Comparative Analysis of the Magnetic Pole Operation of a Conventional Synchronous Machine and a Synchronous Machine Constructed According to the Slot Cutting Conception

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Abstract*: The paper discusses the fundamental relationships connected with the distribution of magnetic fluxes and the generated voltage in a pole of a single-gap conventional synchronous machine and a pole of a multi-gap synchronous machine of a new kind, a model of which has been constructed according to the slot cutting conception. The operation principle of this kind of machines is based on a dissipationless loop of magnetic flux. Due to the applied process of multiplied magnetization of the stator winding, it was possible to compensate the lack of fully insulating materials for magnetic flux in the nature by the assistance of active magnetomotive forces (MMFs) connected with the kinetic system of the rotor. The mechanisms leading to practical dissipationlessness of the winding of the energy circuit of the constructed and tested model of this machine have been revealed. Creation of technical possibilities for limitation of dissipation fluxes in reactive structures of electrical machines enables a new approach to their design. It becomes possible to develop a new kind of low-speed (for 50Hz) machines with large numbers of pole pairs and full loading capacity. The distinguishing feature of these machines – the low diameter – opens the way to high-speed applications, where they appear as high-frequency machines with so far unknown high densities of unit power in relation to conventional machines.*

Key words: Electrical machines. New constructions. New technologies.

INTRODUCTION

The paper presents an analysis of the fundamental relationships of the distribution of magnetic fluxes and the generated voltage in a pole of a conventional machine and a model of a new kind of synchronous machine constructed according to the slot cutting conception, for the same number of pole pairs p=18 and maintaining the same amount of active materials (Cu, Fe) in the stators of the reactive structures of the discussed machines. Assumption of the developed physical model of $E_{el} \Leftrightarrow E_{mech}$ converter based on a dissipationless loop of magnetic flux, presented in [5], for shaping of the reactive structures leads to multiplication of magnetization of the stator winding. Thus the lack of fully insulating materials for magnetic flux has been compensated by the assistance of magnetomotive forces (MMFs) connected with the kinetic system of the rotor. The possibility of limiting the dissipation fluxes opens new possibilities of shaping the reactive structures of electrical machines. It becomes possible to construct low-speed (for 50Hz) machines with large numbers of pole pairs. The distinguishing feature of these machines – the low diameter, opens the way to high-speed applications, where these machines may appear as high-frequency electromechanical converters with high densities of unit power.

Determination of Basic Waveforms of the Magnetic Flux and the Generated Voltage in a Pole of a Single-Gap Conventional Synchronous Machine for Idle Run

For convenience, Fig. 1a and b presents in unrolled form two fragments of reactive structures of synchronous machines with the same amount of active materials (Fe, Cu) in the stators of both machines. These machines have been discussed and presented in [5]. A machine as in Fig. 1a is a single-phase conventional synchronous machine of large number of pole pairs p=18 that could not operate correctly due to the high value of dissipation fluxes connected with incorrect geometry of its reactive structure. For this purpose, in order to limit the dissipation fluxes, a redesigned fragment of the reactive structure of this machine with slot cutting conception has been presented in Fig. 1b. Partition of the magnetic voltage of the exciter into several smaller ones and distribution of these magnetic voltages along the path of the constructed magnetic core in the kinetic system of the rotor leads to multiplication of magnetization of the stator and limitation of the dissipation fluxes to a level permitting correct operation of this type of machines.

Fig. 2 presents a pole fragment of a machine as in Fig. 1a for a given position α of the field magnet in relation to the stator teeth with marked distribution of fluxes. Dissipation fluxes are not taken into consideration in the idealized re-

