Journal of ELECTRICAL ENGINEERING, VOL. 52, NO. 9-10, 2001, 253–263

SOLUTION OF PARTIAL PROBLEMS IN ELECTRICAL MACHINES, APPARATUSES, DRIVES AND POWER ELECTRONICS

Ladislav Hruškovič — Ľudovít Klug — Ľudovít Hüttner
Neitus Lipták — Ferdinand Valent
Ladislav Borba — Ľudovít Jurčacko *

The paper presents partial results of the Department of Electrical Machines and Devices staff members - solving equations of the field-harmonic theory of the induction machine, transformer leakage inductance explanation, solving some problems of synchronous motors with permanent magnets using the final element method and simulation, solving the temperature distribution in the electrical contact, breakdown of small air-gaps and behaviour of breaking arc in the extinguishing chamber of MCB, analysing the influence of equipment containing semiconductor devices on the supply network and the methods of their compensation.

K e y w o r d s: theory of induction machines, leakage inductance, synchronous machines design, contact temperature, small air-gaps breakdown, MCB, active filters

1 INTRODUCTION

The development in the area of electromechanical energy conversion was in the last period strongly influenced by a fast progress of information technologies, electronics and automation. The design of electrical machines and apparatus has been influenced also by the development of new materials, by using miniaturisation, automatic manufacturing and assembling. New mathematical methods and computer programs allowed a higher, even new quality of research and development.

In the contribution some picked-up problems from the area of electric machines, apparatus, drives and power electronics achieved in the Department of Electrical Machines and Devices are presented briefly. The field-harmonic theory of the induction machine presented in the paper describes more complexly its properties as till now and partly also offers a new view at the differential leakage reactance of induction machines. A new approach to the transformer leakage inductance explanation is presented. Further, a method of electromagnetic design of permanent magnet synchronous motors, using FEM and simulation procedures, is referred.

The solution of the temperature field in a switchgear electric contact, mathematical and physical model for breakdown voltage calculation of small air-gaps between contacts, which theoretically verifies the deviation from the Paschen's curve are presented. The problem of short-circuit current breaking in extreme conditions is solved by the design of a new arrangement of contact and extinguishing subsystems.

The wide application of semiconductor devices in power networks causes their contamination with higher harmonics. Suppression of this influence is solved by applications of various kinds of filters. Results of the application of active filters and their design are presented.

2 PARTIAL PROBLEMS OF INDUCTION MACHINES AND TRANSFORMERS

2.1 The field-harmonic theory of induction machine

The field-harmonic theory of the induction machine was derived. The field-harmonic theory is the theory of an induction machine with respect to the real shape of the magnetic field in the air gap of the machine.

In the field-harmonic theory the real shape of the air gap magnetic field is substituted by the field harmonics.

If the stator current of an induction machine is sinusoidal, a magnetic field arises in the air gap, which consists of a infinite number of field harmonics. Each of these field harmonics induces a harmonic current in the rotating rotor, whose frequency depends on the order of the field harmonic which induced this current and on the slip. Each of these harmonic currents creates a rotor magnetic field, which again consists of the infinite number of field harmonics. Each of these rotor field harmonics induces harmonic current in the stator winding, whose frequency depends on the order of the field harmonic, inducing this current and on the slip. From the magnetic field of the

* Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Department of Electrical Machines and Devices, Ilkovičova 3, 912 19 Bratislava, Slovakia,

ISSN 1335-3632

Table. 1 Equations of the field-harmonic theory of a three-phase induction machine with a squirrel cage on the rotor

$$U_1 = \left(R_1 + jX_{\sigma 1} + jX_{m1} \sum_{k_1=-\infty}^{\infty} \frac{k_{w\lambda 1}^2}{k_{w1}^2 \lambda^2} \right) \Bigg|_{\lambda=6k_1+1} \mathbf{I}_{0,1} + jX_{m1} \sum_{k_1=-\infty}^{\infty} \frac{k_{w\mu 1} k_{s\mu} k_{w\mu 2}}{k_{w1} k_s k_{w2} \mu^2} \Bigg|_{\mu=6k_1+1} \mathbf{I}'_{k1,2} \tag{1}$$

$$\begin{aligned} 0 = & \left(R_{k2,1} + js_{k2} X_{\sigma k2,1} + js_{k2} X_{m1} \sum_{k_1=-\infty}^{\infty} \frac{k_{w\lambda 1}^2}{k_{w1}^2 \lambda^2} \right) \Bigg|_{\lambda=6k_1+2k_2g+1, k_2=const\neq 0} \mathbf{I}_{k2.1} + \\ & + js_{k2} X_{m1} \sum_{k_1=-\infty}^{\infty} \frac{k_{w\mu 1} k_{s\mu} k_{w\mu 2}}{k_{w1} k_s k_{w2} \mu^2} \Bigg|_{\mu=6k_1+2k_2g+1, k_2=const\neq 0} \mathbf{I}'_{k1,2} \end{aligned} \tag{2}$$

$$\begin{aligned} 0 = & \left(R'_{k1,2} + js_{k1} X'_{\sigma k1,2} + js_{k1} X_{m1} \frac{1}{k_s^2} \sum_{k'_2=-\infty}^{\infty} \frac{k_{w\mu' 2}^2 p^2}{k_{w2}^2 \mu'^2} \right) \Bigg|_{\mu'=k'_2 Q_2 + (1+6k_1)p \neq 0, k_1=const} \mathbf{I}'_{k1,2} + \\ & + js_{k1} X_{m1} \sum_{k_2=-\infty}^{\infty} \frac{k_{w\lambda 1} k_{s\lambda} k_{w\lambda 2}}{k_{w1} k_s k_{w2} \lambda^2} \Bigg|_{\lambda=2k_2g+6k_1+1, k_1=const} \mathbf{I}_{k2,1} \end{aligned} \tag{3}$$

$$s_{k2} = 1 + 2k_2 g\big(1-s\big) \qquad s_{k1} = 1 - \big(1+6k_1\big)\big(1-s\big) \tag{4}$$

$\mathbf{I}_{0,1}$ - the stator current of network frequency f, $\mathbf{I}_{k2,1}$ - the stator current of the higher frequency $s_{k2}f$, $\mathbf{I}'_{k1,2}$ - the rotor current of the frequency $s_{k1}f$ referred to the stator winding, $R_1, R_{k2,1}$ - stator resistances, $X_{\sigma 1}, X_{\sigma k2,1}$ - stator leakage reactances, $R'_{k1,2}, X'_{\sigma k1,2}$ - rotor resistances, rotor leakage reactances referred to the stator winding, λ - order of the stator harmonic, μ, μ' - orders of the rotor harmonics, X_{m1} - the main reactance of the first harmonic, $k_{w1}, k_{w\lambda 1}, k_{w\mu 1}$ - stator winding factors, $k_{w2}, k_{w\mu' 2}, k_{w\lambda 2}$ - rotor winding factors, $k_s, k_{s\mu}, k_{s\lambda}$ - skew factors, 2p - number of the poles, Q_2 - number of the rotor bars, s, s_{k2}, s_{k1} - slips.

rotor current of one frequency arises then an infinite frequency spectrum of stator currents in the stator winding.

