize the material better. Hence the validity of assuming uniform density as in direct current systems can simplify the computation.



F ig.1 – A cross-section of the cable

In large power cables as in Fig. 1, the proximity and skin effects can not be neglected so that in our analysis we consider them [10]. This high-voltage tetra-core cable has three triangle sectors with phase conductors and round neutral conductor in the lesser area of the cross-section above. All the conductors are made of copper. Each conductor is insulated and the cable as a whole has a three-layered insulation. The cable insulation consists of inner and outer insulators and a protective braiding (steel tape). The sharp corners of the phase conductors are chamfered to reduce the field crown. The corners of the conductors are rounded. Empty space between conductors is filled with some insulator (air, oil etc.).

Let us consider the coupled problem of the magnetic and thermal fields [12]. The magnetic field in A-formulation is described by the equation [1]:

$$\nabla \times (\nu\nabla \times A) + \sigma \frac{\partial A}{\partial t} = J_S \qquad (2)$$

where σ is the electric conductivity, ν is the magnetic reluctivity and J_s is the excitation current density.

This is the case of many practical engineering problems with geometric shape and size invariant in one direction. Let z denote the Cartesian co-ordinate direction in which the structure is invariant in size and shape. In this case the magnetic vector potential A has one component, which is independent of the z co-ordinate. In such a case both the magnetic vector potential and the source current J_S reduce to a single component oriented entirely in the axial direction and vary only with the co-ordinates x and y. Consequently, the component A_z (for simplicity we give up the subscript z) satisfies the diffusion equation [2]:

$$\nabla(\nu\nabla A) - \sigma \frac{\partial A}{\partial t} = -J_S \qquad (3)$$

The thermal field is described by the heat conduction equation ([7], [8]):

$$\frac{\partial}{\partial t}[(c\gamma)(T)\cdot T] + \nabla[-k(T)\cdot \nabla T] = q \qquad (4)$$

$$T(x,0) = T_0(x) \quad x \in \Omega \qquad (5)$$

where: T(x, t) is the temperature in the spatial point x at the time t; point k is the tensor of thermal conductivity; γ is mass density; c is the specific heat that depends on T; q is the density of the heat sources that depends on T; $T_0(x)$ is the initial temperature. In Eqn. (3) the heat source q represents the ohmic losses of the electrical current, that is:

$$q = \sigma(T)\cdot\left(\frac{\partial A}{\partial t}\right)^2 \qquad (6)$$

with σ the electrical conductivity of the material.

In 2D for a spatial domain with the boundary C as a reunion of disjoint parts C1, C2, C3 and C4, the boundary conditions for Eqn. (3) are [7]:

Dirichlet's condition:

$$T(x,y,t)\big|_{C_1} = T_D(x,y,t) \qquad (7)$$

Neumann's condition:

$$\left[k\frac{\partial T}{\partial n} + q_n\right]\Big|_{C2} = 0 \qquad (8)$$

Convection:

$$\left[k\frac{\partial T}{\partial n} + h(T - T_\infty)\right]\Big|_{C3} = 0 \qquad (9)$$

Radiation:

$$\left[k\frac{\partial T}{\partial n} + \varepsilon\sigma_B(T^4 - T_\infty^4)\right]\Big|_{C4} = 0 \qquad (10)$$

In these boundary conditions the significances of the parameters and quantities are: T_D is a known function; q_n is an imposed flux; T_∞ is the environment temperature or the cooling medium temperature; h is the convection heat transfer; ε is the emissivity and σ_B is Stefan-Boltzmann constant.

The equations of the electromagnetic fields and heat dissipation in electrical engineering are strongly and non-linear, since the magnetic material properties are temperature dependent and the heat sources depend on the electrical current density [1].

3. Domain decomposition method

Ones of the motivations for coupled problems are:

- Two or more physical systems interact
- Two or more physical fields co-exist in the same electromagnetic device
- The physical properties of the materials are strongly dependent on the temperature, especially the following characteristics: electric conductivity, magnetic permeability, specific heat and thermal conductivity
- The heat sources in thermal systems represent the Joule effect of the electric currents (driven currents or induced currents)

In the area of the coupled fields we define two levels of decomposition, that is, we define a hierarchy of the decompositions:

- One at the level of the problem
- The other at the level of the field

In our target example, we have a magneto-thermal system. The two physical fields interact strongly. For a numerical simulation, we decompose the coupled problem in two sub-problems: a magnetic problem and a thermal problem, each of them with disjoint or overlapping spatial domains. This is the first level of decomposition. At the next level, we decompose each field domain in two or more subdomains [3]. The decomposition is guided both by the different physical properties of the materials, and the difference of the mathematical models. Practically we have an elliptic-parabolic problem for the magnetic system [9]. In conducting parts of the cable system, the mathematical model of the magnetic system is a parabolic equation. In insulation the magnetic field is described by an elliptic equation [9].

