REPORT ON THE SCIENTIFIC ACTIVITIES OF THE POWER ENGINEERING GROUP AT THE DEPARTMENT OF ELECTROMAGNETIC THEORY OF THE TECHNICAL UNIVERSITY OF BUDAPEST*

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Abstract

The paper summarizes the results of the research work of the power engineering group at the Department of Electromagnetic Theory of the Technical University of Budapest in the fields of network analysis and electromagnetic field calculations.

About twenty-two years ago, at the Department of Electromagnetic Theory of the Technical University of Budapest a group had been formed by the staff members who read lectures and kept practical lessons on the subjects taught by the department primarily for undergraduates in the Section of Power Engineering. It has been a constant aim of this group to deal with research fields which are, as far as possible, applicable to the solution of practical problems of power engineering. Naturally, the scientific results achieved are capable of a more general application.

The scientific topics of this group are, in accordance with the special line of the department, electric network and field theory as well as problems falling under both of these categories. Initially, the employment of analytical methods dominated but later, making use of the possibilities given by computers, numerical methods have gained a greater role.

The results achieved are presented in four groups, namely:

A Transmission lines and transmission line systems

B Application of graph theory to the calculation of electrical networks

C Calculation of electromagnetic fields by numerical methods

D Other results

The results of the research work in group A could also be classified in part into group B and in part into group C.

* Dedicated to Prof. Károly Simonyi septuagenarian

A Transmission lines and transmission line systems

After initial considerations, the telegraph equations are usually written for transmission lines. These equations include voltages, currents, resistances, conductances, inductances and capacitances. In our relevant research work, field theory considerations lead to known results but the limits of these could also be established and for certain transmission line parameters (inductance, capacitance) definitions more accurate than the well-known ones could be given [1, 2].

At power transmission lines, the effect of earth can be taken into account by the Carson formula. Since, in practice, the phase conductors are cyclically interchanged, the asymmetry is disregarded in the calculations i.e. the mutual impedance of any two conductors can be assumed to be equal and, similarly, the impedance of each conductor is equal, too. The aim has been set to calculate the stationary phenomena on power transmission lines with asymmetry (without interchange of phases). To this end, it has been found to be necessary to determine the conditions of earth back-flow transmission lines with an accuracy higher than the one yielded by known methods [3, 4]. The results permitted the establishment of the cases with the Carson approximation applicable.

Thereupon, the theory of parallel, coupled transmission lines was investigated [4, 5, 6, 7, 8]. Certain aspects of this topic had already been discussed in the literature earlier but with results not general enough.

With the simultaneous application of the above results, the theory of lossy power transmission line systems above earth has been founded [4, 5, 6, 7, 8]. A numerical method could be established on the basis of these results for the computation of the subterranean electric field [9, 10].

A model of a 750 kV transmission line has been built at the Institute for Power Engineering of the Technical University of Budapest. Several parameters of the model were determined with the aid of the above theory founded by us.

A further step was taken by the establishment of the theory of the stationary operation of transmission line networks [11, 12]. The apparatus of graph theory was employed to this end. Graph theory methods are known for the calculation of lumped element networks. In transmission line networks, transmission lines and lumped element two-poles modelled by Thevenin- or Norton-equivalents are interconnected. By graph theory concepts, a method has been found for the calculation of such networks. The results are also well applicable to transmission line systems used in telecommunication [13, 14].

The theory of transmission line systems and transmission line networks above earth has been also generalized for networks consisting of multiphase power transmission lines and lumped elements [4, 5, 6, 15, 16].

Parts of the above results have also been published in books [4, 5, 6].

B Application of graph theory to the calculation of electrical networks

An important part of the research and educational work of the power engineering group has been constituted by the investigation of the applicability of graph theory and the solution of related problems. Graph theory permits to write computer codes capable of solving the general analysis problem of networks interconnected of certain types of elements in different ways. One aim of the research work was to modernize the educational material of this topic.

