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Comparative Analysis of Conventional Synchronous Machines and a Synchronous Machine Constructed According to the Slot Cutting Conception

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Abstract: - Presented are fundamental principles of electromechanical energy conversion in idealized reactive structures of conventional synchronous machines with permanent magnets, with various numbers of pole pairs, meeting the conditions of operation as electrical transmission. Given are fundamental relationships of generated torque and mechanical energy in the kinetic circuit **y** of a machine constructed according to the slot cutting conception. Presented are comparisons and diagrams illustrating the differences of achieved parameters between the equivalent reactive structures of conventional machines and the equivalent reactive structure of a machine constructed according to the slot cutting conception. The notion of equivalence means maintaining the same amount of active materials (Cu, Fe) in the reactive structures of described machines.

Key-Words: Synchronous machines; New constructions; New technologies.

1 Introduction
The paper concerns the analysis of fundamental relationships of conventional synchronous electrical machines and the comparison with a model of a new kind of synchronous machine, constructed according to the slot cutting conception. A model of that kind of machine, being under construction, has been presented at the conferences SME\`04 and ICEN\`04. The constructed model of that machine has been tested in the Laboratory of Electrical Machines of the Gdansk University of Technology, confirming the correctness of the adopted conception of operation. Papers with obtained experimental results of the tested machine model has been submitted for publication in PE and IEEE. The base for operation of that type of machines is the loop of ideal magnetic flux and a physical model of dissipationless $E_{el} \Leftrightarrow E_{mech}$ converter designed on its basis. Technical and constructional solutions applied for shaping of the reactive structure of that machine lead to multiplication of magnetization of the stator winding and introduce a substitute of insulator for the magnetic flux. That makes it possible to break the limitations of conventional electrical machines in direction of increasing their density of unit power. The introduced principles of shaping the reactive structure permit the construction of a new type of low-speed (for 50 Hz) electrical machines with large number of pole pairs and ability to generate large torques. The low diameter of those machines opens the way to high-speed applications, where they appear as high frequency machines with so far unknown high densities of unit power. That kind of machines opens a new quality in the field of utilization and conversion of electrical energy, creating a new family of light-weight and efficient electromechanical converters for application in engineering.

2 Determination of Fundamental Relationships of Synchronous Machines Meeting the Conditions of Operation as Electrical Transmission
Fig. 1a, b, and c presents three fragments of the reactive structures of synchronous machines scaled according to the principle of maintaining the same amount of active materials (Fe, Cu) in their reactive structures. A machine as in fig. 1a is the basic single-phase conventional synchronous machine with the number of pole pairs p = 6, whose reactive structure geometry ensures the correctness of operation due to a low level of dissipation fluxes. Fig. 1b presents the reactive structure of that machine scaled to a large number of pole pairs p = 18, with radially maintained winding distribution, (dim. a = const). Unfavourable ratio of tooth height to its width as a/b of that machine is the cause of the large part of dissipation fluxes in a real application, which prevents its correct operation. However, if one considers the analysis of operation of those reactive structures as idealized synchronous machines, i.e. machines where the size of dissipation fluxes is not taken into account in the $E_{el} \Leftrightarrow E_{mech}$ conversion process, then those structures meet the conditions of electromechanical conversion of energy as electrical transmission, according to the following relationship:

$$P_{el}=P_{mech}=T_{N(p=6)}*\omega_{N(p=6)}=T_{N(p=18)}*\omega_{N(p=18)} \quad (1)$$

Condition (1) is met for the same supply voltage frequency, the same cooling conditions determined by the surface S_H, and the same amount of active materials (Cu, Fe) in the reactive zone. Unchanged amount of active materials in the reactive zone of the machine is ensured by the same rotor diameter $\mathbf{d_w}$, the same ratio **c/b**, the same tooth height **a**, and the same depth dimension **d**.

2.1 Determination of the Density of Field Magnet Flux Φ_{MG} & the Density of Stator Flux Φ_S, Φ_{SR}.

The conditions for constancy of electromechanical conversion of energy for both idealized reactive structures as electrical transmission are ensured in the case of maintaining the same densities of field magnet flux Φ_{MG} and densities of stator flux Φ_{SR} that link the stationary system **x** connected with the electrical energy circuit E_{el} and the machine's kinetic system **y** connected with the mechanical energy circuit E_{mech}, into the $E_{el} \Leftrightarrow E_{mech}$ conversion process. Both those fluxes are marked in figures in a separated form for one magnetic pole. For the same density of fluxes and the same depth dimension **d**, the pole pitch expressed in $^{o}{}_{mech}$ determines the value of magnetic pole flux. Therefore:

$$\Phi_{MG(p=18)} / \Phi_{MG(p=6)} = \Phi_{SR\ (p=18)} / \Phi_{SR\ (p=6)} = 1/3 \qquad (2)$$

When operating on relative quantities, the value of magnetic reluctance can be expressed directly in mm as the thickness of gap δ_{air}, and of magnetomotive forces MMF as $\delta_{MMF(T)}$. The magnetic reluctance of iron as $R_{M(Fe)}$ for compatible position of the magnetic pole and the field magnet pole can be assumed as equal to zero due to the lack of saturation of the magnetic pole for that position in relation to the field magnet pole. For that size of described machines it is assumed that:

$$\boldsymbol{\delta_{air}} = 0.2 \text{ mm and } \boldsymbol{\delta_{MMF(T)}} = 3.5 \text{ mm} \qquad (3)$$

Field magnet flux density $B_{M(T)}$ for both machines as in fig. 1a and b can be determined from the relationship:

$$B_{M(T)(p=6)} = B_{M(T)(p=18)} = B_{W(T)} \frac{\delta_{MMF\ (T)}}{\delta_{MMF\ (T)} + \delta_{air}} \qquad (4)$$