It is obviously that a fully coupled model involves a simultaneous solution of the field equations. But we can use the physical considerations in numerical solution of the coupled problem. Thus, the time constants for the magnetic field and thermal field are different so that it is not necessary to update the material electrical properties for each temperature value. Consequently the steady-state of the magnetic field is computed for a large time step or the material electrical properties are updated at imposed temperature values. The temperature is computed at small time steps. A curve for the dependence of the electrical properties with the temperature can be included in a software product.

The analysis domain is not the same for the two fields. For the magnetic field we can consider the whole domain presented in Fig.1. For the thermal field we limit the analysis domain to the conducting parts.

4 Numerical results for coupled model

We shall present the results of the numerical simulation for the cable using the finite element method [10]. It is obviously that the current density is not uniform. The non-uniformity of the current density generates non-uniformity of the temperature distribution and local heating that destroys different parts of the system and finally, the whole system. Fig. 2 shows the temperature map of the cable using the Quickfield program [10].

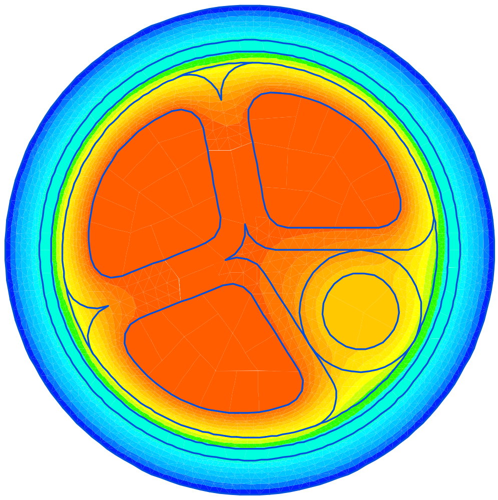


Fig. 2. The temperature map

The load of the conductors are currents of amplitude equal to 250 A at the frequency of 50 Hz. In post-processing stage of the FEM program, a lot of physical quantities can be obtained. They are of great importance for the electrical engineers in the evaluation of the device performance [2]. These derived quantities are presented in user’s manual of any software CAD .The voltage amplitude is 7000 V.

The non-uniformity of the temperature is due to the non-uniformity of the current density in system. In computation of the total current in the cable, the skin effect and proximity effect of the cable cores were not ignored.

Stress analysis problem is very important in a global analysis of the cable performance. A program for the stress analysis imports the temperature field from the heat transfer problem and the magnetic forces from the time-harmonic magnetic problem. The global effect is the deformation of the cable components. The displacement map and the vectors of displacements are shown in Fig. 3.

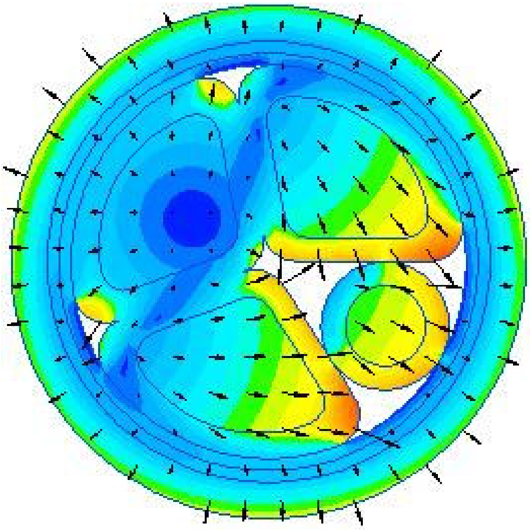


Fig. 3 Displacements map

5. Interactions between electromagnetic field and human body

We live in an electromagnetic-polluted environment. The exposure of the human body to ambient low-frequency magnetic fields results in an induced current density distribution in the weak conductive biological tissue. Possible sources of such fields can originate electrical power lines and domestic electrical devices [15]. The induced current densities inside the human body represent disturbances of the biological system including the nervous system in a holistic model. For the human comfort these disturbances must be reduced or eliminated.