The application of graph theory, as mentioned above, permitted to solve the analysis problem of transmission line networks in stationary operation. It has further been employed for the determination of certain network parameters as e.g. input impedance and admittance matrices [5, 6, 17]. For the computation of the currents and voltages of reciprocal and nonreciprocal linear networks including coupled two-poles as well, two methods have been established which are also applicable to electronic circuits assumed to be linear.

One method employes controlled generators [5, 6, 18], the other uses nullors [5, 6, 19] in the model of the network. To this end, the equivalent circuits containing nullors of two-ports have been also given [5, 6, 20, 21, 22, 23]. A method has also been worked out for writing the state equation of networks not containing controlled sources and later also for ones containing controlled sources. In the latter case, both the models containing the controlled generators and the ones including nullors have been used [24, 25, 26].

By the employment of signal-flow graphs, a method has been established [6, 27, 28, 29] which permits the determination of the response signals of both continuous and sampled-data signal networks in a way substantially simpler than the well-known Mason formula.

C Calculation of electromagnetic fields by numerical methods

About fifteen years ago, in the research work of the power engineering group, the numerical methods of electromagnetic field computation have gained dominance. The target was set to obtain experiences with several methods. The following methods have so far been employed:

1. Galerkin method
2. Methods based on variational principles
   2.1 Global element method
   2.2 Finite element method
3. Integral equation methods
4. Finite difference method
5. Computation by series expansion

A summary of the problems solved by the above methods is presented in Table 1.

At the application of each method, the approximate solution of the two-dimensional Laplace–Poisson equation with Dirichlet and Neumann boundary conditions was first treated. Accordingly, the solutions involved the electric scalar and vector potentials φ^e and $\mathbf{A}^e$ as well as the magnetic scalar and vector potentials φ^m and $\mathbf{A}^m$. Recently, results have been obtained in the solution of three-dimensional problems, too.

In the course of the calculations, several theoretical questions had to be clarified.

Three theoretical problems of electromagnetic field theory had to be solved which were not directly connected to any of the numerical methods.

For the application of variational principles, functionals have been derived [30] for use at the various domains of electrodynamics (e.g. for the calculation of the fields arising in lossy media), all of which involved Neumann type boundary conditions as natural boundary conditions (Table 2).

It has been investigated how to define the boundary conditions on the vector potential $\mathbf{A}$ to obtain the unique solution for a time-varying electromagnetic field problem [31]. According to our results, the function $\mathbf{nA}$ and curl $\mathbf{A} \times \mathbf{n}$ or $\mathbf{n} \times \partial \mathbf{A}/\partial t$ and div $\mathbf{A}$ have to be prescribed on the boundary. ($\mathbf{n}$ is the normal unit vector of the boundary.)

It could be ascertained that the general solution of Maxwell equations can be described by a vector potential with one of its three components identically zero [32].

In the following, the problems solved are presented in the order of the methods used.

Galerkin method

At the Galerkin method, the solution φ of the equation

$$L\varphi = y$$

with the operator L linear is approximated by an expansion of the elements of an entire function set. In order to obtain the coefficients in the expansion, the scalar product of the equation written with the approximate solution is taken with the elements of an entire function set. (The two entire function sets may coincide.) With the aid of the scalar products, a set of linear equations is derived for the coefficients in the expansion approximating φ.

The clarification of the theoretical and practical problems of the method is all the more important, since the same problems arise at variational and integral equation methods. If at a variational approach, no functional is found leading to the problem considered, the Galerkin method is still capable of