After substituting the value from (3) we obtain:

$$B_{M(T)(p=6)} = B_{M(T)(p=18)} = 0.946\ B_{W(T)} \qquad (5)$$

where: $B_{W(T)}$ – MMF self-induction of a conventional machine

Stator flux value Φ_S is determined for the same values assumed of current I_S in the stator, because after scaling of those machines the section of windings remains the same and the same cooling conditions determined by the surface S_H are assumed. But in scaling process , of machines such as in Fig. 1a and 1b from the number of pole pairs p=6 to p=18 involves a decrease of the specific electric loading of the winding and narrowing of the tooth width **b**. Starting from the equation for the flux value: $\Phi = I^*z/R_M$, the

a)

b)

c)

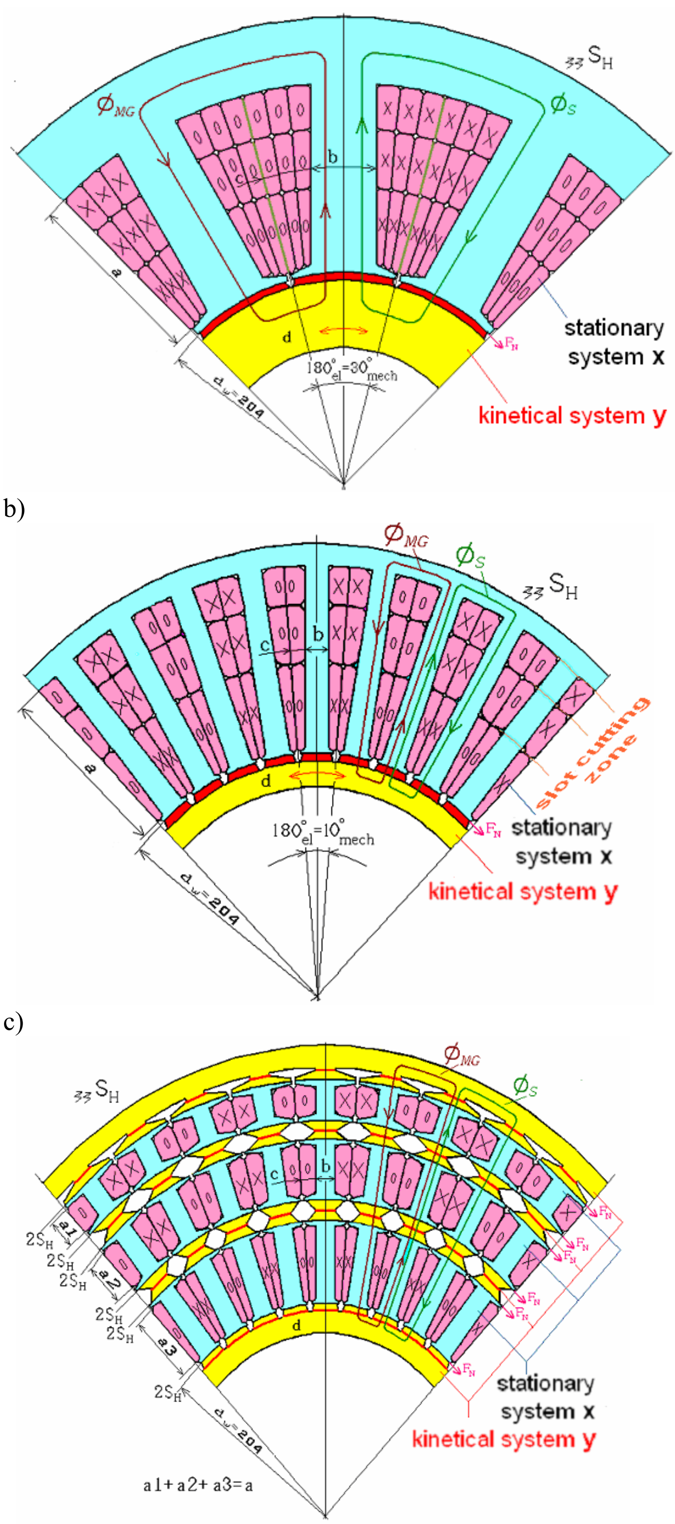

Fig. 1. Fragments of single-phase reactive structures of synchronous machines, where:

a – real conventional machine with the number of pole pairs p=6

b – idealized conventional machine with the number of pole pairs p=18

c – realized machine constructed according to the slot cutting conception, with the number of pole pairs p=18

reluctance value R_M is determined as: $R_M = l/\mu_o * S_P$, where:
l- air gap length, $l=\delta_{MMF}+\delta_{air}$
S_P- magnetic pole surface area. For the same depth dimension **d** of the discussed machines, the magnetic pole surface area S_P determines its width $\mathbf{b}_P$, connected by the relationship:

$$b_{P(p=6)}/b_{P(p=18)} = p_{(p=18)}/p_{(p=6)} = 3 \qquad (6)$$

thus for a machine as in Fig. 1a:

$$\Phi_{S(p=6)} = \frac{I_S * z_{(p=6)}}{\delta_{MMF} + \delta_{air}} * b_{P(p=6)} \qquad (7)$$

And for a machine as in Fig. 1b:

$$\Phi_{S(p=18)} = \frac{I_S * z_{(p=18)}}{\delta_{MMF} + \delta_{air}} * b_{P(p=18)} \qquad (8)$$

Fig. 1a and b shows that, for such scaled reactive structures of those machines, the condition of maintaining the winding turns is met as:

$$z_{(p=18)}/z_{(p=6)} = 3/9 = p_{(p=6)}/p_{(p=18)} = 1/3 \qquad (9)$$

Taking into account the relationships from 6 to 9, for such scaled machines the stator flux value is determined as:

$$\Phi_{S(p=6)}/ \Phi_{S(p=18)} = (p_{(p=18)}/ p_{(p=6)})^2 = 9 \qquad (10)$$

because the magnetic pole section decreases linearly to pole pairs p, thus the stator flux density B_S meets the relationship:

$$B_{S(p=6)}/B_{S(p=18)} = p_{(p=18)}/ p_{(p=6)} = 3 \qquad (11)$$

Scaling of machines while maintaining the same amount of active materials (Cu, Fe) in the reactive zone causes linear decrease of the stator flux density B_S proportionally to the increase of the number of pole pairs. The field magnet flux density B_{MG}, however, remains the same and does not depend on the number of pole pairs.