Substantial however is, that there is only one frequency spectrum of the stator currents induced by the magnetic field of the rotor current of any frequency. Merely the same frequency is induced in the stator winding from the magnetic field of each rotor current of certain frequency by other field harmonic. The same is valid for the frequency spectrum of the rotor currents. This is the principle of the field-harmonic theory.

The field-harmonic theory of an induction machine is an infinite system of equations, where the unknowns are the stator and rotor currents of all frequencies, which, due to rotating rotor, arise as the consequence of the non-sinusoidal distribution of the air gap magnetic field.

The field-harmonic theory of an induction machine was first published in the Journal of Electrical Engineering [1]. The short view of the derivation of the field-harmonic theory is in [2].

Equations of the field-harmonic theory of a three-phase induction machine with a squirrel cage on the rotor, (1) to (4), are summarized in Tab. 1.

The shortened fraction $\frac{Q_2}{p}$ can be written as $\frac{a}{b}$. Then $g=a$ when a is odd and $g=\frac{a}{2}$ when a is even.

Further

$$\mathbf{I}'_{k1,2} = \frac{Q_2}{3} \frac{k_s k_{w2}}{N_1 k_{w1}} \mathbf{I}_{k1,2} \tag{5}$$

$$R'_{k1,2} = \frac{3}{Q_2} \left(\frac{N_1 k_{w1}}{k_s k_{w2}} \right)^2 R_{k1,2}$$

$$X'_{\sigma k1,2} = \frac{3}{Q_2} \left(\frac{N_1 k_{w1}}{k_s k_{w2}} \right)^2 X_{\sigma k1,2} \tag{6}$$

The leakage reactances X_σ in the equations are the reactances only of a slot leakage and an end-turn leakage. They do not include the differential leakage. The conception of the differential leakage in the field-harmonic theory is not necessary at all, because both the first harmonic and the higher harmonics are a part of the main field.

On the other side the equations of the field-harmonic theory can be used for the strict physical definition of the differential leakage reactance in the theory, where as the main field is taken only the first harmonic [2].

If the rotor of an induction machine does not rotate, then the stator and rotor currents are sinusoidal. But (as a consequence of the non-sinusoidal distribution of the air gap magnetic field) non-symmetrical systems of stator and rotor currents can arise also in the case, that the system of terminal voltages is symmetrical. In this case equations of the field-harmonic theory can be transformed into a finite system, where the unknowns are directly the symmetrical components of the stator and rotor currents [2].

2.2 Transformer leakage inductance

A new approach to the transformer leakage inductance explanation, based on the division of the magnetic field of each winding into a common field and a leakage field was presented [2].

The common field is defined as the flux density (field) lines that are linked by all the turns of primary and secondary windings. The essential part of this field is formed by these lines, close as a whole, through the iron core. This field is the main bearer of the inductive coupling between the windings. The leakage field is defined as the flux density (field) lines from which no one is linked by all turns of both windings. Beside this, these flux density lines, whole or most part of them, pass through the air or through the material with air-like permeability. That means through a medium with remarkably lower permeance than that of the iron core.

It was shown that the leakage inductances determined by so defined leakage field are the leakage inductances also from the point of view of the leakage factor.

3 PERMANENT MAGNET SYNCHRONOUS MOTORS

Permanent magnet motors have a broad field of application, in the industry as industrial drives, robots, in the transportation as drives of electric cars, in information equipment as drives of discs of personal computers, printers, plotters, in domestic life as kitchen equipment, in the aerospace and medical and healthcare equipment. The efficiency of the permanent magnet machines in comparison with dc and ac induction machines is higher.

The dc excitation of the field winding in a synchronous machine can be provided by permanent magnets. The choice of permanent magnets for a motor is influenced by factors such as the motors performance, weight, size, efficiency, material and production specialities. There are different arrangements of permanent magnets in the rotors of synchronous motors. The surface mount arrangement is popular and simple for production and with high coercivity rare earth magnets that are not easily susceptible to demagnetization. Other arrangement of the magnets is shown in Fig. 1, where the magnets are embedded, buried in the rotor. This arrangement will allow a bigger surface of magnet than the surface mount magnet arrangement and there is space for flux focusing. The magnets are asymmetrically distributed in the rotor, therefore for this case of arrangement it is difficult to calculate the form factor of the field. It is better to use FEM to determine the amplitude of the first harmonic and other harmonics.

3.1 Sizing procedure and main dimensions

To determine the main dimensions of a synchronous motor let we start from the maximum electromagnetic power developed by a permanent magnet synchronous motor. The maximum power is expressed as follows [3, 4, 5]

$$P_{\max} = \frac{\pi^2}{2}\frac{\xi B_r}{k_f}\frac{H_c}{k_{ad}\,(1+\varepsilon)} f V_m, \tag{7}$$

where ξ is the coefficient of utilization of the permanent magnet, k_t is the form factor of the rotor excitation flux, k_{ad} is the d-axis armature reaction factor, $\varepsilon = U_{ip}/U_1$ is the ratio of induced voltage to input voltage, B_r is the remanent magnetic flux density, H_c is the coercive force, V_m is the volume of all permanent magnets in the motor.