The influence of the electromagnetic field on the human health is a major issue, not only for its implications on the definition of industrial standards, but also for medical research where the effects of the electrical currents induced in the human body are dangerous for the life and health of the people. It is well-known that the electromagnetic field is harmful for the human health. For this reason the governments have imposed some limitations to the authorized radiated fields by the power systems, especially in the electrical stations where the workers are daily exposured to an electromagnetic environment.

In all civilized countries the authorities have been proposed a set of maximum values of current density or specific absorption rate (SAR), according to the frequency. The restrictions refer to reference levels for the electromagnetic field. The problem is the estimation of these levels using computational techniques based on very simple models. Obviously the measured values of the field validate the computational results but in the design stage we must use mathematical models for the magnetic field and its effects, especially the Joule-Lenz's effect of the eddy-currents induced in the biological tissues.

In electrical engineering, the designers are focusing on electromagnetics, but a comprehensive model has to consider thermal processes due to Joule heat generation and the coolant flow. The motivation is simple: too many physical parameters depend on the temperature so that an uncoupled solution does not offer an accurate computation of the electromagnetic field.

The human body has a complicated structure, consisting of organs with varying dimensions and geometrically complicated shapes. More, the physical properties of the organs are different and depend on the electromagnetic field. If we compare the physical properties of the human body with the properties of the materials from the electromagnetic devices, we see a large difference. We must not forget that the water is the principal substance from the biological tissues so that a biological tissue can not be considered a conductor or a pure dielectric. A biological tissue can be compared with a dielectric with losses and can be represented as a heterogeneous and lossy dielectric, whose macroscopic electrical properties are described by complex permittivity.

It is known that the electromagnetic properties are highly depending on the frequency. Compared to classical dielectric materials, the permittivity of blood is very high: at 1 KHz, the relative permittivity of the blood is 435000 and decreases with frequency. The electric conductivity is low but different of zero.

5.1. A coupled model for human body

The reference levels of the electromagnetic field are obtained by measurement techniques but they are external values of the field. These values cannot take into account the field distribution in the human body and the environment of the exposed person. We must not forget that the human body is a complex system with internal properties that depend on each person.

An accurate estimation of the distribution of the field inside the body is necessary in order to give more acceptable limits to the reference levels or of the standard. The human body is the house of many fields that interact and these fields are electromagnetic field, thermal field and mechanical fields. In most cases, the problem is actually a coupled magneto-thermal problem because the thermal effect is one of the major effects of the electromagnetic field and the heat conduction equation (bioheat equation) depends strongly by the blood circulation.

Compared to the material usually used in classical electromagnetic systems from electrical engineering industry, the human body is made of a large number of materials, each of them having specific properties. A coupled model must be developed taking into account the particularities of this live complex system:

- The electrical properties of the biological tissues have very unusual electrical properties (especially electric conductivity and electric permittivity)
- The thermal properties depend on the temperature
- The physical properties depend on the person activity
- The human body is an active material at the cell scale
- The geometry is complex and generally environment of the human body has to be taken into account.

The determination of the physical properties in biological tissues is a crucial problem for numerical simulation of the interaction between electromagnetic field and biological tissues. This is an open problem [13].

It is not the goal of this work to present different viewpoints of the health and disease because there is a long history and sometimes there are opposing viewpoints. In this area two opposing viewpoints of health and disease have been evident since ancient times. The holism was defined [8] as: "*The tendency in nature to form wholes that are greater than the sum of the parts through creative evolution*". Concept led on to General Systems Theory where the system is viewed more than the sum of its parts and there are hierarchical and interacting organisations.

In a coupled magneto-thermal model, the magnetic field is described by Maxwell's equations and the thermal system is defined by the heat conduction with its special form which is Pennes bioheat equation. The difficulties of estimation of physical properties of the biological tissues can lead to wrong results of the numerical simulation.

5.2. Thermal model of the human body

In professional literature a measure of the energy absorption is the Specific Absorption Rate (SAR) that offers a measure of the internal fields which could affect the biological tissue without heating [13]. SAR is defined as:

$$SAR = \frac{\sigma |E|^2}{\rho_m} \tag{11}$$

where σ is the electrical conductivity (S/m), E is the mean-root-square magnitude of the electric field (V/m) and ρ_m is the mass density (Kg/m^3) of the tissue at that point.