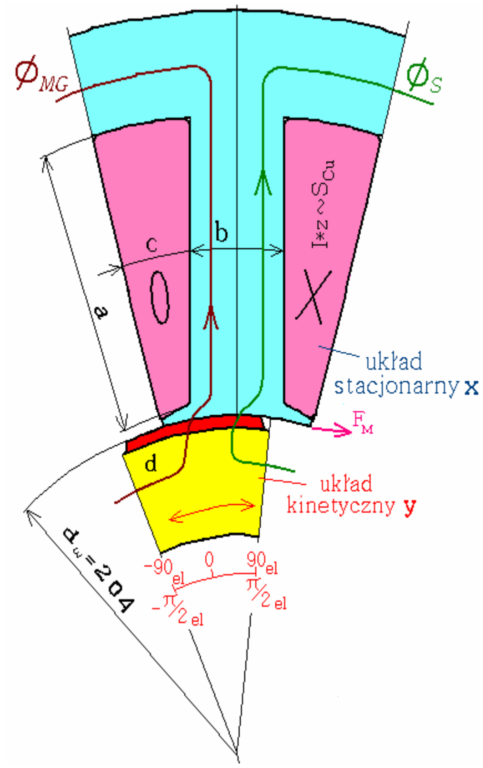

Fig. 2. Unitary magnetic pole meeting the condition of generating constant density of flux Φ_{MG}, and density of flux Φ_S proportional to the magnetic pole width **b** as **b** = var.

2.2 - Generated Torque and Energy Value in Unitary Magnetic Pole.

Fig. 2 presents an unitary magnetic pole for the same depth dimension **d**, the same tooth height **a**, and the same rotor diameter $\mathbf{d_w}$. MMF thickness as $\delta_{MMF(T)}$ and gap thickness as δair also remain constant and determined as in (3). Also the ratio **c/b** remains constant. The tooth width, however, is treated as variable **b=var**. Also the field magnet pole width is changing proportionally to **b**. Thus specified unitary magnetic pole ensures constant density of flux Φ_{MG} for any width **b**. The density of stator flux Φ_S is changing proportionally to **b**.
When determining the torque generated in unitary magnetic pole, it should be noted that a deflection of the main flux ϕ_{MG} by $90^0{}_{el}$ in order to generate the maximum torque is effected by lateral flow of flux Φ_S. The path of that deflection, expressed in ${}^0{}_{mech}$, is dependent on the number of pole pairs.
For a machine with p=6 for $90^0{}_{el}$ the offset on the pole pitch is $15^0{}_{mech}$. For a machine with p=18 for $90^0{}_{el}$ the offset on the pole pitch of the machine is $5^0{}_{mech}$. Therefore, when the number of pole pairs is increased, the decreasing induction of the flux Φ_S is "sufficient" for generating the maximum torque value. The dependence of the offset path on the number of pole pairs is connected with the characteristic value of the field magnet flux Φ_{MG} as $d\Phi/d\alpha_{mech}$ and it must be taken into account in the equation for the value of generated torque. The characteristic value of the field magnet flux can be determined by the relationship:

$$\frac{d\Phi_{(p=6)}/d\alpha_{mech}}{d\Phi_{(p=18)}/d\alpha_{mech}} = p_{(p=6)}\Big/p_{(p=18)} = 1\Big/3 \qquad (12)$$

Instantaneous value of the generated torque T_M is determined by the relationship:

for p=6 $\quad T_M = p_{(p=6)}/p_{(p=6)} * B_{MG} * B_{S(p=6)} * \sin\alpha_{el}$
for p=18 $\quad T_M = p_{(p=18)}/p_{(p=6)} * B_{MG} * B_{S(p=18)} * \sin\alpha_{el}$ (13)

In result of multiplication of the stator induction B_S by the characteristic value of the field magnet flux B_{MG}, it is possible to introduce the notion of recalculated inductance of the stator B_{SR}, as:

for p=6 $\quad B_{SR} = p_{(p=6)}/p_{(p=6)} * B_{S(p=6)} = B_{S(p=6)}$
for p=18 $\quad B_{SR} = p_{(p=18)}/p_{(p=6)} * B_{S(p=18)} = B_{S(p=6)}$ (14)

Thus determined value of recalculated inductance of the stator B_{SR} makes the stator magnet reluctance independent of tooth section and ensures a constant value of the stator inductance B_{SR} for any number of pole pairs p.
Having thus determined value of inductance B_{SR}, the value of instantaneous torque T_M generated in unitary magnetic pole depends on the field magnet flux density B_{MG} and the stator flux density B_{SR} according to the relationship:

$$T_M = B_{MG} * B_{SR} * \sin\alpha_{el} \qquad 15)$$

and does not depend on the magnitude of fluxes Φ_{MG} and Φ_{SR}.
The average value of torque T_{AV} in its full range of variability from $-90^o{}_{el}$ to $90^o{}_{el}$ can be determined as:

$$T_{AV} = \frac{1}{\pi}\int_{-\pi/2}^{\pi/2} B_{MG} * B_{SR} * \sin\alpha * d\alpha \qquad (16)$$

because the field magnet flux density B_{MG} may be treated as constant in a properly designed geometry of the reactive structure of a machine. The magnitude of generated average torque T_{AV} in the magnetic pole is determined by the course of changes of the stator flux induction B_{SR}. For any position of the magnetic pole in relation to the field magnet, the magnetic reluctance of the magnetic pole as $R_{MFe(\alpha)}$ must be taken into account, because it plays the key role in switching on and off of the fluxes Φ_{MG} and Φ_{SR} while they enter and leave the field magnet influence zone. It is a complex non-linear relationship connected with saturating the iron of the stator magnetic pole. In that case $R_{MFe(\alpha)}$ is represented as substitute gap thickness expressed in mm.