When using the overload capacity factor equal to two, the output power P_{out} of the motor is a half of the maximum power P_{max}, therefore the volume of all permanent magnets of the motor is at given output power of the motor

$$V_m = \frac{P_{out}}{f B_r H_c}\frac{4}{\pi^2}\frac{k_f}{\xi} k_{ad}(1+\varepsilon). \tag{8}$$

The inner stator diameter D_{1in} can be estimated from the apparent power crossing the air-gap of the machine. On introducing the output power P_{out}, stator line current

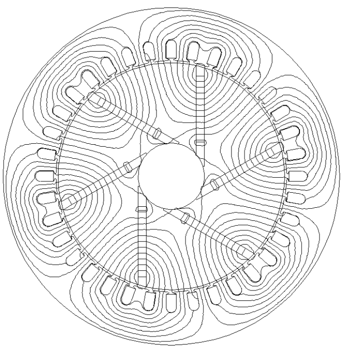

Fig. 1. Embedded magnets rotor motor

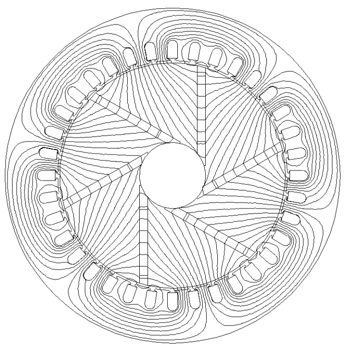

Fig. 2. Map of the armature reaction magnetic field in d-axis direction

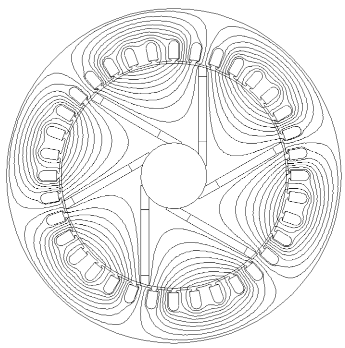

Fig. 3. Map of the armature reaction magnetic field in q-axis direction

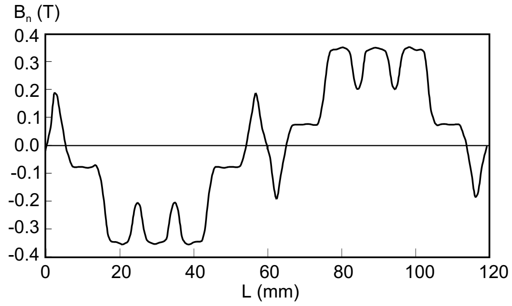

Fig. 4. Flux density line in the air gap in d-axis direction

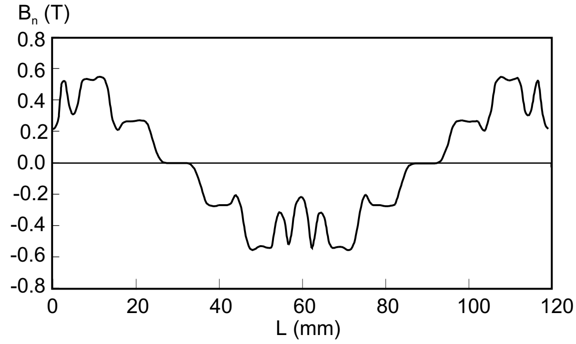

Fig. 5. Flux density line in the air gap in q-axis direction

density A_m, flux density in the air gap B_g, the product $D_{1in}^2 L_i$ takes the form

$$D_{1in}^2 L_i = \frac{P_{out}}{\sigma_p} \frac{\varepsilon}{n_1}, \tag{9}$$

where the coefficient σ_p expresses the electric and magnetic utilisation of the machine

$$\sigma_p = \frac{1}{2} \pi^2 k_{w1} A_m B_g \eta \cos \varphi. \tag{10}$$

For the rotor with buried permanent magnets asymmetrically distributed in the rotor, according to Fig. 1, it is difficult to determine the form factor of the excitation field k_f and the form factor of the armature reaction field in d - axis direction k_{fd} and the resultant armature reaction factor $k_{ad} = k_{fd}/k_f$ analytically. Therefore in special asymmetrical cases the FEM modelling of the magnetic fields is used.

Modelling the map of the excitation magnetic field in the machine on no load condition is also shown in Fig 1. Modelling of the map of the armature reaction magnetic fields in the d - axis and q - axis direction is shown in Figs 2 and 3, and the normal component of the flux density line in the air gap of the machine in the d - axis and q - axis directions is shown in the Figs 4 and 5. The coefficients necessary to determine the magnetic conditions of the machine are extracted from the lines of the magnetic flux density distribution in the d - axis and q - axis direction by means of Fourier analysis.

3.2 Simulation of dynamic behaviour of the machine

A circuit model of a permanent magnet motor, which is used for predicting its transient behaviour, can be obtained using equivalent circuit representation for permanent magnets. The magnetic field produced by the permanent magnets is created by a field coil which is passed by excitation current I_f . The field coil inductance is the common d-axis mutual inductance of the stator L_{md} and the current I_f is the equivalent magnetizing current of the permanent magnets, referred to the stator side. The corresponding voltage equations are then similar to those of a synchronous machine excited by a field coil and equipped with a damper cage winding.

The equivalent field winding is created by a number of turns N_f and the current is determined from the magneto-motive force F_0, as $I_f = F_0/N_f$. Let us consider the number of turns of the field winding $N_f = 1$. The mutual inductance of the field winding in the d-axis direction is determined as $L_{md} = \Phi_M / F_{ad}$, where Φ_M is the flux of permanent magnets, F_{ad} is the armature reactive mmf in d-axes direction. The set of all equations for flux linkages, winding currents and rotor motion for simulation and all circuit diagrams in MATLAB/SIMULINK can be found in [6].

4 PARTIAL PROBLEMS OF LOW–VOLTAGE ELECTRICAL APPARATUS

In the area of electrical apparatus, theoretical and experimental problems of electrical arc in switching and protecting low-voltage devices are solved: current limitation at short-circuit current breaking, passage through current zero, design and properties of a deion chamber, subsystems of protection devices, solution of the thermal field, model of electrical breakdown of small air gap and breaking process in the deion chamber are presented.

4.1 Time-space distribution of the temperature

The breaking arc, as a short-time thermal source, supplies heat into the contact. The heat is transmitted away from the place of its origin (root of the arc) into the contact by conduction. The solution of the temperature field comes out from the basic equation for heat conduction

$$\frac{\partial \vartheta}{\partial t} = \frac{\lambda}{c\rho} \left(\frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2} + \frac{\partial^2 \vartheta}{\partial z^2} \right) = a \nabla^2 \vartheta. \tag{11}$$

Here are: ϑ - temperature, λ - thermal conductivity, c - specific thermal capacity, ρ - specific density, t - time, x, y, z - co-ordinates, a - temperature conductivity. The solution of the time-space distribution is complicated. When it is possible, we better use a simplification and the task is then solved as a single dimension problem.