For harmonically varying fields, the SAR in a coordinate system Oxyz is defined as

$$SAR = \frac{\sigma}{2\rho_m}\left(|E_x|^2 + |E_y|^2 + |E_z|^2\right)$$

where E_x , E_y , and E_z are the peak values of the electric field components, σ and ρ_m, denoting the conductivity and the mass density of the tissue, respectively.

For calculating temperature increases in the living tissue, the Pennes bioheat equation based on the classical Fourier's law and has the generalized form:

$$\rho c \frac{\partial T}{\partial t} = \nabla(k \nabla T) + \omega_b \rho_b c_b (T_a - T) + q_{met} + q_{ext} + \rho \cdot SAR \tag{12}$$

Here, ρ, c, k and $T(x, t)$ denote density, specific heat, thermal conductivity and temperature of tissue in point x at the time t. The density, specific heat, and perfusion rate of blood are denoted by ρ_b, c_b and ω_b, respectively. The heat source is denoted by q and represents the sum of two components: q_{met} which is the metabolic heat generation in the skin tissue and q_{ext} is the heat source due to external heating. T_a is the arterial temperature and it is regarded as a constant and equal to 37 ^{0}C.

For localized exposures, T_a is simplified as a constant, since the electromagnetic power absorption is much smaller than the metabolic heat generation. The boundary condition between air and tissue for Eqn. (2) is given by the following equation:

$$-k \left.\frac{\partial T}{\partial n}\right|_{skin} = h(T_\infty - T) + Q_e \tag{13}$$

where n is the outward normal at the boundary of computational domain, h is the heat transfer coefficient and T_∞ is ambient temperature and Q is the heat loss due to sweat evaporation. The heat transfer coefficient h is given by the summation of radiative heat loss h_{rad} and convective heat loss h_{conv}.

The effect of blood perfusion rate has a significantly large influence on temperature distribution during cooling than that during heating. In general, the skin temperature decreases with an increasing blood perfusion rate. And the environment factors can have an important influence in the thermoregulation of the human body [14].

5.3. Simplified geometrical models of the human body

The models of the human body in a computer-aided analysis of the interaction between electromagnetic field and human body can be included in the classes:

- Complex models (Multi-segmented models)
- Simplified models

Complex models [17] divide the body into many segments as in fig. 4. The disadvantage of these models is: a large amount of empirical data is required to simulate each segment of the body ([17], [12]).

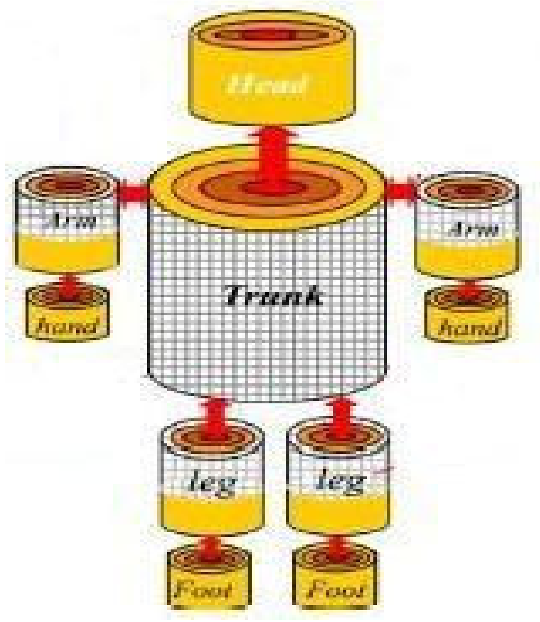


Fig. 4 Schematic of the multi-segment model

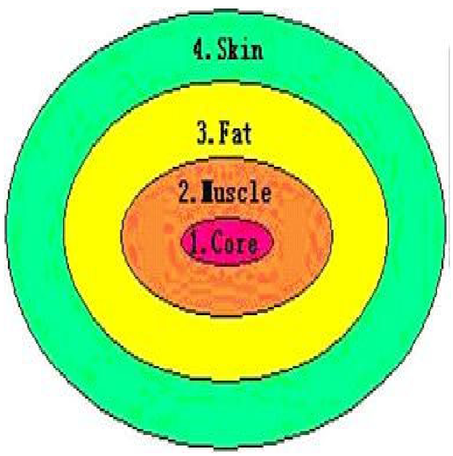


Fig. 5 A cross-section of a body part

The model of the Fig. 4 is based on the division of the human body in more cylindrical segments. The cross-section of a segment is presented in fig. 5. Each segment is a multi-layer model presented in Fig.6. It is obviously that we have covered parts and uncovered parts of the human skin [11]. The clothing is considered an insulation layer in the interaction of the human body with the environment.