In the considered range of variability of the generated torque from $-\pi/2$ to $\pi/2$, the value of exchanged energy in the unitary magnetic pole E_U between the stationary system **x** and the kinetic system **y** is determined by the relationship:

$$E_U = \frac{1}{\pi}\int_{-\pi/2}^{\pi/2} B_{MG} * \frac{I_S * z}{\delta_{MMF} + \delta_{air} + R_{MFe(\alpha)}} * \alpha * \sin\alpha * d\alpha \qquad (17)$$

The offset value in expression (17) may represent the angle α due to the constancy of diameter $\mathbf{d_w}$ of the discussed unitary magnetic pole. The value of energy E_U in the unitary magnetic pole can be calculated using modern, field-type, numerical computing methods and it is proportional to the energy accumulated in the magnetic field of fluxes Φ_{MG} and Φ_{SR}. Therefore, if the course of current I_S in relation to the pole pitch of stators of both reactive structures as in fig. 1a and b, expressed in $^{o}{}_{el}$, is described by the same function, then the average values of torques T_{AV} and of exchanged energy E_U in the unitary magnetic pole meet the conditions:

$$T_{AV(p=6)} = T_{AV(p=18)} \text{ and } E_{U(p=18)}/\, E_{U(p=6)} = 1/3 \qquad (18)$$

The magnitudes of fluxes Φ_{MG} and Φ_{SR} decide about the span of magnetic pole on the pole pitch of a machine, expressed in $^{o}{}_{mech}$, and about the conversion path in the full range of variability of the generated torque, counting from $-90^{o}{}_{el}$ to $90^{o}{}_{el}$. Thus, the magnitude of magnetic pole flux decides about the number of pole pairs. Because the total value of fluxes Φ_{MG} and Φ_{SR} on the entire perimeter of the rotor remains the same in machines as in fig. 1a and b, the magnitude of the converted power also remains constant, meeting the condition of operation as electrical transmission, since:

$$T_{N(p=6)} = T_{AVN} * 2p_{(p=6)} \text{ and } \omega_{N(p=6)} = \omega_{N(p=1)}/p_{(p=6)}$$
$$T_{N(p=18)} = T_{AVN} * 2p_{(p=18)} \text{ and } \omega_{N(p=18)} = \omega_{N(p=1)}/p_{(p=18)} \qquad (19)$$

2.3 Comparative Characteristics of Described Machines as in fig. 1a and b.

For the depth dimension **d** = 50 mm of the reactive structures of machines as in fig. 1a and b, their power has been estimated on the level of approx. 6 kW, and examples of basic characteristics have been presented on that basis, as in fig. 3.

The external characteristics 1 and 2 present the range of

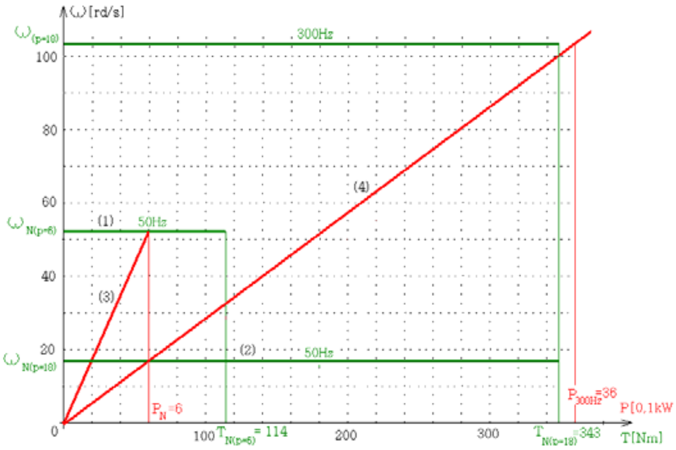

Fig. 3. Basic characteristics of idealized reactive structures of synchronous machines as in fig. 1a and b.

variations of the load torque up to the nominal torque for both machines, at the nominal voltage frequency of 50 Hz. The characteristics (3) and (4) present the course of developed power for the nominal load torque for both machines versus the rotational speed and thus also the operating voltage frequency. For 50 Hz the developed power for both machines is 6 kW.

It can be seen that the electrical machine with reactive structure presented in fig. 1b has a hidden potential for increasing the density of unit power. Its basic features are the ability to develop large torques at very low speeds. At the same time its low diameter opens the way to high-speed applications. For ω = 105 rad/s (1000 rpm) its equivalent power increases to 36 kW at the voltage frequency of 300 Hz. Unfortunately, both in conventional and real electrical machine the marginal effects, connected with narrowing the magnetic pole width **b** at its constant height **a**, cause most of the flux to close in form of dissipation fluxes, without binding the systems **x** and **y** in the $E_{el} \Leftrightarrow E_{mech}$ conversion process. That prevents the correct operation of such a redesigned machine.

3 Analysis of Fundamental Relationships of the Reactive Structure of a Machine Constructed According to the Slot Cutting Conception

For that purpose, in order to reduce the values of dissipation fluxes in the reactive structure of a machine as in fig. 1b, it was decided to assume the conception of slot cutting and to introduce additional magnetomotive forces MMF, connected with the kinetic system of the rotor, into the cutting zone. Such a constructional solution leads to multiplication of magnetization of the stator winding and to reduction of dissipation fluxes of the machine. That solution is forced by the specific conditions of shaping the magnetic circuit, for which there are no insulating materials to limit the dissipation fluxes. In result of the developed principles of correct operation of shaping the reactive structures of conventional machines, the ratio of toot length to its width as a/b cannot exceed adequate factors. An attempt to increase that ratio leads quickly to the increase of dissipation fluxes that spoil the quality of the $E_{el} \Leftrightarrow E_{mech}$ conversion. The ratio a/b for a magnetic circuit can be treated as its quality factor. For the lack of insulating materials, the only way to improve it is, to divide the magnetic potential of the exciter into several smaller potentials and to arrange them along the flow path of the constructed magnetic core, as in the reactive structure of the machine in fig. 1c. Such a constructional solution permits the implementation of practical applications for the attractive reactive structure of a machine as in fig. 1b, which introduces a high characteristic value of the flux $d\Phi/d\alpha^{o}_{mech}$, which is unattainable in conventional machines, and which intensifies the $E_{el} \Leftrightarrow E_{mech}$ conversion process.