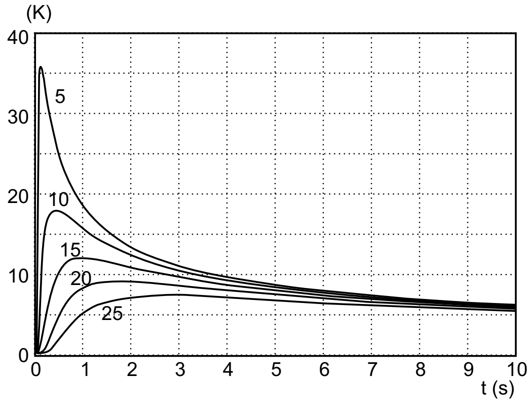

Fig. 6. Calculated time behaviour of temperature

In the case of the short-time thermal source as *eg* breaking arc, it is possible to use the method of sources [7]. The physical principle of the source method is such, that the process of heat dissipated in a solid body can be imagined as a sum of elementary heat sources decomposed in space and time. The influence of an elementary heat source is given by the function

$$F(x, x_1, t) = \frac{b}{\sqrt{4\pi at}}\, \mathrm{e}^{-\dfrac{(x-x_1)^2}{4at}} \tag{12}$$

This function is the basic solution of equation (11) and expresses the temperature in point x, when at the beginning, in the point x_1, a heat quantity $Q = bcp$ is supplied, where b is a coefficient, which characterizes the impulse heat source. For a short time of heat source influence, nearly the whole heat quantity is concentrated in the surrounding of point x_1.

In our case the contact presents a semi-bordered solid body and the task can be solved in a single-dimension field, with simplifications as follows:

- heat impulse acts at time t = 0 in position x_1,
- thermal-physical coefficients are constant and they are independent of temperature
- the Joule losses caused by the current flowing through the contact are neglected. For a short-time and small dimensions cooling of contacts can be neglect. This allows for a simpler form of equation

$$\vartheta(x, t) = \frac{Q}{S\rho c\sqrt{4\pi at}} \left\{ \mathrm{e}^{-\dfrac{(x-x_1)^2}{4at}} + \mathrm{e}^{-\dfrac{(x+x_1)^2}{4at}} \right\}. \tag{13}$$

Here is Q - quantity of supplied heat, S - cross -section of contact, x_1 - place of arc root. This equation shows the settlement of temperature in a semi-bordered solid after absorption of a thermal impulse in place x_1.

In equation (13) we assume that at the beginning the temperature is equal to zero $\vartheta(x, 0) = 0$. Then the equations are valid both for temperature and temperature rise.

Calculation of temperature distribution has been solved by equation (13), for copper contacts with dimensions 10.5 x 1.5 x 30 mm. The resulting temperature rise-time curve can be seen in Fig. 6. An important parameter which enters the calculations is the performance of the heat source. Its value can considerably influence the final value of temperature.

4.2 Calculation of breakdown voltages in small air-gaps

Mathematical-physical model of breakdown voltages in small air-gaps, including the influence of the field emission phenomenon is similar to the described model in [8], which also considers the effect of thermal emission. Physical idea of the model is based on the Towsend's criterion of the breakdown.

The breakdown voltage U_p is easy to calculate from the formula

$$\frac{kA}{aB} U_p \mathrm{e}^{-\dfrac{BV_i\rho d}{kU_p}} \left(1 - \mathrm{e}^{-\dfrac{BV_i\rho da}{kU_p}} \right) = \ln\left(1 + \frac{1}{\gamma^*}\right) \tag{14}$$

where A, B, a, k are constants influencing the distribution of electrical field at the cathode and the position and magnitude of minimum of Paschen's curve, d is the distance of electrodes, V_i potential of ionisation, and p density of the space between the electrodes. Into the Towsend's coefficient the field emission effect is also included

$$\gamma^* = \gamma\left(1 + \frac{i_a}{i_{\mathrm{sec}}}\right) \tag{15}$$

where γ is Towsend's coefficient without the effect of field emission, i_a is the field emission current, and i_{sec} is the current of secondary electrons. The current density of field emission current j_a is determined by the formula

$$j_a = 3.1 \times 10^{-6} \frac{E^2}{W} \mathrm{e}^{-6.8 \times 10^9 \dfrac{W^{1,5}}{E}}. \tag{16}$$

Here W is the work function of the material of the cathode and E is the electrical field intensity on the surface of the cathode without the effect of the microrelief of the cathode.

The calculation of breakdown voltage U_p in dependence on the microlength d was realised for air medium at athmospheric pressure, for $W \approx 4.5$ eV, $\gamma = 0.02$. Amplification of the electrical field on the surface of cathode by microrelief was considered, according to [9] in the range $20 \div 100$. Calculated relations can be seen in Fig. 7 for amplification of field 20, 60, 100 (full line).

From Fig. 7 it is seen, that the breakdown voltage expressively depends on the amplification of electrical field by the microrelief of cathode surface. This explain

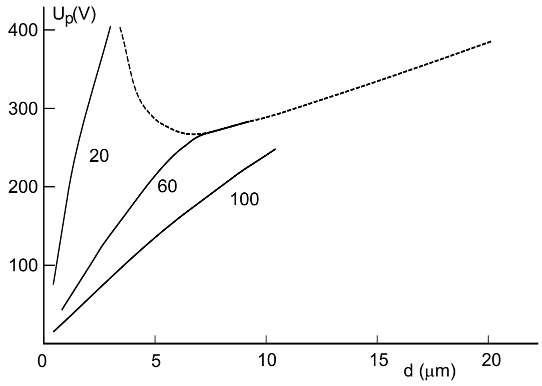

Fig. 7. Relation of breakdown voltage *vs*distance of electrodes at different amplification of field

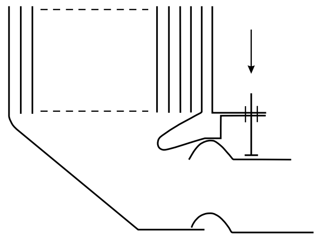

Fig. 8. Design of arrangement of contact and extinguishing subsystems of MCB

the expressive leakage of measured values shown in [10]. Calculation results confirm experimental test results. For small distances of electrodes and high amplification of field, the breakdown voltages can achieve tens of volts.