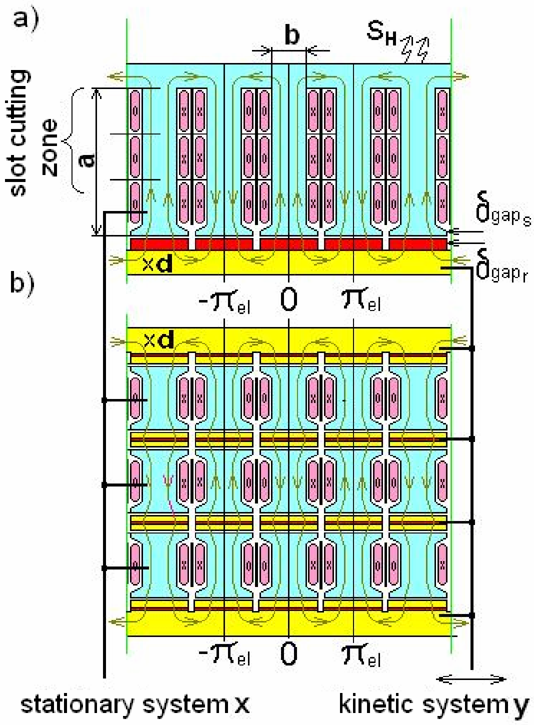

Fig. 1. Fragments of single-phase reactive structures of synchronous machines in unrolled form, where:
a - conventional machine with the number of pole pairs p=18

b - machine constructed according to the slot cutting conception with the number of pole pairs p=18 for three cuts of the stator teeth.

iron of stator teeth; copper of stator windings;

iron of rotors; MMF of permanent magnets.

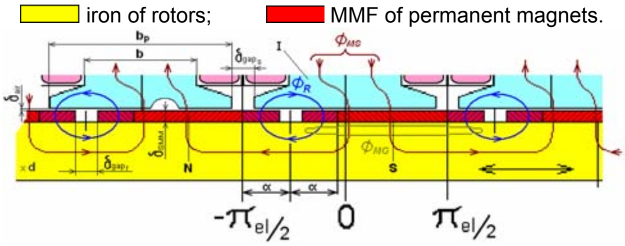

Fig. 2. Distribution of the field magnet flux Φ_{MG} into the component fluxes Φ_{MS} and Φ_R for a given angle α of the field magnet shift in relation to the stator teeth.

active structure of the machine. For simplification, the change of induction of the flux Φ_{MS} resulting from different width of the magnetic pole $\mathbf{b_p}$ and the tooth itself **b** is also not taken into consideration. The influence of the gap size $\delta_{gap(s)}$ and $\delta_{gap(r)}$ on the resultant value of the field magnet flux Φ_{MG} is also neglected. For the compatible position of the field magnet in relation to a stator tooth we have the minimum magnetic reluctance $R_{M(\alpha=0)}$ for the magnetic flux Φ_S and the algebraic summation of the electric loading of the stator winding with the magnetic voltage Q of the exciter pole. For relative values $R_{M(\alpha=0)}$ is equal to:

$$R_{M(\alpha=0)} = \delta_{MMF(T)} + \delta_{air} \tag{1}$$

where: $\delta_{MMF(T)}$ = 3.5mm – thickness of the permanent magnets of the field magnet
δ_{air} = 0.2mm – value of the air gap

It is assumed that $R_{M(\alpha=0)}$ refers to the width of the magnetic pole and the field magnet pole equal to π_{el} and applies to the same depth size **d**=50mm of the discussed machines as in Fig. 1a and b.

From Fig. 2 it is visible that shifting the field magnet pole **N** by the angle α towards the magnetic pole **I** causes the field magnet flux Φ_{MG} to divide into two fluxes: the short-circuited flux Φ_R and the flux in the stator tooth Φ_{MS}. The correctness of the magnetic pole geometry should ensure its non-saturation under the influence of the flux Φ_R at idle run of the machine. In such a case the value of the flux Φ_R is determined by the position-related reluctance of the field magnet in the range of angle α from 0 to $\pi/2$ according to the relationship:

$$\Phi_R = Q_{N(T)} * \frac{\alpha}{\delta_{MMF(T)} + \delta_{air}} \quad 2)$$

Due to the constant value of δ_{MMF} and δ_{air}, the flux Φ_R closes above the pole **S** on the same range of angle α. The value of the stator flux Φ_{MS} in the same range of angle α is determined as:

$$\Phi_{MS} = Q_{N(T)} * \frac{\pi - 2\alpha}{\delta_{MMF(T)} + \delta_{air}} \quad 3)$$

Where: $Q_{N(T)}$ – magnetic voltage as electric load in [A] of permanent magnet of traditional machine.