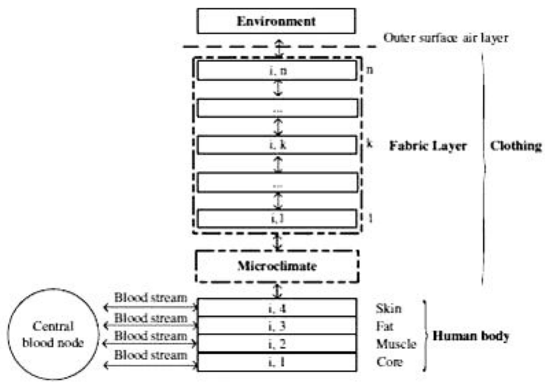


Fig. 6 Unclothed human body segment ***i***

In the class of the simplified models, Gagge's two-node model is commonly used for evaluation of human body thermal response and prediction of thermal sensation under transient personal and environmental conditions [16]. The body is represented by two concentric cylinders in this model as in Fig. 7.

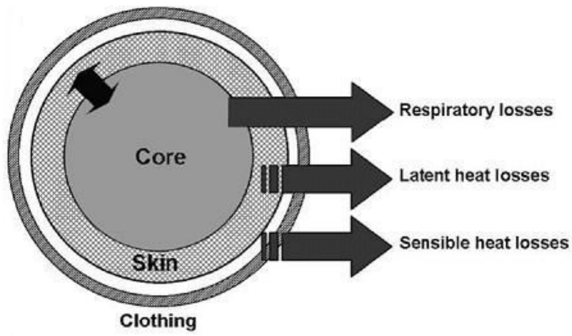


Fig. 7. - A simplified model

The outer cylinder represents the outer layer of the body (skin and its related tissues). The inner cylinder represents the inner parts of the body consisting of skeleton, muscles and internal organs. These inner and outer cylinders are respectively called "core" and "skin" compartments of the body. The clothing system is simulated as an overall insulation over the whole body.

The national systems for energy distribution include substations that operate at high voltages and currents so that the resultant electric and magnetic fields are high. Consequently the risk of the adverse health effects is increased. The electromagnetic environment at substations is very complex because it includes multiple lines, conducting metallic structures, buses and other current-carrying elements with variable current values. But a lot of people work in this environment so that a control of the electromagnetic field level is imposed by international standards in order to protect the health and life of the humans and animals.

Commonly used in bioelectromagnetics, the SAR measures the power absorbed by tissues, its unit is W/kg and can be calculated from the *E* field generated by the variable magnetic field in biological tissues of the human body. The influence of human body shape on the whole body SAR must be estimated because the real body is deformed. There is a relation between the height, weight and SAR of the whole body. The inverse problem is that from a given value of SAR we must find the level of incident field above which the absorption exceeds the limits of safety recommendations.

5. 4. A simplified mathematical model for the human body simulation

A complete physical description of electromagnetic field is given by Maxwell's equations in terms of five field vectors: the magnetic field **H**, the magnetic flux density **B**, the electric field **E**, the electric field density **D**, and the current density **J**. In low-frequency formulations, the quantities satisfy Maxwell's equations:

$$\nabla \times \boldsymbol{H} = \boldsymbol{J}$$
$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial \boldsymbol{t}}$$
$$div\ B = 0$$
$$div\ D = \rho_C$$

with ρ_c the charge density, σ – the electric conductivity, and μ the magnetic permeability. For simplicity we give up to the bold notations for vectors.