The results of experiments and the results of calculation of the breakdown voltage of microdistances on a simple mathematical model proved that electrical breakdown can be caused by voltages of the range of tens of volts. The decrease in the breakdown voltage is expressively influenced by field emission and by the microrelief of the cathode. The breakdown can have an avalanche, or evolutionary character. The obtained results contribute to the explanation of arc movement in the quenching system of low voltage contact breakers.

4.3 Development of arc in MCB in extremely difficult conditions of breaking process

An important parameter, characterising the switching properties of a miniature circuit breaker (MCB), is its switching ability. The following part of contribution is dealing with problems of the switching process in MCB while switching off short-circuit current.

The requirement on the breaking process is distinct: it is important for a MCB (from the very beginning of short - circuit current) to start separating contacts as soon as possible and to push-out the arc from the place of its origin into a quenching chamber, to remain there until the interruption of current. Current limiting effect of MCB is inevitable [11]. Breaking-up a short circuit current up to 6 kA by standard MCB makes no problems, but reaching a high value of breaking capacity 10 (15) kA MCB with high rated current (63 A), lowered sensitivity of electromagnetic release (tripping characteristics C, D) and modular scales with width of module 17.5 mm is in fact a very difficult task and switching process is extremely difficult.

The basic limiting factors of breaking capacity, *ie* thermal stress of the deion chamber [12], duplicating arcing between contacts or under the extinction chamber, caused by breakdown of arc voltage or recovery voltage [13], pressure stress [14], more difficult testing conditions (verifying of flow of ionised gases through potential grating), result in a slow movement or even temporary stopping of the moving arc in the area of its development with thermal overload and erosion of contact system parts with resulting effect of great value JI, eventually dysfunction of MCB. That is the reason why it is inevitable to use a construction layout of arc development (AD) which is not a limiting factor of the breaking process and allows reaching the required breaking capacity 10 (15) kA.

According to the orientation of the arc jump from the burn-off part of the moving contact on arc runner in MCB, by European producers is used basic construction of AD with directing the jump area on an external arc runner, Fig. 8.

The quick AD without negative phenomena is strongly influenced by the phase of arc developing velocity and continuity of arc movement from the place of contact and in the junction region. The solution of given problems resulted into a new construction lay-out of area of the arc development with outstanding properties in the phase of AD.

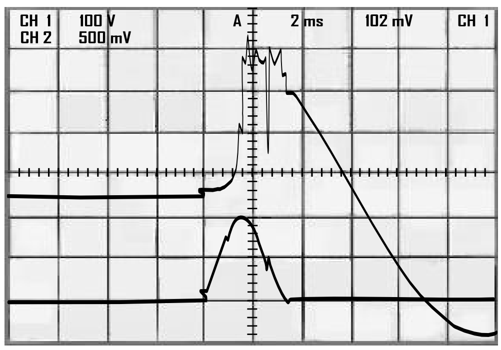

Fig. 9. Oscillogram of 10 kA short-circuit breaking with adjustable MCB (upper trace - arc voltage, lower trace - arc current) 100 V/d, 2.5 kA/d, 2 ms/d.

A record of short-circuit current breaking 10 kA adjusted MCB in a testing circuit with short-circuit generator is in Fig. 9. The time voltage curve on MCB and current flow in MCB were recorded by digital oscilloscope Tektronix 2430 A. Experiments and oscillograms prove reaching an extremely short time of AD in MCB. The typical time is 0.5 ms. It is also inevitable for MCB,

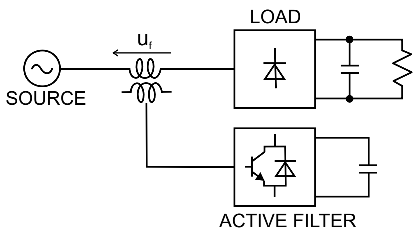

Fig. 10. Block schematics of the series active filter (SAF).

from aerodynamic point of view, to have a well developed extinction system [11] with working circulation flow of environment. This condition is well fulfilled by a deion chamber with a separated reversed circulation flow inside the deion chamber [15], which allows maximal use of space for the extinction chamber and thus reaching of its greater thermal capacity.

5 QUALITY OF POWER SUPPLIED FROM ELECTRIC DISTRIBUTION NETWORK

Industrial semiconductor power equipment are in its nature non-linear units. Supplied from the network they demand non-harmonic currents, thus deforming the curve of the supply voltage. Their switching mode of work causes RFI (radio frequency interference). Because the above influences are of dynamic character, the situation in the distribution network calls urgently for compensating equipment, able to improve its power factor ($cos\varphi$), to filter higher harmonics and to symmetrize any nonsymetric loads. All this shall be done not only in steady states, but also in transient states. The solution has been found in active filters

A series type active filter (SAF) is the best one for compensation goals, Fig. 10. For the scheme we can write according to the 1st Kirchhoff law for instantaneous current values:

$$i_s = i_I + i_f \tag{17}$$

A parallel type active filter (PAF) is a controlled current source. It injects current into the input to the load. If the current is equal to the sum of all higher harmonics that are present in the source current, higher current harmonics may be compensated (filtered). Also, if the current generates the reactive component of the 1st harmonics, reactive power may be compensated and the power factor improved. This principle can be described by the following equations:

$$i_I = i_p + i_q + i_h \qquad i_f = -i_q - i_h \tag{18}$$

so that

$$i_s s = i_p + i_q q + i_h - i_q - i_h \qquad i_s = i_p \tag{19}$$

where index p indicates an active current component, q indicates idle, reactive component, h indicates current higher harmonics The influence of the PAF was examined in two options, and verified by both physical and simulation experiments.

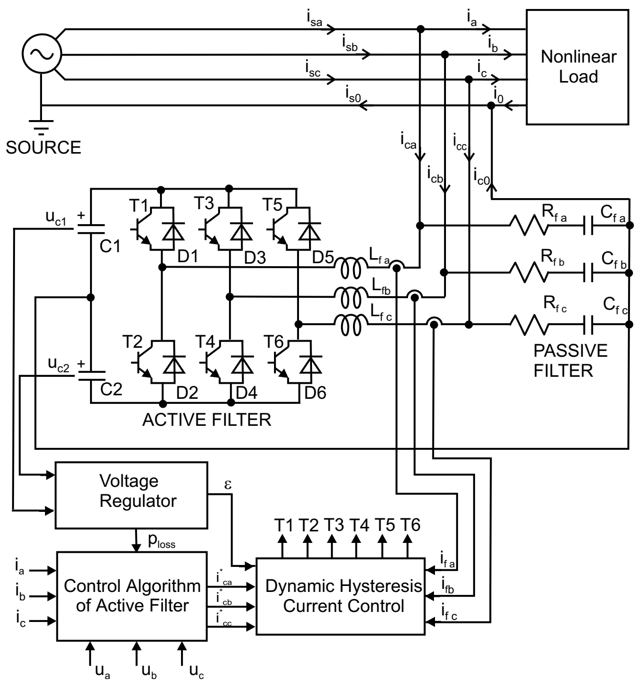

Fig. 11. 3-Phase/4-wires Parallel Active Filter.