Table 1

Problems solved and methods used

Type of problem	Scope of application	Methods							Remarks
			Variational			Integral equations			
		Galerkin	Finite element	Global element				Finite difference	
				Reduced to N. type	R functions	Ritz–Gal.	Boundary element		
Static electric field	General computer codes	×	×	×	×	×	×	×	Inhomogeneous medium anisotropic medium programs for field plotting
Stationary electric field	General computer codes	×	×	×	×	×	×	×	Nonlinear, inhomogeneous medium, anisotropic medium, programs for field plotting
Stationary magnetic field	General computer codes D.C. machine, iron extracting equipment	×	×	×	×	×			Nonlinear, inhomogeneous medium, anisotropic medium, programs for field plotting
Quasy-stationary field	Wires of arbitrary cross-section, asynchronous machine, transformer leakage field, kilowatthour meter, eddy currents in laminated iron, end-region of turbogenerator, linear motor	×		×	×				Inhomogeneous, anisotropic medium, programs for field plotting
Electro-magnetic waves	LPD antenna, waveguides	×	×			×			Programs for field plotting
Problems coupled with nonelectric phenomena	Ionisator, eddy current break, kilowatthour meter	×		×		×		×	Programs for field plotting

Table 2

Functionals

Electric potentials	Magnetic potentials

Vector + scalar potential

Electric potentials — $\mathbf{J}_v^e$ is known

$$I_h^e=\int_0^t\int_V\left[\mathbf{A}^e\mathbf{J}_v^e-\varrho^e\varphi^e+\frac{\varepsilon}{2}\left(-\operatorname{grad}\varphi^e-\frac{\partial\mathbf{A}^e}{\partial\tau}\right)^2-\frac{1}{2\mu}\operatorname{rot}^2\mathbf{A}^e\right]\mathrm{dVd}\,\tau+\int_0^t\oint_S[\mathbf{A}^e\mathbf{K}^e-\sigma^e\varphi^e]\,\mathrm{dS\,d}\tau$$

Magnetic potentials

$$I_h^m=\int_0^t\int_V\left[\mathbf{A}^m\mathbf{J}_v^m-\rho^m\varphi^m+\frac{1}{2\varepsilon}\left(-\operatorname{grad}\varphi^m-\frac{\partial\mathbf{A}^m}{\partial\tau}\right)^2-\frac{\mu}{2}\operatorname{rot}^2\mathbf{A}^m\right]\mathrm{dV\,d}\tau+\int_0^t\oint_S[\mathbf{A}^m\mathbf{K}^m-\sigma^m\varphi^m]\,\mathrm{dS\,d}\tau$$

Electric potentials — $\mathbf{J}_v^e=\sigma_v^e\mathbf{E}$

$$I_h^e=\int_0^t\int_V\left[\mathbf{A}^e\sigma_v^e\left(-\operatorname{grad}\varphi_p^e-\frac{\partial A_p^e}{\partial\tau}\right)+\frac{\varepsilon}{2}\left(-\operatorname{grad}\varphi^e-\frac{\partial\mathbf{A}^e}{\partial\tau}\right)-\frac{1}{2\mu}\operatorname{rot}^2\mathbf{A}^e\right]\mathrm{dV\,d}\tau+\int_0^t\oint_S[\mathbf{A}^e\mathbf{K}^e-\sigma^e\varphi^e]\,\mathrm{dS\,d}\tau$$

Vector potential

Electric potentials

$$W^e=\int_V\left[\mathbf{A}^e\mathbf{J}^e-\frac{1}{2\mu}\operatorname{rot}^2\mathbf{A}^e\right]\mathrm{dV}+\oint_S\mathbf{K}^e\mathbf{A}^e\mathrm{dS}$$

$$\mathbf{J}^e=\mathbf{J}_v^e-\varepsilon\frac{\partial^2\mathbf{A}_p^e}{\partial\tau^2}+\frac{1}{\mu}\operatorname{grad}\operatorname{div}\mathbf{A}_p^e$$

$$\mathbf{J}^e=-\sigma_v^e\frac{\partial\mathbf{A}_p^e}{\partial\tau}-\varepsilon\frac{\partial^2\mathbf{A}_p^e}{\partial\tau^2}+\frac{1}{\mu}\operatorname{grad}\operatorname{div}\mathbf{A}_p^e$$