3.1 Constructional Solutions Aimed at Ensuring the Same Densities of Fluxes Φ_{MG} and Φ_{SR} in the Reactive Structures of Machines from fig. 1b & c.

In order to divide the magnetic potential of the exciter for shaping the magnetic circuit in the reactive structure of a machine as in fig. 1c, conventional MMFs have been replaced with prepared elements of low reluctance for magnetic flux, as sandwich MMFs according to [6]. In order to ensure the same densities of stator fluxes Φ_{SR} in the reactive structures of the described machines as in fig. 1b and c, which have the same specific electric loading of windings, the condition of equal magnetic reluctance for compatible position of the magnetic pole in relation to the field magnet must be met, when the minimum reluctance $R_{M(Fe)} \cong 0$, thus:

$$R_{M(T)} = R_{M(CZ)}$$

$$\delta_{MMF(T)} + \delta_{air} = 4 * \delta_{MMF(CZ)} + 6 * \delta_{air} \qquad (20)$$

whereas the density of field magnet flux $B_{MG(CZ)}$ can be determined from the relationship:

$$B_{MG(CZ)} = B_{W(CZ)} * \frac{4 * \delta_{MMF(CZ)}}{4 * \delta_{MMF(CZ)} + 6\delta_{air}} \qquad (21)$$

From the condition (15) and the determined values of $\delta_{MMF(T)}$ and δ_{air} as in (3), the thickness $\delta_{MMF(CZ)}$ can be determined as:

$$\delta_{MMF(CZ)} = \frac{\delta_{MMF(T)} - 5\delta_{air}}{4} = 0.626 \text{ mm} \qquad (22)$$

Having determined the thickness of sandwich MMF as in (17), the density of field magnet flux can be determined from (16) as:

$$B_{MG(CZ)} = 0.676 B_{W(CZ)} \qquad (23)$$

For that purpose, in order to have the same densities of field magnet flux in the reactive structures of both machines as in fig. 1b and c, the self-induction of sandwich MMF $B_{W(CZ)}$ must be higher and can be determined by comparing the flux density of a conventional machine as in (5) and of a machine with slot cut as in (23), as:

$$B_{W(CZ)} = \frac{0.946}{0.676} * B_{W(T)} = 1.4 * B_{W(T)} \qquad (24)$$

Thus the specified parameters of the reactive structure of a machine as in fig. 1c ensure the same densities and magnitudes of fluxes Φ_{MG} and Φ_{SR} as in the reactive structure of a machine from fig. 1b.

3.2. - Fundamental relationships connected with generation of torque and energy in a machine constructed according to the slot cutting conception as in fig. 1c.

Table 1. Dimensions of the reactive structure of the constructed model.

Specification of structure elements		Dim. [mm]
Diameter of internal rotor:	internal	182
	external	204
Diameter of internal stator:	internal	204
	external	240
Diameter of internal intermediate rotor:	internal	240
	external	257
Diameter of intermediate stator:	internal	257
	external	287
Diameter of external intermediate rotor:	internal	287
	external	304
Diameter of external stator:	internal	304
	external	325
Diameter of external rotor:	internal	325
	external	352
Depth dimension d		50
Air gaps δ_{air}		0.2
Winding loop section in [mm^2]		75

Table 1 presents the basic dimensions of the reactive structure of the constructed machine model, based on a conventional machine as in fig. 1b, with application of three cuts of stator slots. Fig. 4 presents one pole of the reactive structure of the machine for any position of the stator magnetic pole in relation to the field magnet. Fig. 4 shows that in thus created reactive structure of a machine there are n = 6 reactive bands, which for the given densities of fluxes Φ_{MG} and Φ_{SR} give 6-fold increase of electromagnetic forces. The dimensions presented in table 1 have also been used to determine the substitute diameter d_{sr} of multi-gap reactive structure of a machine for the action of the resultant force F_{WYP} as:

$$d_{sr} = (204+240+257+287+304+325)/6 = 270 \qquad (25)$$

Considering the increase of average radius of action of the resultant forces, the relationship for the value of instantaneous torque $T_{M(CZ)}$ in the entire conversion variations range from -90^{0}_{el} to 90^{0}_{el} can be written as:

$$T_{M(CZ)} = n * \frac{d_{sr}}{d_w} * B_{MG} * B_{SR} * \sin\alpha \qquad (26)$$

and respectively, the value of average torque $T_{AV(CZ)}$ of

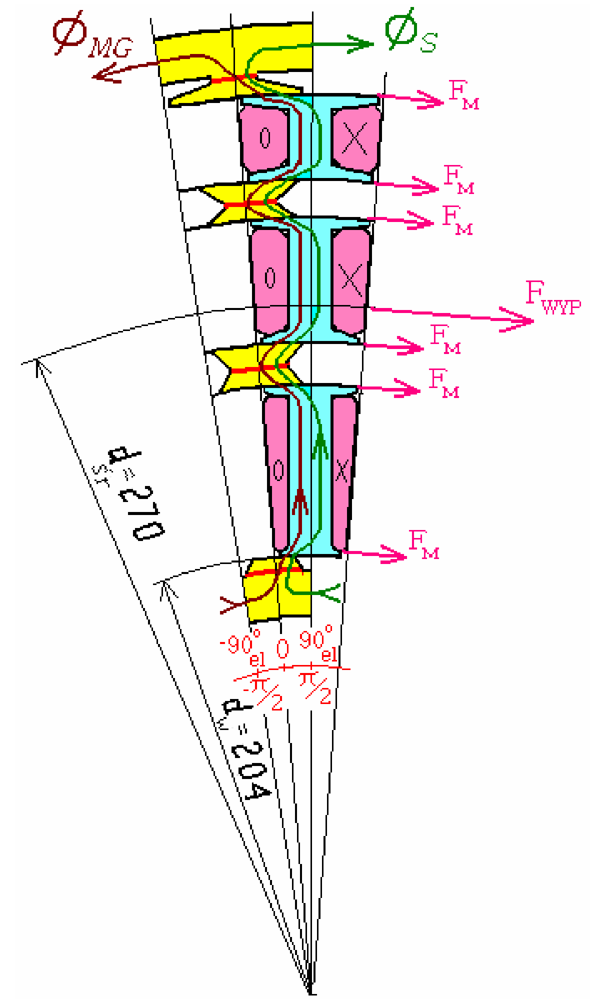

Fig. 4. Unitary magnetic pole of the constructed synchronous machine model for three slot cuts.