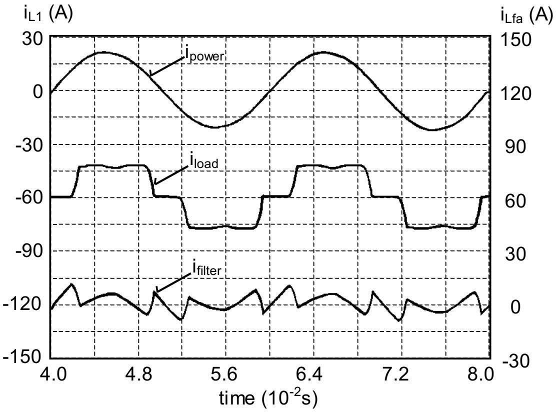

Fig. 12. Instant values of the current in system network-filter-load", (load - 3 phase bridge rectifier)

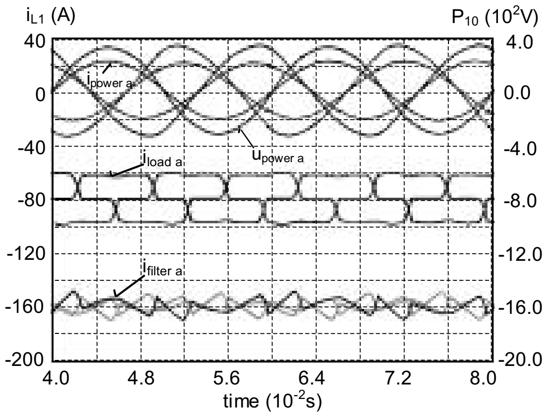

Fig. 13. Instant values of the current in phases a, b, c in system network-filter-load", (load - 3 phase bridge rectifier)

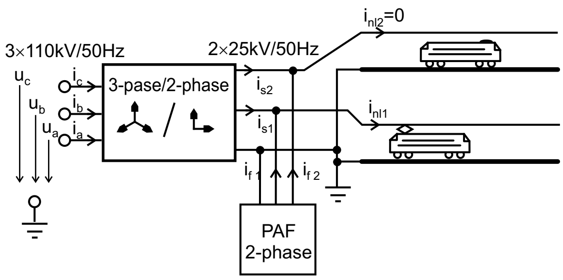

Fig. 14. Electric traction 3-phase parallel active filter

5.1 The 3-phase / 4-wires PAF

The power circuitry (Fig. 11) consists of a 2-quadrant converter working with one voltage polarity and two current polarities. Principially it works as a current source controlled by immediate reactive power. The block scheme of the control circuitry for the 3-phase 4-wires PAF performs a control assuring an instant active 3-phase power to be supplied from the network. If the network voltages are harmonic and the network system is symmetrical, this type of control assures that the currents supplied from the network into the system "filter-load " are harmonic too, regardless of the load type. The correctness of the method is approved by simulation experiments, Fig. 12, Fig. 13 [17].

5.2 1-phase active filter for the traction network 25kV / 50 Hz

Supplying 1-phase traction systems from 3-phase distribution network is a special task. A scheme using a 2-