At the angle of $\pi/2$ there occurs a change of polarization of the flux Φ_{MS} in accordance with the direction of the field magnet **N**, and also of the marginal conditions connected with determination of the position-related magnetic reluctance for further rotation angles α from $\pi/2$, in order to reach the maximum $\Phi_{MS} = \Phi_{MG}$ for $\alpha = \pi$ in accordance with the polarization of the pole **N**. During rotation of the field magnet, the variable flux Φ_{MS} generated in the stator teeth influences the electrical winding in the stator and the field magnet pole, and thus conditions are created to bind

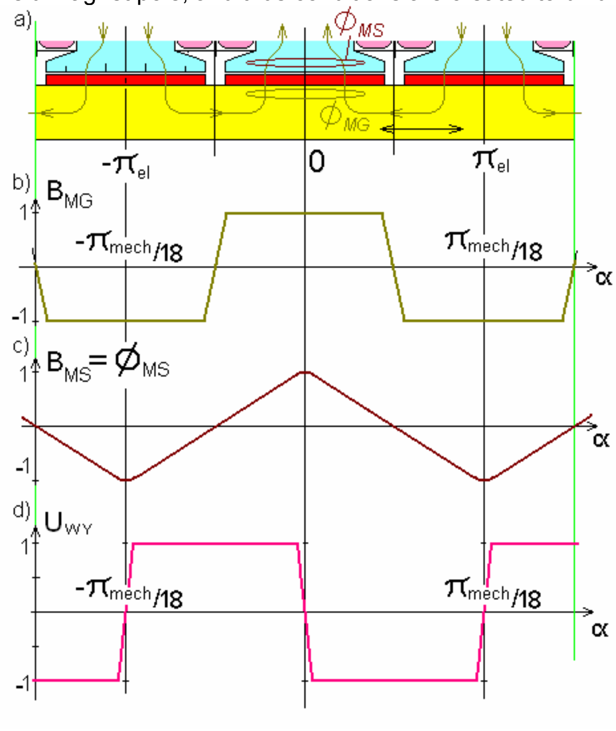

Fig. 3. Basic waveforms of magnetic fluxes in the reactive structures of machines as in Fig. 1a and b during movement of the field magnet poles in relation to the stator, where:
a) stator and rotor fragment of a conventional machine with p=18
b) density distribution of the field magnet flux Φ_{MG} of a machine in the rotor
c) density distribution of the field magnet flux Φ_{MS} of a machine in the stator
d) waveform of the output voltage

the circuit of the stator electrical energy E_{el} and the rotor kinetic energy E_{mech} into the $E_{el} \Leftrightarrow E_{mech}$ conversion process.

Fig. 3 presents the distribution of the field magnet flux induction B_{MG} and the stator flux induction B_{MS} during rotation of the field magnet in relation to a stator tooth. The constancy of the field magnet flux induction B_{MG} is ensured by the correctness of the magnetic pole geometry connected with non-saturation for the flux Φ_R, and the linear course of changes of the stator induction B_{MS} is ensured by the constancy of gaps δ_{MMF} and δ_{air} which, with the rotation angle α, generate the linearity of the position-related magnetic permeance of the field magnets as $\gamma_{M(\alpha)} = 1/R_{M(\alpha)}$. Because the stator tooth width **b** is constant, the changes of the flux density B_{MS} and its magnitude Φ_{MS} remain equivalent as shown in Fig. 3c. In thus constructed machine, the linear course of changes of the flux Φ_{MS} as a function of the field magnet rotation angle α causes inducing a trapezoidal waveform of the output voltage as in Fig. 3d.

Determination of Basic Waveforms of the Magnetic Flux in a Pole of a Multi-Gap Synchronous Machine Constructed According to the Slot Cutting Conception for Three Cuts of Stator Teeth and Idle Run

Fig. 4 presents a pole of the constructed machine model according to the slot cutting conception in order to determine the fundamental relationships connected with the distribution of fluxes and generated voltages. In this machine, four concurrent field magnets are distinguished in it