Magnetic potentials — $\mathbf{J}_v^m=0;\quad\mathbf{J}_v^m=\sigma_v^e\mathbf{E}$

$$W^m=\int_V\left[\mathbf{A}^m\mathbf{J}^m-\frac{1}{2\varepsilon}\operatorname{rot}^2\mathbf{A}^m\right]\mathrm{dV}+\oint_S\mathbf{A}^m\mathbf{K}^m\mathrm{d}S$$

$$\mathbf{J}^m=-\mu\frac{\sigma_v^e}{\varepsilon}\frac{\partial\mathbf{A}_p^m}{\partial\tau}-\mu\frac{\partial^2\mathbf{A}_p^m}{\partial\tau^2}+\frac{1}{\varepsilon}\operatorname{grad}\operatorname{div}\mathbf{A}_p^m$$

Complex form

$$W(\mathbf{a},\mathbf{a}^*)=\int_\Omega[-\mathbf{f}^+\mathbf{a}\mathbf{f}^+\mathbf{a}^*j\omega\mu\sigma_v^e-\operatorname{rot}\mathbf{f}^+\mathbf{a}\operatorname{rot}\mathbf{f}^+\mathbf{a}^*]\,\mathrm{d}\Omega+\oint_l\mu\mathbf{K}^e\mathbf{f}^+\mathbf{a}^*\,\mathrm{d}l$$

yielding an approximate solution. If the functional is known, the two methods may lead to the same set of linear equations.

It has been established for the application of the Galerkin method, what are the conditions on a function set defined in Cartesian coordinates to be entire [31, 33]. The existence of a set of trigonometric functions has been shown which is entire in the Lebesgue sense but not entire in the Sobolev sense although it can be made to be entire.

The Galerkin method has been applied to conductors moving in magnetic field, namely to compute the braking force due to eddy currents in a linear motor [34] as well as to obtain the eddy currents in the disc of a kilowatthourmeter [35].

This method has also been applied to the examination of an ionisator. A program package has been developed for modelling the ion source and to calculate the ion flow. The motion of air has also been taken into account at the analysis of ion flow.

Methods based on variational principles

An electromagnetic field problem can be solved in a variational way by establishing a functional with its first variation vanishing at the solution of the relevant equation.

Functionals have been obtained for the various spheres of electrodynamics with the Neumann boundary condition as their natural boundary condition (Table 2). This means that at the zero variation of the functional the potential satisfies not only the relevant differential equation but also the Neumann boundary condition specified.

The establishment of a functional for sinusoidally time varying fields presented some problems.

Global element method

At the global element method, the function sought is approximated by the same expansion in the entire region examined. The coefficients of the expansion are determined from extremum conditions. Two methods are employed for taking boundary conditions into account. In case of one of these, the differential equation to be solved is transformed to have the function sought satisfy homogeneous Dirichlet boundary condition. This is approximated by an expansion with all of its terms fulfilling homogeneous Dirichlet boundary condition. Such functions can be formulated if the curve bounding the planar region examined can be described by the equation $f(x_1, x_2)=0$ with the function $f(x_1, x_2)$ nonzero within the region. Functions suitable for the approximation can be derived by the method of Rvachev even if the curve constituting the boundary of the region can be composed of or approximated by sections described analytically [36, 37, 38, 39, 40, 41, 42].

This method has been used for the development of computer programs for two-dimensional electrostatic, stationary magnetic and stationary electric fields in piecewise homogeneous media, too and also for quasi-stationary field in homogeneous medium. The programs are suitable for problems with translational or axial symmetry. Field distributions of a few problems thus solved are shown in Figs 1 and 2.

