Magnetic equivalent circuit model
for unipolar hybrid excitation synchronous machine

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Abstract: Lately, there has been increased interest in hybrid excitation electrical machines. Hybrid excitation is a construction that combines permanent magnet excitation with wound field excitation. Within the general classification, these machines can be classified as modified synchronous machines or inductor machines. These machines may be applied as motors and generators. The complexity of electromagnetic phenomena which occur as a result of coupling of magnetic fluxes of separate excitation systems with perpendicular magnetic axis is a motivation to formulate various mathematical models of these machines. The presented paper discusses the construction of a unipolar hybrid excitation synchronous machine. The magnetic equivalent circuit model including nonlinear magnetization curves is presented. Based on this model, it is possible to determine the multi-parameter relationships between the induced voltage and magnetomotive force in the excitation winding. Particular attention has been paid to the analysis of the impact of additional stator and rotor yokes on above relationship. Induced voltage determines the remaining operating parameters of the machine, both in the motor and generator mode of operation. The analysis of chosen correlations results in an identification of the effective control range of electromotive force of the machine.

Key words: hybrid excitation, magnetic equivalent circuit, synchronous machine

1. Introduction

Synchronous machines excited with permanent magnets, thanks to their high efficiency, good power to mass ratio and absence of sliding contacts, are becoming increasingly popular, both in stationary and mobile applications. However, inability to direct control of the induced voltage is a fundamental disadvantage in drive applications that require a wide range of speed control or stabilization of output voltage with variable load in case of operation as a generator. The search for an effective solution of this problem has been continuing for a few dozens of years now. It is worth mentioning here the systems of capacitive or choke stabilization of output voltage of generators [1] and the methods of control of induced voltage that are based on the change of the flux linkage with the armature phase belt. Among the methods of flux

changes, the most interesting are the ones that are based on the saturation of certain parts of the magnetic circuit with additional winding, resulting in change of the reluctance on the excitation flux path [1], as well as methods based on the mechanical change of this flux by displacement the rotor from the active stator area, or by changing magnets position inside the rotor [14]. However, the above methods are not broadly applicable so far, due to the increased mass of the machine or to the short life-period of the "mechanisms" of the flux change. Synchronous machines excited with permanent magnets together with field windings, that have influence on the shared area of air-gap, are an alternative solutions. These are called hybrid excitation machines.

The constructions of hybrid excitation synchronous machines has been under consideration for many years [3-5, 7-13]. Previously, the main objective of constructing such machines was to assure stabilization of voltage in generating mode during operation under variable loads and speeds with non-slip-ring rotor construction or self-exciting generators with the rectifier in the field winding supply circuit, operating autonomously [3, 5]. Currently, these are considered mostly for application in vehicle propulsion, due to the possibility of extending the range of speed control compared to an analogous machine excited with permanent magnets, together with the relatively high efficiency and absence of sliding contacts [10]. Moreover, the proper adjustment of fluxes generated by both sources makes possible to shift the highest-efficiency area into the most frequently used operating zone of the torque/speed plane to improve energy efficiency [10].

This article presents a simplified magnetic equivalent circuit model as well as examples of calculation results for a unipolar hybrid excitation synchronous machine. This machine is also known in the literature of the subject as consequent pole permanent magnet machine [7] or inductor generator with combined excitation [5].

2. Types of hybrid excitation

Hybrid excitation circuits may be divided into two groups, depending on how excitation flux sources are combined – in series or in parallel [13]. In the series design, the main electromagnetic excitation flux passes through the permanent magnet which constitutes high reluctance, and so the impact of the excitation winding on the flux in the air-gap is relatively low. Such constructions usually have a limited range of control of the electromotive force, and a high value of electromotive force at zero excitation current [13]. In the parallel design, the electromagnetic excitation flux passes through ferromagnetic elements, bypassing the permanent magnet, and joins the permanent magnet flux in the air-gap area. This way, it is possible to reach a much broader range of control of electromotive force than in the case of a machine with series hybrid excitation [13].