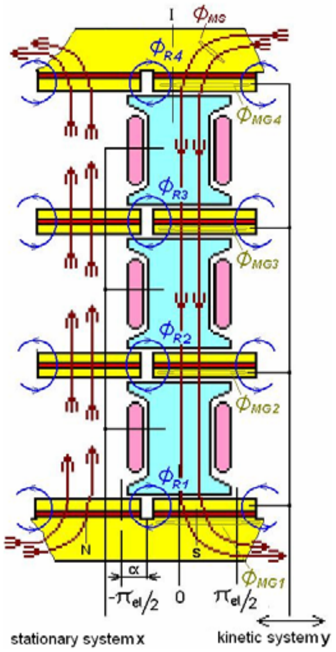

Fig. 4. Distribution of magnetic fluxes in a pole of a machine as in Fig. 1b during rotation of the field magnet by angle α in relation to a stator tooth for the idle run state.

kinetic system that, in relation to the exciter of a conventional machine, partition the magnetic voltage of the exciter into several smaller magnetic voltages with their distribution along the constructed magnetic core. Like in a conventional machine, the flux of each separate field magnet $\Phi_{MG(1\text{-}4)}$ remains constant for any position angle α of the field magnets as in Fig. 3b, provided that a correct geometry of the stator magnetic poles and the rotors does not cause saturation of the iron. In the range of the field magnets rotation angle α from 0 to $\pi/2$ short-circuit fluxes $\Phi_{R(1\text{-}4)}$ are formed, determined as:

$$\Phi_{R(1,4)} = \frac{Q_{N(SC)} * \alpha}{\delta_{MMF} + \delta_{air}} \qquad \Phi_{R(2,3)} = \frac{Q_{N(SC)} * \alpha}{\delta_{MMF} + 2\delta_{air}} \tag{4}$$

and the flux Φ_{MS} is formed as superposition of MMFs of all four field magnets determined as:

$$\Phi_{MS} = \frac{4 * Q_{N(SC)} * (\pi - 2 * \alpha)}{4 * \delta_{MMF} + 6 * \delta_{air}} \tag{5}$$

Where: $Q_{N(SC)}$ – magnetic voltage as electric load in [A] of permanent magnets of slot cutting machine.

The waveform of the flux Φ_{MS} as a function of the concurrent field magnets rotation angle α does not differ essentially from the waveform as in a conventional machine and presented in Fig. 3c. The variable flux Φ_{MS} influences all windings of the cut teeth of the stator and all field magnets of the rotors of a given pole, binding the circuit of electrical energy E_{el} and mechanical energy E_{mech} into the $E_{el} \Leftrightarrow E_{mech}$ conversion process.
The linear course of changes of the flux Φ_{MS} causes also generation of trapezoidal output voltage as in Fig. 3d.

Discussion of Operation of a Machine Pole as in Fig. 1a and 1b Under Load

The conditions of distribution of magnetic fluxes and the generated voltage presented above concerned the idle run state of poles of machines as in Fig. 1a and 1b, i.e.

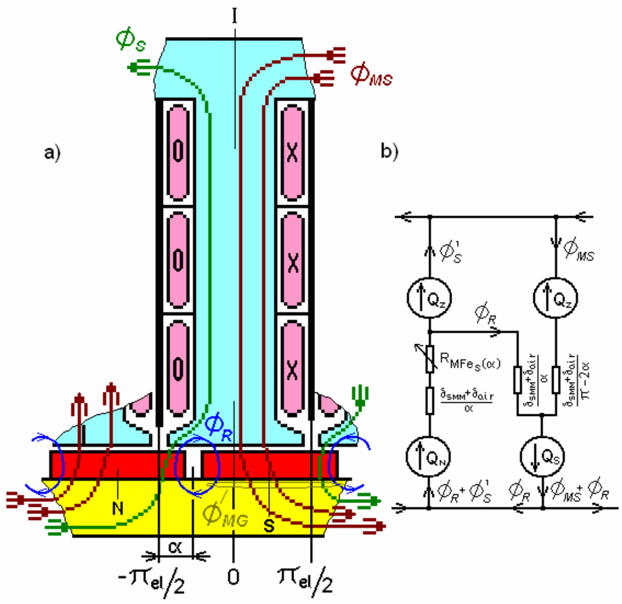

Fig. 5a. View of a pole of a conventional machine for the loaded state with marked distribution of magnetic fluxes for the assumed direction of the winding current and the field magnet rotation angle α.

b. simplified magnetic circuit of the pole with marked flux $\Phi`_S$ component compatible with the polarization of the field magnet pole Q_N.