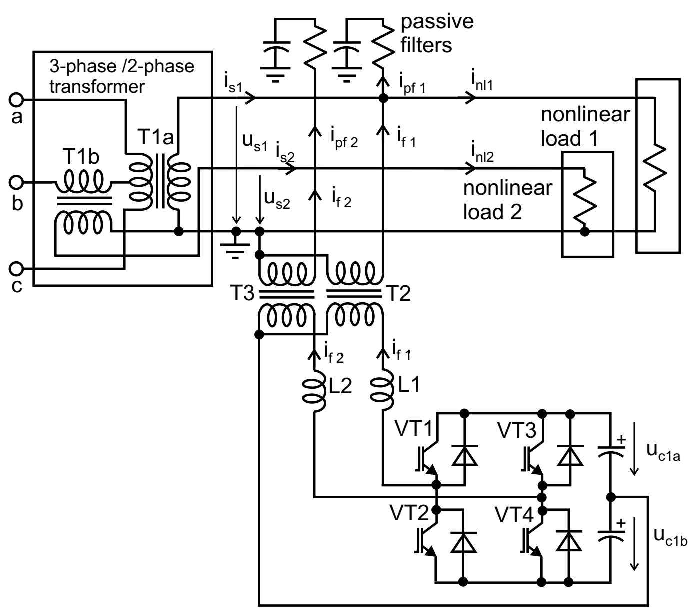

Fig. 15. 3-phase parallel active filter wit a pull-down transformer

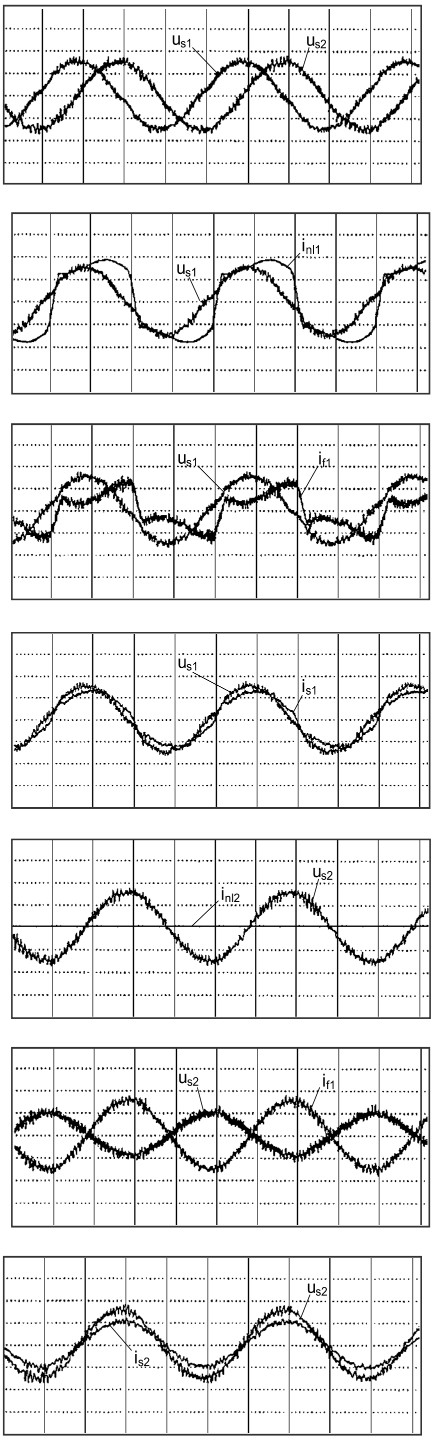

Fig. 16. Reaching a symmetry (50 V/div, 2 A/div, 5 ms/div)

phase active filter is in Fig. 14. Using the active filter is motivated

- by severe unsymmetrical load of 3-phase supplying network in spite of the presence of a special supplying transformer,
- by higher current harmonics and
- by degradation of the power factor in non-compensated traction system.

Application of 2-phase active filter in a system shown in Fig. 15 was investigated. Measured oscillographs from the realised physical model are in Fig. 16 (scheme parameters are the same as in Fig. 14 and Fig. 15) [16].

In the experiment phase 1 was loaded by a non-controlled rectifier (presenting a traction rectifier in a railway wagon), while phase 2 was unloaded. The Figures display symmetrical (!) load of the 3-phase supplying network and supplied network phase current *vs* time of the 1^{st} harmonics for a non-symmetrical and non- linear load. Simulation experiments allow to calculate (for this scheme and 1245 kVA) an increased power factor from 0.64 up to 0.96.

5.3 4-quadrant converter

Another way to solve the quality of supplied electrical energy for electronically controlled appliances is the use of a converter taking no higher harmonics and no reactive power from the supplying network. Say, a 4-quadrant converter is the case. It loads the network by almost harmonic current, in phase with the network voltage.

The subject of investigation was a 4-quadrant converter with PWM, supplied from secondary of a traction drive transformer. Figure 17 gives a scheme of a converter with a condenser (as a source of energy) coupled in parallel to the DC side [17].

A 4-quadrant converter is able to work in all 4 quadrants of the phase angle between the source voltage and current, *ie* it is able to change the phase shift of the supplied current with respect to the supply voltage, controlling the idle, reactive power. This scheme allows for recuperative braking, *ie* changing the kinetic energy of a traction vehicle into electric energy and returning it back to the distribution 110 kV network through the traction supplying network and supplying plant.

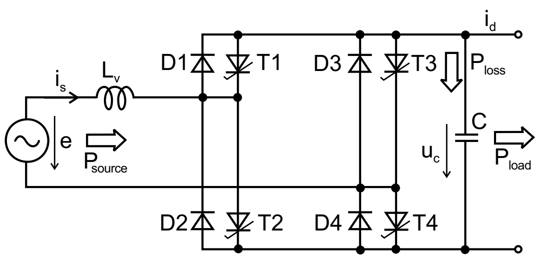

Fig. 17. The scheme of a 4 quadrant converter

The heart of a converter of this type is a current controller. It controls the load current by switching semiconductor valves so that the load current shape copies the shape of a reference current.

The properties of the system controlled by different types of controllers (with different dynamic behaviours) and systems with vector control of the 4-quadrant converter were analysed by simulation experiments. The general goal was to achieve a sinusoidal shape of the supplied

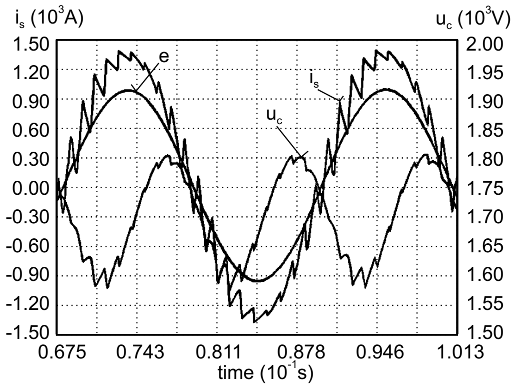

Fig. 18. Time dependence of i_s, U_s and e in a 4 quadrant converter at a switching frequency $f_c = 1kHz$

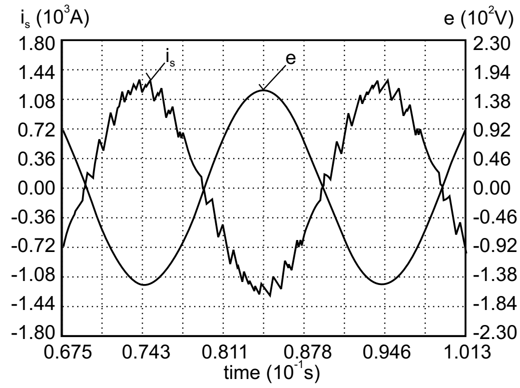

Fig. 19. Instant values of the current in phases a, b, c in system network-filter-load", (load - 3 phase bridge rectifier)

network current, in phase with the supply voltage, ability to keep the voltage in the DC intermittent circuit at a reference average value (this is a controlling condition of the converter).

Individual controlling methods are illustrated in Fig.18 (circuit parameters of the system using a hysteresis controller with constant switching frequency 1 kHz and power of traction motors equal to 1 MW), and in Fig.19 (circuit parameters of the system using the vector control, harmonic modulating voltages and power of traction motors equal to 1 MW).

The results of all the experiments allow us to say that the system is perspective for optimization of power supply from the distribution AC network.

6 CONCLUSION

The results published here are contributions of the Department staff members to the progress of knowledge in the field of electric machines, apparatus, drives and power electronics. A more detailed description of individual problems is not possible with respect to the range and character of this paper. We refer the reader to the next list of articles published by our authors. A wide range of topics were solved on demand of industry and to its support.

Acknowledgement

We gratefully acknowledge that the results presented here were solved as partial goals of the research tasks VEGA No 4293, VEGA No 1/7604/20, VEGA No 1/8127 /01 and IPVT/6/98.