The parallel hybrid excitation systems can be additionally divided into bipolar and unipolar [8]. In the bipolar system, the electromagnetic excitation flux influences both pole zones of the machine, and in the unipolar system – only the zone of like poles.
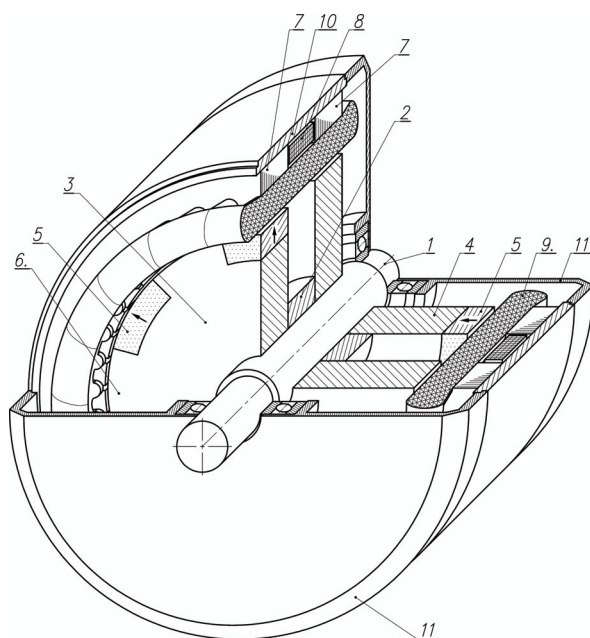
3. Construction of the machine

Fig. 1. Construction of the considered unipolar hybrid excitation synchronous machine
(description in the text)

In this article, authors consider the construction of an unipolar hybrid excitation synchronous machine presented in figure 1 [7]. It is composed of a rotor with two segments (3 and 4) and two stator stacks (7) connected with an external yoke (10) made of ferromagnetic material, which constitutes the frame, and with an internal yoke in the form of a sleeve (2) and shaft (1) made of ferromagnetic material. A cylindrical electromagnetic excitation coil (8) is placed between the conventional construction stator stacks (7) with shared winding (9). In the air gap zone of the rotor segments, permanent radial-flux magnets (5) and teeth (6) made of ferromagnetic material are placed alternately. The rotor segments mounted on the shaft are angularly displaced one against the other by one pole pitch. Magnets on one segment of the rotor create like and opposite poles to the poles created by magnets on the other segment. In the machine with this type of construction, it is possible to apply shared (or separate) armature winding for both stator stacks. Mounting both segments of the rotor in the same position in respect of the shaft makes it necessary to separate the stator winding and to introduce end-winding connections in to the zone between stacks (e.g. [12]).

