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.

**Keywords:** 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.

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
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.

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

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_1 = \left( R_1 + jX_{\sigma 1} + jX_{m1} \sum_{k_1=-\infty}^{\infty} \frac{k_{w1}^2}{k_{w1}^2 + \omega_1^2 \lambda^2} \right) \bigg</td>
<td><em>{\lambda=6k_1+1} + jX</em>{m1} \sum_{k_1=-\infty}^{\infty} \frac{k_{w1} k_{w2} k_{w3}}{k_{w1} k_{w2} k_{w3}^2} \bigg</td>
</tr>
<tr>
<td>( 0 = \left( R'<em>{k1,2} + j s</em>{k1} X'<em>{k1,2} + j s</em>{k1} X_{m1} \frac{1}{k_s} \sum_{k_2=-\infty}^{\infty} \frac{k_{w1} k_{w2} k_{w3}}{k_{w2} k_{w3}^2} \right) \bigg</td>
<td><em>{\mu'\mu \lambda = 6k_2 + 6k_1 + 1, k_1 = \text{const}} + j s</em>{k1} X_{m1} \sum_{k_2=-\infty}^{\infty} \frac{k_{w1} k_{w2} k_{w3}}{k_{w2} k_{w3}^2} \bigg</td>
</tr>
<tr>
<td>( s_{k2} = 1 + 2k_2 (1 - s) )</td>
<td>( \mathbf{I}<em>{k1,2} = \frac{Q_2}{3N_1 k</em>{w1}} \mathbf{I}_{k1,2} ) (5)</td>
</tr>
<tr>
<td>( s_{k1} = 1 - (1 + 6k_1) (1 - s) )</td>
<td>( \mathbf{R}'<em>{k1,2} = \frac{3}{Q_2} \left( \frac{N_1 k</em>{w1}}{k_{w2}} \right)^2 \mathbf{R}_{k1,2} ) (6)</td>
</tr>
</tbody>
</table>

Further equations in the equations are the reactances only of a slot leakage and an end-turn leakage. They do not include the differential leakage. The concept 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 disks 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]

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

where \( \xi \) 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 \( P_{\text{out}} \) of the motor is a half of the maximum power \( P_{\text{max}} \), therefore the volume of all permanent magnets of the motor is at given output power of the motor

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

The inner stator diameter \( D_{\text{in}} \) can be estimated from the apparent power crossing the air-gap of the machine.

On introducing the output power \( P_{\text{out}} \), 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
density $A_m$, flux density in the air gap $B_g$, the product $D_{11n}^2 L_i$ takes the form

$$D_{11n}^2 L_i = \frac{P_{out} \varepsilon}{\sigma_p n_1},$$

(9)

where the coefficient $\sigma_p$ expresses the electric and magnetic utilisation of the machine

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

(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 $\Phi_M$ is the flux of permanent magnets, $F_{ad}$ is the armature reaction 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

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

(11)

Here are: $\vartheta$ - temperature, $\lambda$ - thermal conductivity, $c$ - specific thermal capacity, $\rho$ - 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.
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 Townsend’s criterion of the breakdown.

The breakdown voltage $U_p$ is easy to calculate from the formula

$$
\frac{kA}{aB}U_p e \frac{BV_{pd}}{kU_p} \left( 1 - \frac{BV_{pd}}{kU_p} \right) = \ln \left( 1 + \frac{1}{\gamma} \right)
$$

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 Townsend’s coefficient the field emission effect is also included

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

where $\gamma$ is Townsend’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

$$
j_a = 3.1 \times 10^{-6} \frac{E^2}{W} - 6.8 \times 10^9 \frac{W^{1.5}}{E}.
$$

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 atmospheric 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 20:100. 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...
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 Jt, 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.](image)
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 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 non-symmetric 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:

$$i_s = i_I + i_f$$ (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:

$$i_I = i_p + i_q + i_h \quad i_f = -i_q - i_h$$ (18)

so that

$$i_s = i_p + i_q q + i_h - i_q - i_h \quad i_s = i_p$$ (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. Principally 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-
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 1st 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, i.e. 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, i.e. 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.

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

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.

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

![Fig. 17. The scheme of a 4 quadrant converter](image)
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.

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