when the value of electric loading of the windings Q_Z in [A] was zero. Fig. 5a presents a pole of a conventional machine with assumed direction of the winding current and a given field magnet rotation angle α in relation to a stator tooth. Fig. 5b presents a simplified diagram of the magnetic circuit of the pole in form of concentrated elements. For better clarity it was decided to divide the electric load Q_Z and also to mark the flux $\Phi`_S$ component only in the branch compatible with the polarization of the field magnet pole Q_N. As presented before for the switched off winding load $Q_Z = 0$ with a correctly designed magnetic pole the magnetic reluctance $R_{MFes(\alpha)}$ will be equal to zero, while the distribution of the fluxes Φ_R and Φ_{MS} is decided by the position-related reluctances of the field magnets marked on the diagram. For loaded state of the machine, the flux $\Phi`_S$ component compatible with the polarization of the pole Q_N causes additional magnetization of the stator tooth and its saturation. Then the magnetic reluctance of the magnetic pole $R_{MFes(\alpha)}$ is revealed, which takes on the „obligation" of switching off the flux Φ_S, when the field magnet rotation angle $\alpha \rightarrow 0$. For large values of electric loading Q_Z the „iron" of the magnetic pole may saturate up to $\mu_r \rightarrow 1$ and then the gaps $\delta_{gap(s)}$ and $\delta_{gap(r)}$ may assist by selves the process of switching off the flux Φ_S. For polarization of the field magnet pole Q_S, a flux component $\Phi``_S$, which is not marked in the diagram, forces operation in the linear part of the magnetic pole magnetization characteristic curve and the resultant distribution of the flux in the demagnetization zone is decided by the position-related reluctances of the field magnet poles.

Fig. 6a presents a pole of the machine from Fig. 1b with the resultant electric loading of the winding Q_Z switched on, which generates the stator flux Φ_S in the circuit of the cut teeth of the stator and the field magnets of the rotors. The field magnets of the rotors introduced according to [7] have thin-layer pieces of permanent magnets and are enclosed with caps of low-lossiness electrical steel. Sand

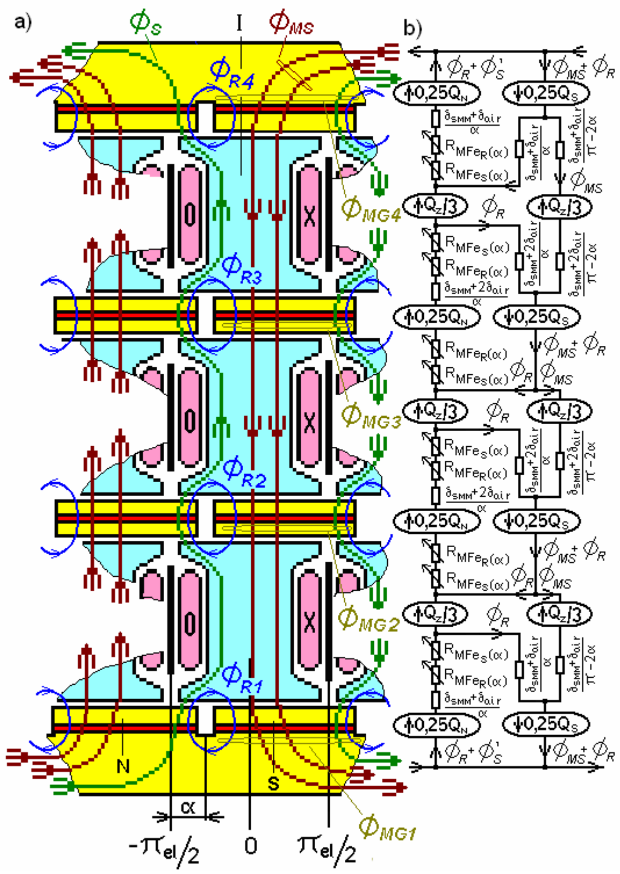

Fig. 6a. View of a pole of the machine model constructed according to the slot cutting conception for the loaded state with marked distribution of magnetic fluxes for the assumed direction of the winding current and the field magnet rotation angle α.

b. simplified magnetic circuit of the pole with marked flux $\Phi`_S$ component compatible with the polarization of the resultant field magnet pole Q_N.