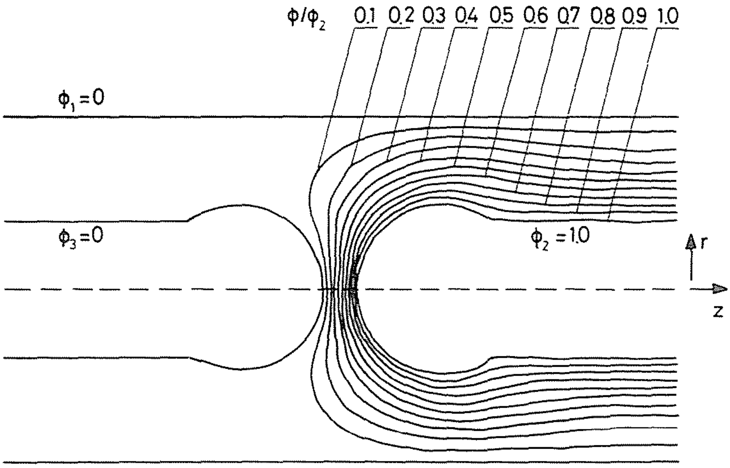

Fig. 1

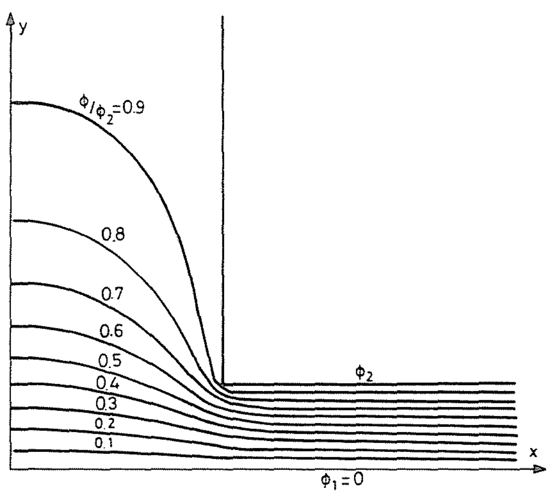

Fig. 2

In case of the other method used for taking boundary conditions into account, the Dirichlet boundary condition is reduced to a Neumann one [30]. This is of the advantage that the boundary condition presents no further problem since it is now a natural boundary condition of the functional.

This latter method has been used to develop computer programs for the computation of static and stationary fields in nonlinear and anisotropic media,

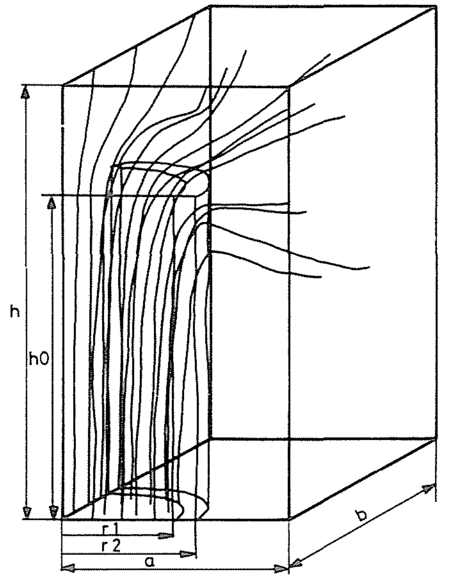

Fig. 3

too. It has also been employed to compute three-dimensional stationary magnetic field (Fig. 3).

Numerous quasi-stationary field problems can be solved by the programs developed. So, for example, the skin phenomenon in conductors of arbitrary cross-section, the proximity effect of parallel conductors can be examined [43] (Fig. 4). In these cases the field in the isolators surrounding the conductors has been assumed to be approximately described by a potential function satisfying Laplace equation.

Programs have also been developed for computing eddy currents. So, calculations have been carried out for eddy currents in homogeneous conductors [31] and in laminated iron cores when the inducing magnetic field is perpendicular to the plane of the lamination [44]. In the latter case, the conductivity of the plate is described by a tensor pertaining to an anisotropic medium.