the discussed magnetic pole in that range can be determined as:

$$T_{AV(CZ)} = \frac{1}{\pi}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} n * \frac{d_{sr}}{d_w} * B_{MG} * B_{SR} * \sin\alpha * d\alpha \qquad (27)$$

In order to determine the relationship for the value of energy $E_{U(CZ)}$ exchanged in the entire range of variations of the generated torque from -90^0_{el} to 90^0_{el} in the multi-gap structure of the magnetic pole, it is necessary to introduce the notion of average circuital flux density, because the constant flux density concerns the constant tooth width **b**, whereas the conversion path increases proportionally to the diameter. For the substitute value of diameter d_{sr}, the average circuital flux density is in an inverse relationship as for the diameter d_w and the increase of diameter of action of the resultant forces while determining $E_{U(CZ)}$ is compensated. It can thus be written that:

$$E_{U(CZ)} = \frac{1}{\pi}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} n * B_{MG} * \frac{I_S * z}{4\delta_{MMR(CZ)} + 6\delta_{air} + R_{MFe(n\alpha)}} * \alpha * d\alpha \qquad (28)$$

Since the designed reactive structures of machines as in fig. 1c and 1b ensure the same densities and magnitudes of fluxes Φ_{MG} and Φ_{SR}, therefore for the same course of current I_S for both machines the value of converted energy for one magnetic pole meets the condition:

$$E_{U(CZ)} = E_{U(p=18)} \qquad (29)$$

because the conversion path expressed in $^o{}_{mech}$ for both discussed machines as in fig.1b and c is the same too, so the average values of developed torque also meet the condition:

$$T_{AV(CZ)} = T_{AV(p=18)} \qquad (30)$$

That apparent contradiction results from the fact that in expression (28) for the value of energy $E_{U(CZ)}$ exchanged in the magnetic pole, apart from n-fold increase of electromagnetic forces, there is the multi-gap magnetic reluctance denoted as $R_{MFe(n\alpha)}$ and it is also hidden under the symbol B_{SR} in (26) and (27).

If the condition of equality of the minimum magnetic reluctance R_{MFe} for single-gap and multi-gap machine as in fig.1b and c is met, then the multiplied magnetization of the stator introduces a substitute of insulator into the reactive structure of a machine.

The transfer of energy between the magnetic flux and the mechanical circuit occurs at n-fold increase of electromagnetic forces and n-times shorter conversion path, and responsible for that is just the multi-gap reluctance $R_{MFe(n\alpha)}$.

One may say that the operation of machine as in fig. 1c corresponds to the operation of machine from fig. 1b working in a medium whose relative magnetic permeability outside the magnetic circuit is $\mu_r = 1/n$, where n = 6 in this case. Nature does not give direct possibilities to have materials of such insulating properties, usable for construction of magnetic circuits.

If one would consider a redesigned real correctly operating conventional machine as in fig. 1a, with application of the slot cutting conception, then the result of those actions would be very depressing. Apart from the limitation of dissipation fluxes, which are insignificant in this case, the introduction of the multi-gap structure will not cause proportional, or any other, increase of the average value of electromagnetic forces $T_{AV(CZ)}$. Also the increase of average reaction radius will not bring any result, if it will not be accompanied by adequate increase of the total flux on a given circumference.

Probably that is the reason why, despite so many years of intensive study and research aimed at increasing the density of unit power, such a great mystery of Nature in the electrical machines has remained concealed.

Utilization of the slot cutting conception should not have been applied for redesigning of a real correctly operating conventional machine in order to increase power, because it would have no effect, but for a non-existent and unreal reactive structure of a machine whose winding would be „immersed" in large values of dissipation fluxes, in order to limit them. With such an approach, the level of converted power is not changed also (for 50 Hz), but the realized reactive structure of such a machine introduces to the $E_{el} \Leftrightarrow E_{mech}$ conversion process, as if from itself, a high characteristic value of $d\Phi/d\alpha^{o}_{mech}$, unattainable for conventional machines.

And that is just what has been the point all the time, because in such a real created structure as in fig. 1c in relation to the real reactive structure of a machine as in fig. 1a on the basis of the principles of electromechanical conversion of energy in machines as electrical transmission, for a constant level of converted power there occurs a transformation of rotational speed into torque.

Next, the low diameter of such a constructed machine opens the way to high-speed and high-frequency applications, which leads to multiplication of the values of equivalent power with full respect for the magnitude of energy accumulated in the magnetic field.

In the $E_{el} \Leftrightarrow E_{mech}$ conversion process the energy of magnetic field is an intermediate stage in the exchange between the electrical energy and the mechanical energy in the stationary system **x** and the kinetic system **y** of an electrical machine.

The magnetic field thus cannot transfer more energy than it is able to accumulate in itself.

If ferromagnetic materials, due to saturation, do not allow to increase the quantity of flux utilized for the $E_{el} \Leftrightarrow E_{mech}$ conversion process in a given machine volume, then the only possibility left is to increase the characteristic value of that flux as $d\Phi/d\alpha^{o}_{mech}$, as in result of the applied process of multiplied magnetization of the stator according to the assumed slot cutting conception.