wich MMFs have been thus prepared, as magnetic elements of low reluctance for magnetic flux. In the pole structure of the constructed model of this machine, on the path of the switched off flux Φ_S there are six magnetic poles of the cut teeth of the stator and six caps of magnetically soft steel of the sandwich MMFs. For the loaded state of the machine, they create twelve concurrent variable magnetic reluctances connected in series as $R_{MFes(\alpha)}$ and $R_{MFer(\alpha)}$ and shown in the diagram of the magnetic circuit for this pole as in Fig. 6b. For idle run, when $Q_Z = 0$, for correct geometry of the magnetic poles of the cut teeth of the stator and the caps of the field magnets of the rotors, when there is no „iron" saturation effect, the reluctances $R_{MFes(\alpha)}$ and $R_{MFer(\alpha)}$ are not revealed, and the distribution of the fluxes $\Phi_{R(1\text{-}4)}$ and Φ_{MS} is decided by the position-related reluctances of the field magnets shown in the diagram. For the switched on total winding electric load Q_Z, the appearing component of the flux $\Phi`_S$ compatible with the polarization of the field magnets poles Q_N causes additional magnetization of this part of the magnetic poles of the cut teeth of the stator and the caps of the sandwich MMFs. When the field magnets position angle $\alpha \rightarrow 0$, then in the process of switching off the flux Φ_S all these magnetic reluctances $R_{MFes(\alpha)}$ and $R_{MFer(\alpha)}$ are revealed and take part in the process of switching off this flux. Such concurrent, multiplanar and serial switching off of the magnetic flux Φ_S produces very beneficial effects for the operation of this type of machines. If for a single-gap machine as in Fig. 1a switching off of the flux Φ_S leads to saturation of the magnetic pole up to the value $\mu_r \rightarrow 1$ and requires the „assistance" of the gaps $\delta_{gap(s)}$ and $\delta_{gap(r)}$, then for a multi-gap machine constructed according to the slot cutting conception as in Fig. 1b the process of switching off the flux Φ_S, for the same value of the total electric load Q_Z, will occur at the saturation value of the magnetic poles of the cut teeth of the stator and the caps of the field magnets for $\mu_r \sim 12$. In such a case the gaps $\delta_{gap(s)}$ and $\delta_{gap(r)}$ with their relative permeability $\mu_r = 1$ may still effectively fulfil their insulating functions with respect to the flux Φ_S being switched off in the „iron", whose μ_r is twelve times larger. It can be said that the substitute value of the gap is $12\delta_{gap}$, or the substitute gap for its maintained size δ_{gap} has the resultant relative permeability $\mu_r \sim 1/12$. The nature does not give direct possibilities of having magnetic materials of such insulating properties with respect to magnetic flux.

This is the first mechanism that leads to significant reduction of dissipation fluxes in thus shaped reactive structure of a machine.

The second mechanism that causes further significant reduction of dissipation fluxes is the partition of the magnetic voltage of the exciter of a conventional machine and distribution of these magnetic voltages in additional rotors of the kinetic system on the path of the constructed magnetic core of the cut teeth in the stationary system of the machine. This is the only way that permits the increase of the quality factor of the magnetic circuit with no insulating materials to improve it. The field effects of the spatially distributed MMFs lead to auto compensation of the potential dissipation fluxes to their small differential value.

The third mechanism that causes even further reduction of dissipation fluxes consists in the introduced constructional solutions that distribute spatially in the ferromagnetic material the necessary magnetic reluctances of the air gaps δ_{air} and the permanent magnets δ_{MMF} to their necessary minimal value as in the machine from Fig. 1b. The substitute value of dissipation fluxes thus obtained is lower than in the case of these elements put together as in the reactive structure of the machine from Fig. 1a.

It should be expected that these three presented mechanisms together lead to strong reduction of dissipation fluxes in the reactive structure of the constructed model of this machine. In order to estimate the parameters of the energy circuit, it became necessary to cooperate with an electronic power converter that would permit to force a pure lateral flow of the flux Φ_S being in phase with the internal voltage of the machine. For this kind of load, the compensation of the synchronous reactance of the winding becomes possible, because the converter itself has the ability to deliver the capacitive component of the output voltage to the circuit.