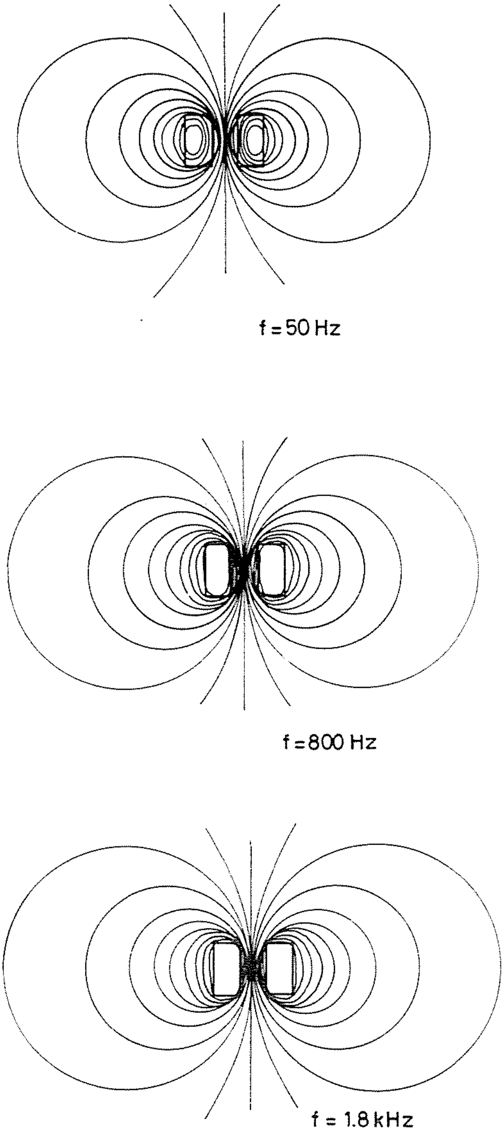

Fig. 4

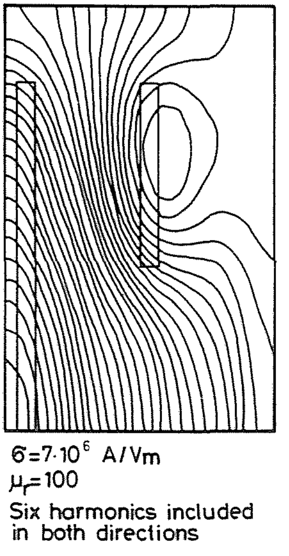

Fig. 5

The method has also been applied to structures of greater complexity. So, a program has been developed for the computation of the magnetic field of an asynchronous machine [45, 46], of the leakage magnetic field in the end-region of a synchronous machine [31]. At the computation of the leakage field of a transformer, the eddy currents in the transformer tank can also be taken into account (Fig. 5).