The second set of relationships, called the constitutive relations, is for linear materials:

$$B = \mu H;\ D = \varepsilon E;\ J = \sigma E$$

The problem in a power station is the determination of the electric fields and currents that are induced inside a human body standing at different locations. The difficulty is the model selection of the human body. In reference [12] the human body is simulated as a spheroid (with a height of 2*a* and width of 2*b*). A Cartesian coordinate system is used. The human height is taken in the *Y*-direction while the width is taken in the *X*–*Z* plane. In accordance with Maxwell's laws, a variable magnetic field described by the flux density B produces an internal electric field with the body and consequently an induced current. The following formulas are used [15]:

$$E_x = j\omega\left(\frac{zB_y}{2} - \frac{kyB_z}{1+k}\right)$$
$$E_y = \frac{j\omega}{1+k}(xB_z - zB_x)$$
$$E_z = j\omega\left(\frac{kyB_x}{1+k} - \frac{xB_y}{2}\right)$$

where E is the internal induced electric field; E_x, E_y and E_z are the three components of the internal induced electric field; B_x, B_y and B_z are the three components of the external magnetic field; $k = (b/a)^2$ and ω is the angular frequency of the alternating external magnetic field.

In accordance with Faraday's law, an induced electrical current is produced. Its density is

$$\overline{J} = \sigma \overline{E}$$

where σ is the electrical conductivity of the human body.

In this analytical model there is the possibility to analyze the effects of different geometrical and physical parameters of the human body. Thus, effects of the incident angle of the external magnetic field, the height and width of the human body can be considered.

5. 5. A numerical model for the thermal field

It is obviously that all phenomena depend on the time so that a complete numerical model must include a discretization scheme for the time variable. When applying the FEM to time dependent problems, the time variable is usually treated in one of two ways:

- Time is considered as an *extra dimension* and shape functions in space and time are used
- The *nodal variables* are considered as *functions of time* and the shape functions in space are used.

A common approach for transient problems is to solve time dependent partial differential equations by finite differences approximation of time derivative terms, combined with some weighted residual method in space.

A widely used finite difference scheme for the first-order equations is the so-called θ-rule. Certain values of θ correspond to well known methods for time stepping:

θ =0	the forward difference method;
θ =1/2	Crank-Nicholson's method;
θ =2/3	central difference method;
θ =1	the backward difference method.

We illustrate the method by applying the θ-rule in time and Galerkin method in space for bioheat equation in a simplified form:

$$\rho c\frac{\partial T}{\partial t} = \nabla(k\nabla T) + \omega_b \rho_b c_b (T_a - T) + Q \quad (14)$$

where Q includes all heat sources.

For a typical time interval $[t_{m-1}, t_m]$ we approximate the temperature T(x, t) and its derivative with respect t by a finite difference method [18]. This strategy begins with the time discretization of the mathematical model by a finite difference method.

$$T(x,t) = \theta.T^{(m)}(x) + (1-\theta)T^{(m-1)}(x)$$

$$Q(x,t) = \theta.Q^{(m)}(x) + (1-\theta)Q^{(m-1)}(x)$$

$$\frac{\partial T}{\partial t} = \frac{T^{(m)} - T^{(m-1)}}{\tau}; \quad \tau = t_m - t_{m-1}$$

where the superscripts *m* and *m-1* refer to subsequent time instances and τ is the time step size.

Applying this rule to the bioheat equation (14) results in the following sequence of spatial problems:

$$T^{(0)} = T_0(x); \quad x \in \Omega \quad (15)$$

$$(\rho c)\frac{T^{(m)} - T^{(m-1)}}{\delta t} = \theta\nabla(k\nabla T^{(m)}) +$$

$$(1-\theta)\nabla\cdot(k\nabla T^{(m-1)}) + +\omega_b \rho_b c_b (T_a - T^{(m)}) \quad (16)$$

$$+ \theta Q(x,t_m) + (1-\theta)Q(x,t_{m-1})$$

where superscript *m* represents the index of the time moment. The boundary conditions are discretized in the same manner. For example, a Neuman boundary condition is approximated as

$$-k\frac{\partial T^{(m)}}{\partial n} = h(x,t_m); \quad x \in \partial\Omega \quad (17)$$

Now we do the approximation:

$$T^{(m)} = \sum_{j=1}^{r} T_j^{(m)} N_j(x)$$

where $T_j^{(m)}$ are constants to be determined by the method, and $N_j(x)$ are linearly independent shape functions. The N_j functions span a vector space with finite dimension. In our research we used the finite element grids consisting of linear triangles.