Cooperation of the Constructed Model of the Machine as in Fig. 1b with an Electronic Power Converter

Tests have been performed in the Laboratory of Electrical Machines of the Gdansk University of Technology in order to verify the operation of this machine with lack of the demagnetization current component caused by the shift on the synchronous reactance of the stator together with an accessible and adapted electronic power converter. Fig. 7 presents a block diagram of the configuration of the control system. The encoder embedded in the clutch plate generates the control signal EC synchronized with the idle run voltage that has been feed to the hysteresis-type regulator of the converter current programmed as a controllable and polarizable current source. From the waveforms of the flux Φ_{MS} and the output voltage U_{WY} as in Fig. 3c and d it can be seen that the forced current in phase with the idle run voltage ensures a pure lateral flow of the flux Φ_S connected with the winding current in relation to the stator flux Φ_{MS}. This forces a pure resistive character of the load.

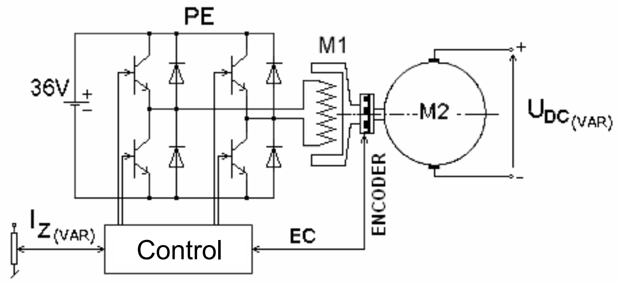

Fig. 7. Diagram of connection of the tested machine model to the electronic power converter for determination of the external characteristics of the machine, where:
36V – power supply battery; PE – electronic power converter; M1 – tested machine model; M2 – driving motor of the tested assembly; EC – signal synchronizing the controllable polarizable current source of the converter; I_Z – setting signal of the current source of the converter.

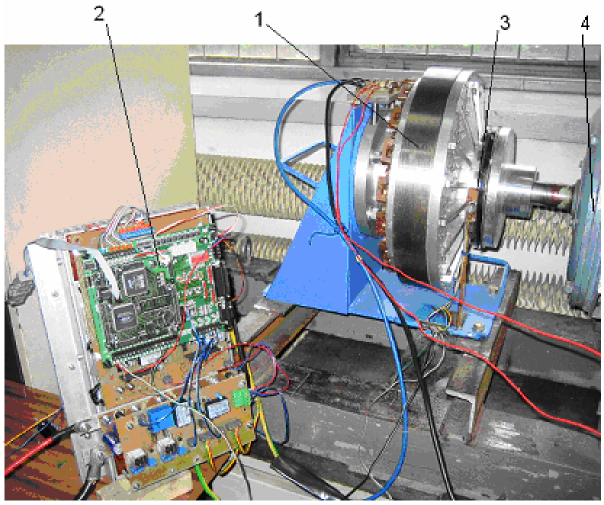

Fig. 8. Assembled model of the machine (1) constructed according to the slot cutting conception on the test stand together with the electronic power converter (2), the embedded encoder (3) and the driving machine (4).

Fig. 8 presents the constructed machine model on the test stand together with the adapted electronic power converter and the embedded encoder for synchronization of the load current with the idle run voltage. Fig. 9 presents example waveforms of the encoder signal, the voltage on the converter output, and the load current, that confirm the correctness of the assumed control conception.

Forcing of this kind of load has revealed the unique character of the energy circuit of this machine. Although it is an alternating current machine, its winding has pure resistive character that confirmed obtaining the practical dissipationlessness in the tested range of loads and frequencies. Stiff external characteristics have been obtained, as in Fig. 10, with constant inclination coefficient connected with the voltage drop on the stator resistance. In thus compensated magnetic circuit for the upper range of the