References

[1] HRUŠKOVIČ, L.: A contribution to the Linear Theory of Induction Machines, Elektrotechnický časopis No. 3 (1960), 139-146. (in Slovak)

[2] HRUŠKOVIČ, L.: Equations and Leakage Reactances of Transformers and Induction Machines, Slovak University of Technology, 2000. (in Slovak)

[3] J. F. GIERAS—M. WING: Permanent Magnet Motor Technology, Marcel Dekker, Inc. New York, 1997.

[4] I. L. OSIN—V. L. KOLESNIKOV—F. M. JUFEROV: Sinchronnye mikrodvigateli s postojannymi magnitami, Energija, Moskva, 1976.

[5] R. MAGUREANU—N. VASILE: Servomotoare fara perii tip sincron, Editura Tehnica, Bucuresti, 1990. (in Romanian)

[6] CH. M. ONG: Dynamic Simulation of Electric Machinery using MATLAB/SIMULINK, Prentice Hall Ptr, New Jersy, 1998.

[7] KARSLOU, G.—JAEGER, D.: Teploprovodnost tverdych tel, Nauka, Moskva, 1964.

[8] VALENT, F.: Current Zero Phenomena at Low-voltage Circuits Breaking, Thesis EF STU, Bratislava, 1989. (in Slovak)

[9] SLIVKOV, I. N.—MICHAJLOV, V. I.—SIDOROV, N. I.—NASTJUCHA, A. I.: Elektriceskij proboj a razrjad v vakuume, Atomizdat, Moskva, 1966. (in Russian)

[10] TAJEV, I. S.—KUZNECOV, V. N.: Probivnyje naprjazenija mikropromezutkov v vozduche, Elektrotechnika (1975), 54-57.

[11] VALENT, F.—HÜTTNER, L.—JURCACKO, L.: Influence of Extinction Device of the Low-voltage Circuit Breaker on the Limiting of Short-circuit Current, Proc. of the Switching arc Phenomena, Ľodž Poland, 1993, pp. 85-89.

[12] HÜTTNER, L.: Contribution to the Design of Extinguishing Chamber of MCB Proc., XII-th Symposium on Physics of switching Arc (1996), 98-102, Brno.

[13] VALENT, F.: Influence of Cathode Sheet and Temperature on the After-arc Breakdown Voltage of AC Low-voltage Switch gears, Elektrotechnicky obzor **79** No. 5 (1990), 271-276. (in Slovak)

[14] JURČACKO, L.: The Time Pressure Curve During Breaking of the Short-circuit Current in the Miniature Circuit Breaker as a Diagnostic Element of Contact Activities, Proc. XIth Symposium on Physics of switching arc, 1994, Brno, pp 109-112.

[15] JURČACKO, L.: Deion Chamber for Electrical Switch Gears of Low-voltage, Patent No 277843, 1995, SK. (in Slovak)

[16] VRANKA, M.: Design of 1-Phase Active Filter for Higher Harmonics Elimination, Electric Traction Supply Network 25kV, 50Hz. Final project of Engineering study, KESP FEI STU, Bratislava, 2000 (in Slovak).

[17] BOROŠ, T.: 4-Quadrant Converter, Final project of Engineering study, KESP FEI STU, Bratislava, 2000. (in Slovak)

[18] ČERŇAN, P.: Design of 3-Phase Active Filter, Final project of Engineering study, KESP FEI STU, Bratislava, 2000. (in Slovak)

Received 25 May 2001

Ladislav Hruškovič (Prof, Ing, DrSc) was born in Dolné Hámre, Slovakia in 1929. He received his Ing degree in Electrical Engineering from the Faculty of Electrical Engineering of the Slovak University of Technology, Bratislava, in 1952, the PhD degree in 1958, and the DrSc degree in 1988. He is author of text books in the field of electrical machines and electrical machines for controlled drives as well as of papers in the field-harmonic theory of the induction machine, in the theory of leakage reactances of electrical machines, single-phase induction machines and rotating transformers.

Ľudovít Klug (Prof, Ing, PhD) was born in Komárno, in 1935. He received his Ing degree in Electrical Engineering from the Faculty of Electrical Engineering of the Slovak University of Technology, Bratislava, in 1959, the PhD degree in 1973, Prof. degree in 1997. He is author of many publications in the field of electrical machines, permanent magnet machines, generalized theory of machines, modeling of the magnetic fields in the machines by FEM, electromagnetic design of the machines and their simulation.

Ľudovít Hüttner (Doc, Ing, PhD) was born in Bratislava, Slovakia, 1946. He graduated from the Faculty of Electrical Engineering, Slovak University of Technology, Bratislava, in 1969. He gained the PhD degree in Electrical Machines and Devices, in 1988. At present he is Associate Professor and head of the department of Electrical Machines and Devices. The main field of his research and teaching activities are switching and protective low-voltage apparatus and using of computers in education.

Ferdinand Valent (Doc, Ing, PhD) was born in Kokava nad Rimavicou, Slovakia, 1940. He graduated from the Faculty of Electrical Engineering, Slovak University of Technology, Bratislava, in 1963. He gained the PhD degree in Electrical Machines and Devices, in 1990. At present he is Associate Professor of the department of Electrical Machines and Devices. The main field of his research is the theory of electric arc, switching processes and development of switch and protective low-voltage apparatus.

Neitus Lipták (Doc, Ing, PhD) was born in Ružomberok, Slovakia, 1933. He graduated from the Faculty of Electrical Engineering, Slovak University of Technology, Bratislava, in 1958 . He gained the PhD degree in Electrical Machines and Devices, in 1980. At present he is retired but still works for the Department of Electrical Machines and Devices. The main field of his research activities are modern methods in control drives and CAMS.

Ladislav Borba (Ing, PhD) was born in Bratislava, Slovakia, in 1943. He graduated from the Faculty of Electrical Engineering, Slovak University of Technology, Bratislava, in 1967. He gained the PhD degree in Electrical Machines and Devices, in 1985. At present he is staff member of the department of Electrical Machines and Devices. The main field of his research activities are power semiconductor converters and systems for electric controlled drives.

Ludovít Jurčacko (Ing) was born in Bratislava, Slovakia, 1947. He graduated from the Faculty of Electrical Engineering, Slovak University of Technology, Bratislava, in 1971. At present he is staff member of the Department of Electrical Machines and Devices. The main field of his research activities are problems of breaking process of low-voltage electric apparatus and development of switch and protective low-voltage apparatus.