Discretizing the equations (16) by the method of weighted residuals gives a system of algebraic equations for every time step. At each time step we must solve a linear or non-linear system and this is a serious disadvantage in 3D problems.

5.6. A thermal wave model

In computer-aided analysis of the skin tissue temperature rise or estimation of the burn caused by spatial heating such as the electromagnetic apparatus or high-voltage lines, equation of the bioheat must include the heat source due the electromagnetic energy absorbed by tissue. In the professional literature there are some mathematical models based on the wave equation. Thus, in reference [19] a wave model is included in the bioheat equation. For example, if we consider a semi-infinite tissue exposed to incident electromagnetic wave, the right hand in bioheat equation includes a term Q_r defined by formula [19]:

$$Q_r(x,t) = \frac{2I_0\Lambda}{\delta} e^{-\frac{2x}{d}U(t)}$$

where I_0 is the power density of incident electromagnetic wave (W/m^2), Λ is power transmission coefficient between air and tissue, d is penetration depth, and U(t) is the unit step function. The SAR within the tissue can be computed for different particular cases. Thus, for a plane uniform electromagnetic wave incident normally to the skin surface, the SAR can be computed as $Q_r(x, t)/\rho$, where ρ is the density [kg/m^3].

6 Software for coupled fields

The coupled problems are natural problems because of some major motivations:

- Two or more physical systems interact
- Two or more physical fields co-exist in the same electromagnetic device
- The physical properties of the materials are strongly dependent on the temperature, especially the following characteristics: electric conductivity, magnetic permeability, specific heat and thermal conductivity
- The heat sources in thermal systems represent the Joule effect of the electric currents (driven currents or induced currents)

Application software for time-varying problems can be classified into two classes:

- time-domain programs
- frequency-domain programs

First class has the following characteristics:

- Time-domain programs generate a solution for a specified time interval at different time moments
- A large amount of data that must be stored to recover the field behaviour.

The second class is characterized by:

- Frequency-domain programs solve a problem at one or more fixed frequencies
- We obtain a compact and a cheap program in terms of the computer resources
- It is applicable only to linear problems (all phenomena are sinusoidal)

A finite element program for coupled problems has a modular form. The block diagram is presented in fig. 6. Finite element method (FEM) involves three stages:

- Pre-processing
- Solution or processing
- Post-processing

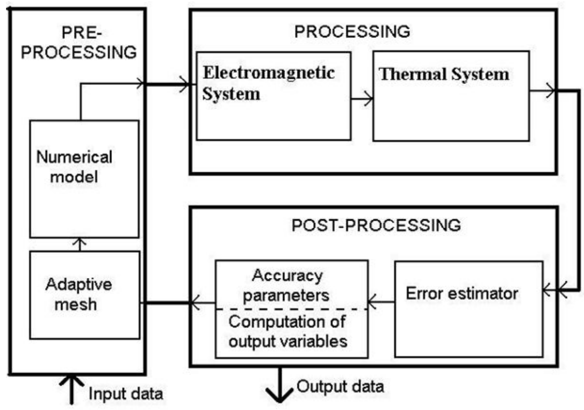


Fig. 8. – Block diagram of a CAD software

7 Conclusions

The influence of human body shape on the whole body SAR must be estimated because the real body is deformed. There is a relation between the height, weight and SAR of the whole body. The inverse problem is that from a given value of SAR we must find the level of incident field above which the absorption exceeds the limits of safety recommendations

The analysis of distributed parameter systems is a complex problem so that the analytical solutions can not be obtained. Many practical engineering problems involve geometric shape and size invariant in one direction. In the case of the electric cables we considered the axis Oz as the co-ordinate direction in which the structure is invariant in size and shape. This is the case of *a plane-parallel field* or *translational field* problem, where A has one component.

The model of large power cable is a combination of an electromagnetic, a thermal, a mechanical and a hydraulic part. The interconnection of the four parts is given on the one hand implicitly by the temperature dependence of the material constants, on the other hand explicitly by the heat sources in the thermal model controlled by the Joule heating in the electromagnetic model.

Domain decomposition offers an efficient approach for large-scale problems or complex geometrical configurations [12]. This method in the context of the finite element programs leads to a substantial reduction of the computing resources as the time of the processor.

Although we limited the presentation to the domain decomposition considering physical properties of the field problem, the partitioning of the domain can be performed according to the mathematical models of the field problem (operator decomposition).

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