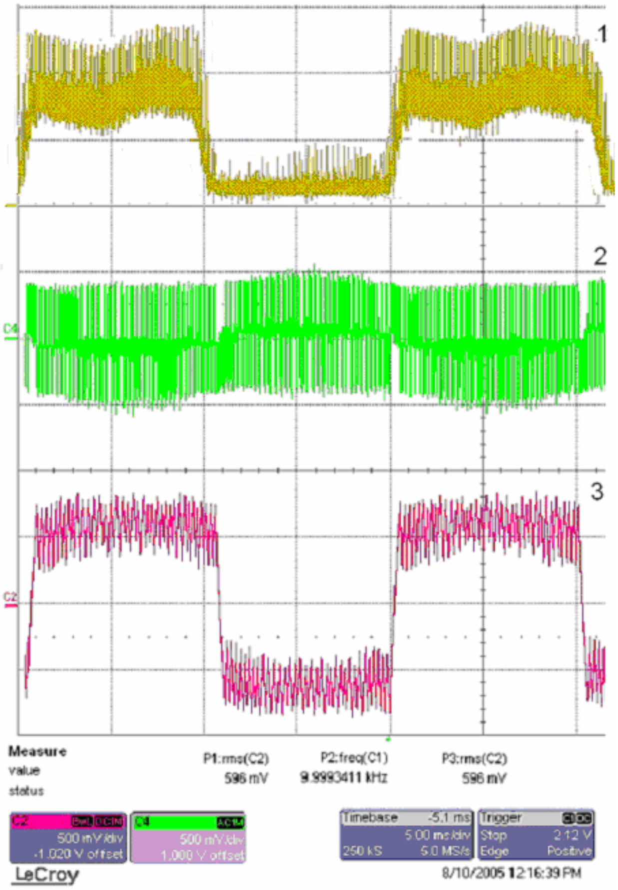

Fig. 9. Basic waveforms of current and voltage for generator operation of the machine for 50Hz, where:
1 synchronization signal of the encoder
2 waveform of the output voltage of the machine
3 forced waveform of the load current

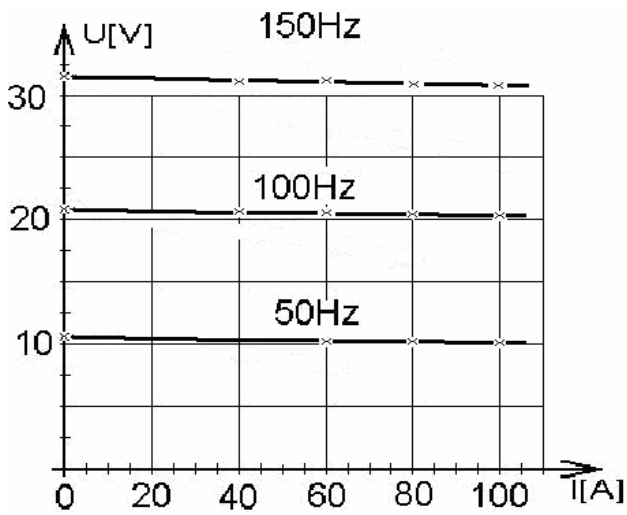

Fig. 10. External characteristics of the machine at loading with the electronic power converter with forced waveform of the current compatible with the internal voltage of the machine, for the frequencies 50, 100 and 150Hz (shaft speeds 167, 333 and 500rpm, respectively).

tested frequency 150Hz no additional voltage drops could be observed, connected with the effects of current displacement or increase of dissipation reactance. This proves the correctness of the assumed principles for shaping of the reactive structure for this type of machines. Limitation of the load current to 100A resulted from the current capacity of the available converter, and the upper range of the tested frequency has been limited to 150Hz for fear of damaging the machine.

Conclusions

The presented constructional principles used for construction of the machine model according to the slot cutting conception are based on a dissipationless loop of the magnetic flux and additional magnetomotive forces in the kinetic system of the rotor create technical possibilities for introduction of an insulator substitute for magnetic flux in the reactive structures of electrical machines. Multiplication of magnetization of the stator winding leads to significant increase of the quality factor of the magnetic circuit understood as the ratio a/b (Fig. 1) for a given level of dissipation fluxes. Thanks to this, it becomes possible to construct machines of large numbers of pole pairs and full ability to develop torques. The distinguishing feature of these machines – the low diameter – opens the way to high-speed applications, where machines of this type appear as high-frequency machines with so far unknown high densities of unit power. The paper is limited to discussion of the distribution of magnetic fluxes and generated voltages in selected reactive structures of machines, while the values of flux distribution, magnitudes of generated forces and transferred energy as a function of the field magnets rotation angle α in relation to the stator teeth shall be the subject matter of another paper.

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