The presented paper is limited only to the analysis of fundamental relationships concerning the quantities of generated torques and mechanical energy E_{mech} in the kinetic system **y** of conventional machines, and a machine constructed according to the slot cutting conception.

Connection of the magnetic field energy with the electrical energy E_{el} in the stationary system **x** of discussed machines shall be the subject of another paper.

3.3 Comparative Characteristics of Electrical Machines for Reactive Structures as in fig. 1a, b, and c

Also the increase of constructional complexity of the reactive structure of a machine as in fig. 1c is not without effect. That change of construction results in a great increase of surfaces passing directly through the zones of emitted heat.

If constructional solutions as in [8] will force lateral air flow in the reactive structure of a machine, then those additional surfaces will be included in the cooling process.

That results directly in an increase of the limiting thermal current I_{TH}. Assuming a constant surface film conductance for all additional surfaces of the reactive structure of a machine, the increase of the limiting thermal current can be determined as:

$$I_{TH(CZ)} = \sqrt{\Sigma S_H / S_H} * I_{TH(T)} = k_{SH} * I_{TH(T)} \qquad (31)$$

For the constructed machine model, for the same depth dimension **d** the increase of the cooling surface is determined by the diameters of individual gaps as in table 1, thus:

$$k_{SH} = \sqrt{\frac{352+2*325+2*304+2*287+2*257+2*240+2*204}{352}} = 3.2 \qquad (32)$$

Assuming the linearity of the magnetic circuit for flux Φ_{SR} in the reactive structure of a machine, the increase of equivalent power between a real conventional machine as in fig. 1a and a machine constructed according to the slot cutting conception as in fig. 1c is as determined in (32). For a constant supply voltage frequency, the increase of equivalent power is connected with increasing the ability to develop torque of such a redesigned machine.

Assuming for conventional machines as in fig. 1a and b the level of nominal power $P_{N(T)} = 6$ kW, the power of a machine constructed according to the assumed slot cutting conception as in fig. 1c, taking into account the increase of the limiting thermal current I_{TH}, shall amount to:

$$P_{N(CZ)} = k_{SH} * P_{N(T)} = 19.2 \text{ kW} \qquad (33)$$

For such levels of assumed powers, fig. 5 presents diagrams illustrating the differences of obtained parameters of such constructed machines.

The characteristics 1, 2, and 3 present the range of developed torque up to the nominal torque determined by the limiting thermal current for the nominal supply voltage frequency of 50 Hz. The characteristics 4, 5, and 6 present the developed power versus frequency for the nominal values of load torques. Note that the characteristics 2 and 5 concern an idealized structure of a conventional machine as in fig. 1b, whose performance in reality is far

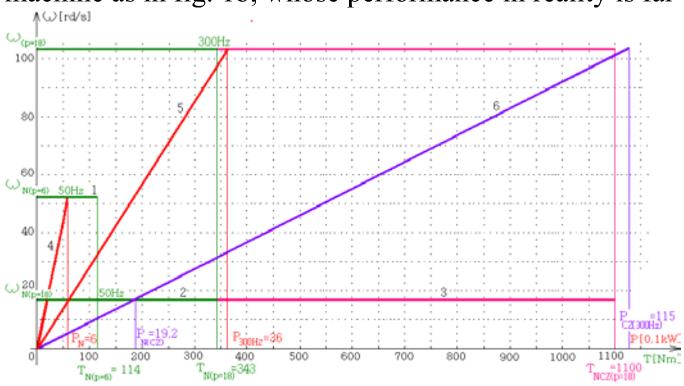

Fig. 5. Basic characteristics of electrical machines whose reactive structures are presented in fig. 1a, b, and c.

beyond the range of presented values. Available for practical comparison remains the performance of real machines, i.e. the conventional machine from fig. 1a, whose parameters are illustrated by the characteristics 1

and 4, and the machine from fig. 1c, constructed according to the slot cutting conception, whose parameters are illustrated by the characteristics 3 and 6.
Those are theoretical calculations that reveal the potential possibilities of such a shaped structure, which should be aimed at in practice by solving problems related to field, strength, materials, heat, technology, and construction, which are connected with built of that type of machines.

a)

b)

c)

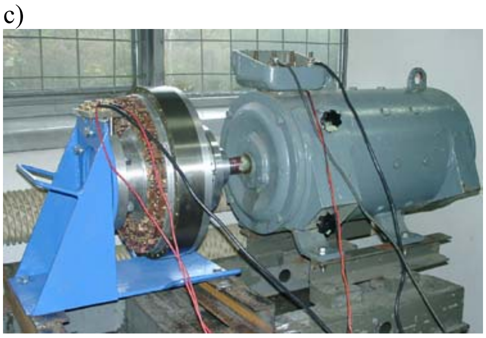

Fig. 6. View of constructional elements of the machine model constructed according to the slot cutting conception, where:
a – machine stator in form of three coaxial reactive cylinders with cut teeth and a part of the associated winding.
b – machine rotor in form of four coaxial field magnets, ensuring multiplied stator magnetization
c – assembled machine on a test stand.

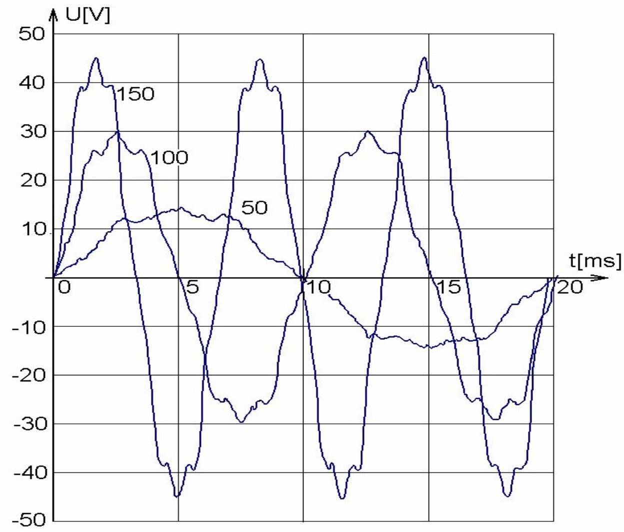

Fig. 7. Voltages generated in the machine for idle running at output voltage frequencies of 50, 100, and 150 Hz.