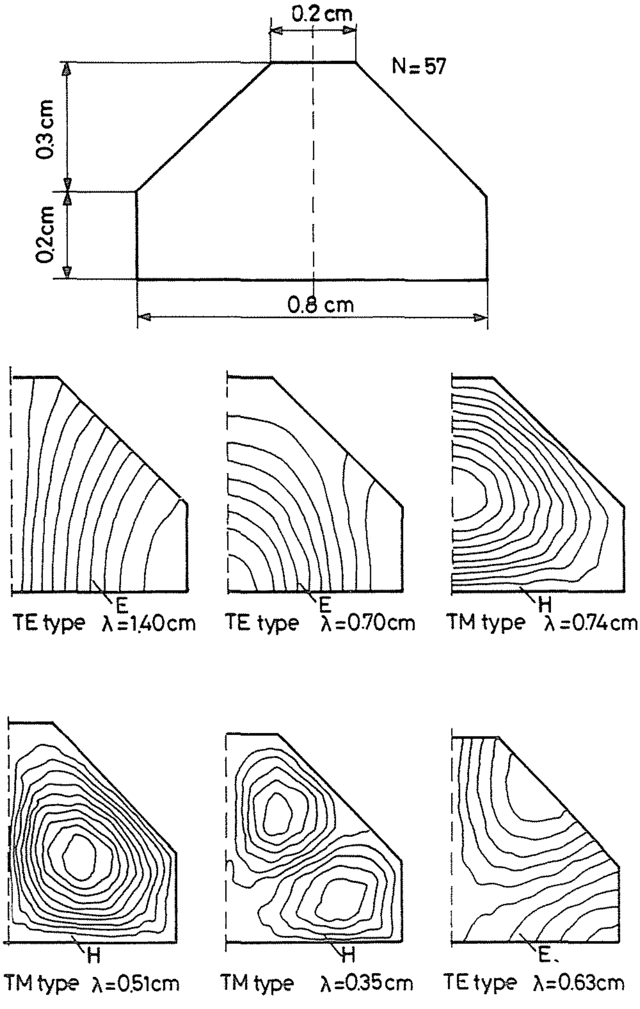

Fig. 6

Finite element method

At the application of the finite element method, the planar region is divided into triangular elements, and the function sought is approximated in the triangles by linear functions. The potentials in the nodes of the triangles are approximately obtained from extremum conditions.

Having computed static and stationary fields, the calculation of the electromagnetic field of waveguides with homogeneous medium has been carried out [47]. In the course of this, the integrals to be evaluated could be expressed analytically with the nodal potential values.

Integral equation methods

The foundation of integral equation methods is that the ensuing electromagnetic field can be regarded to originate from surface charges on the boundary in case of Neumann boundary condition and from a double-layer in case of Dirichlet boundary condition. A Fredholm integral equation of the second kind can be derived for the surface charge density or the moment of the double-layer. This can be approximately solved by Galerkin or boundary element method.

In order to determine the electromagnetic field of a logperiodic dipole antenna, the current distribution of the dipoles can be calculated by the solution of a Hallén type integral equation [48, 49, 50, 51, 52]. In the knowledge of the current distribution, characteristics can also be computed.

Finite difference method

At the finite difference method, the planar region examined is divided by a rectangular grid. It can be shown that the potential of each grid node can be approximately expressed by a simple formula with the aid of the potentials of the neighbouring grid nodes. This results in a set of linear equations for the node potentials.

Initially, this method was applied to the solution of electrostatic field problems and later it has also been used to solve a compound problem of electric field and heat transport [53]. In recent years, this method has lost its importance in our work.

Computation by series expansion

The subterranean electromagnetic field of power transmission lines can be written by a Fourier integral. The integral has been approximated by series expansion [9, 10]. This work is connected to the research of transmission lines.

It is noted that graphic programs for plotting lines of force or equipotential lines have been developed for each method employed. The methods are also applicable in case of inhomogeneous medium. The Galerkin method has been applied to the development of a program for the calculation of the field in nonlinear and anisotropic medium, too. Problems have also been solved where, besides the electromagnetic field, other physical phenomena (e.g. mechanical motion, electronemission, convective flow) had also to be taken into account.

In October 1985, at the IGTE Symposium '85 in Graz (Austria) twenty-four papers were read. The participants were among the European scholars on numerical field computation and all of them took part in the Symposium on a personal invitation. The fact that four of the papers were read by members of our group demonstrates the international acknowledgement of our results in this field.

D Other results

Besides the above topics, scientific results have been achieved by us on other fields, too. The more important ones are:

a) The theoretical foundations of the decomposition into symmetrical components has been clarified [54, 55].
b) For a simple conductor placed in the slot of an electrical machine, a method more accurate than the one known in the literature has been established for the calculation of the electromagnetic field and the impedance [56, 57].
c) The paper presenting the classification of electromagnetic waves on the basis of the nature of the propagation coefficient obtained a Virág–Pollák award [58].
d) Network models of electrical machines have been established which take account of both electrical and mechanical phenomena. The models contain sources, nonreciprocal two-ports and passive two-poles. Their application also permits the investigation of transient phenomena in machines and machine groups [59, 60, 61, 62, 63, 64, 65, 66]. The models can be analyzed by the graph theory procedures worked out.

It is noted that some of our research work has been carried out for industrial application.

The research work of the members of the power engineering group has been documented so far by 52 papers in Hungarian, 79 papers in foreign languages, 5 books, 27 university lecture notes and 6 dissertations.

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