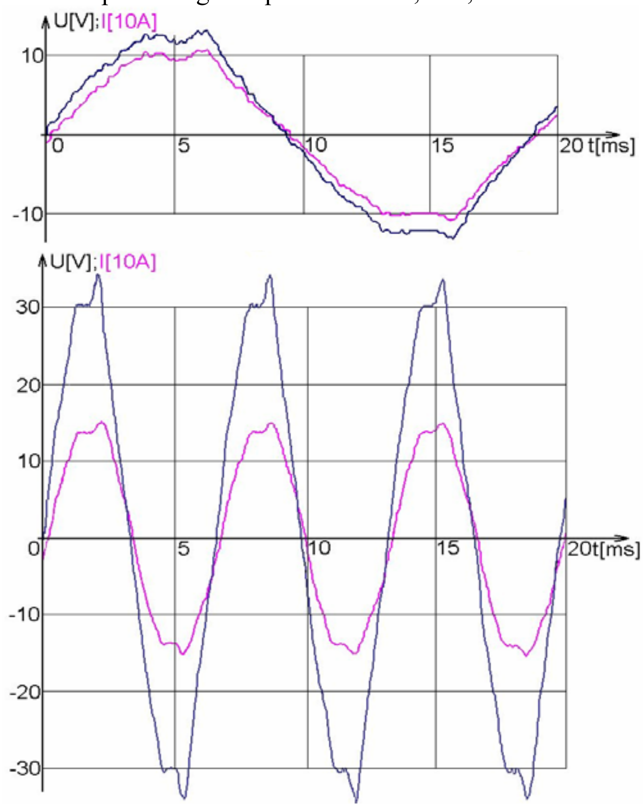

Fig. 8. Voltages and currents generated for resistive load:
a) at generated voltage frequency of 50 Hz and shaft rotational speed of 167 rpm;
b) at generated voltage frequency of 150 Hz and shaft rotational speed of 500 rpm.

Fig. 6 a, b, and c presents constructional details of the machine model constructed according to the assumed slot cutting conception, whose reactive structure is presented in fig. 1c and 4.
Fig. 7 to 9 present basic diagrams of output voltage and current for different levels of load and frequency. They

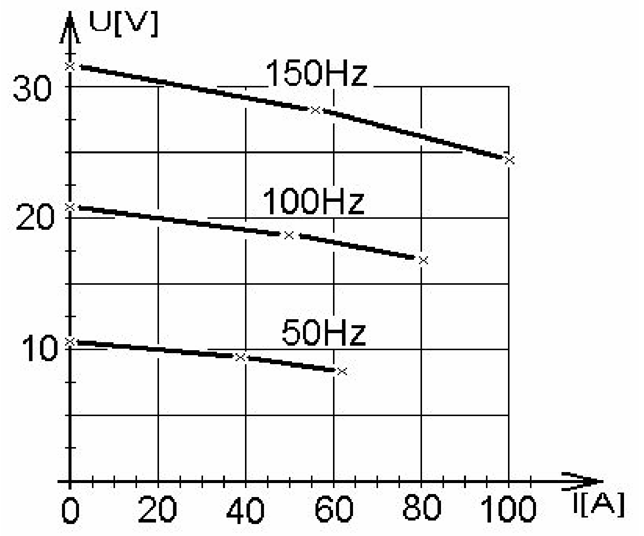

Fig. 9. External characteristics for resistive load at output voltage frequencies of 50, 100, and 150 Hz.

demonstrate correctness of the assumed principles for shaping the reactive structure for such kind of machines. For fear of damaging the constructed model, the testing has been limited to relatively narrow range of loads and speeds.

4. Conclusions

The paper presents the analysis of fundamental relationships connected with generation of torques and energy in the kinetic system **y** of selected reactive structures of two scaled conventional machines fulfilling the principle of electromechanical energy conversion as electrical transmission for a constant level of converted power.

Thus some hidden possibilities have been revealed in the idealized structures of electrical machines with large number of pole pairs, for multiple increase of the density of unit power.

However, technical basis must have been created for limitation of dissipation fluxes in such compact structures On the basis of the developed physical model of a dissipation less $E_{el} \Leftrightarrow E_{mech}$ converter, based on ideal loop of magnetic flux and presented at SME04 and ICEN04, it has been decided to assume the slot cutting conception for shaping of the reactive structure of electrical machines.

The applied constructional solutions lead to multiplied magnetization of the stator winding.

Thus the lack of fully insulating materials for magnetic flux has been compensated by the assistance of active MMFs connected with the kinetic system **y** of the rotor.

For a reactive structure as in fig. 1c of the constructed machine model, the performed analysis for limit values of developed torque and transferred energy gives equivalent powers in relation to a conventional machine as in fig. 1a reaching the level of tens.

That is the structure assumed ad hoc for constructing the model, in order to prove the correctness of the assumed operational principle for such type of machines, and it absolutely does not determine the limits of their possible development.

If one may say that, in result of more than one hundred years of research and development work on conventional machines, the limit of increasing the quantity of flux in a given machine volume used for the $E_{el} \Leftrightarrow E_{mech}$ conversion process has been reached, then the solutions presented in the paper open the way to multiplication of the characteristic value of that flux, as $d\Phi/d\alpha^{o}_{mech}$.

That liquidates the limitations for conventional machines in direction of increasing the density of unit power, and opens the way to construction of a new generation of lightweight and efficient electromechanical converters for engineering applications.

Due to important strategic features of electrical machines constructed according to the assumed slot cutting conception, for the development of modern technologies of control and conversion of electrical energy, they must continue to be researched, developed, and implemented intensively, for the further development of Science and Technology, and for public benefit.

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