The effect of the introduction of additional yokes (frame and shaft) is such that, in case of zero excitation current, a part of the flux from permanent magnets passes through these yokes, weakening the voltage induced in the armature. By influencing this flux with the axial flux from the electromagnetic excitation, it becomes possible to control the voltage induced in the winding of the machine's armature.
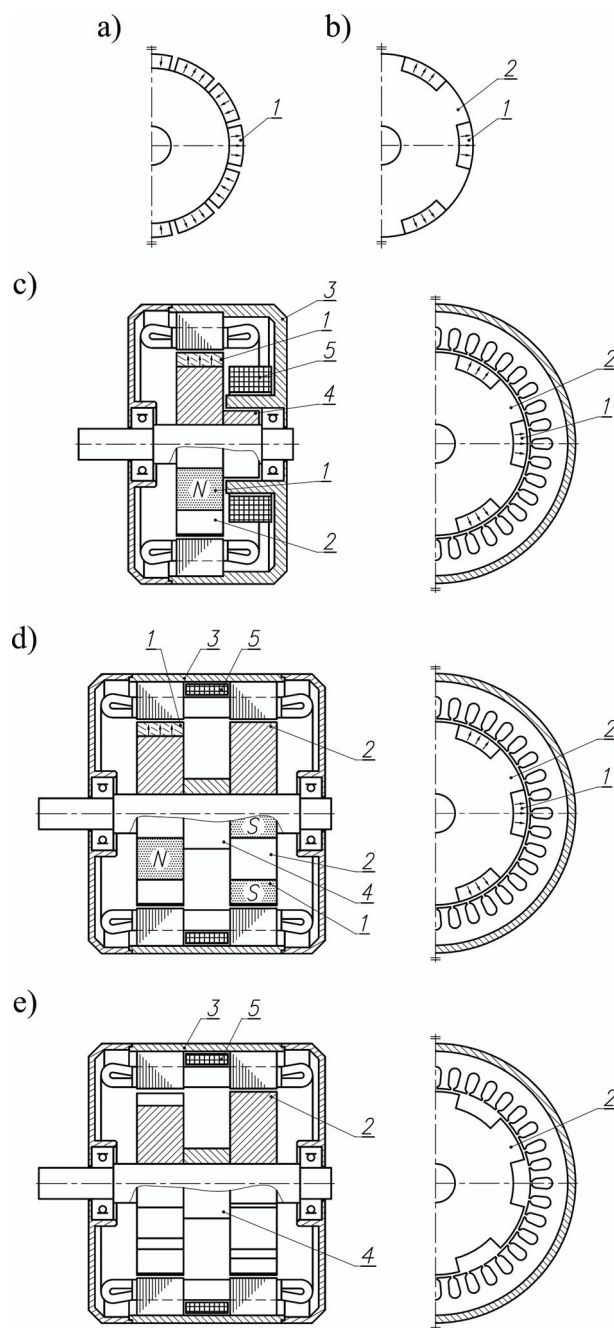
Fig. 2. Alternative construction solutions for the synchronous machine: a) conventional rotor with surface-mounted magnets, b) rotor with one magnet per pole pair, c) single-stack construction with unipolar hybrid excitation, d) two-stack construction with unipolar hybrid excitation, e) two-stack inductor construction: 1 – permanent magnet, 2 – ferromagnetic rotor tooth, 3 – additional stator yoke, 4 – additional rotor yoke, 5 – electromagnetic exciting coil

The construction of the considered machine may be inferred from the construction of a machine excited with permanent magnets (Fig. 2a), by replacing the system of alternately polarized permanent magnets poles (on the rotor circuit) (Fig. 2a) with a pole system of unidirectional polarized permanent magnets (Fig. 2b). Thus, a field magnet of a non-uniform construction is created, in which the like poles are magnets and the unlike poles are the ferromagnetic rotor teeth (Fig. 2b) (consequent pole permanent magnet machine [6]). If this machine is equipped with an additional circuit to magnetically couple the stator with the rotor, and if an exciting coil is introduced as an additional source of *mmf* (Fig. 2c), it will be possible to control the flux passing through the passive rotor teeth, and thus to control also the electromotive force. However, the introduction of an additional circuit for the electromagnetic excitation flux passing through the bearing shields and the shield-to-rotor air-gap increases the mass of the machine, due to its large cross-section. It is also necessary to increase the magnetomotive force of the exciting coil for balancing the *mmf* across the fragments of the magnetic path in the bearing shield and in the shield-to-rotor air-gap. The solution avoiding these disadvantage is a construction containing two machines connected with a shared stator yoke (frame), with a cylindrical excitation coil placed between the stacks, and containing a two-segment rotor (Fig. 2d). The rotor segments are connected with sleeve ring yoke mounted on the shaft. This eliminates the additional air gap on the path of the electromagnetic excitation flux. The permanent magnets mounted on one segment of the rotor create like poles, while the magnets on the other segment create unlike poles.

A different approach to the solution of a considered synchronous machine construction was proposed in papers [4, 5]. This solution is based on equipping the classic inductor machine (Fig. 2e) with permanent magnets filling the rotor slots, while the vector of magnet polarization on one segment of the rotor is turned outwards and on the other segment it is tuned inwards (Fig. 2d).

4. Magnetic equivalent circuit

Due to the initial stage of research, regarding the recognition of magnetization states of the magnetic circuit, with consideration of the significance of yokes structure in the process of magnetization, a magnetic equivalent circuit of sparse discretization has been applied. Particular attention has been paid to shape elements of the external yoke (frame) and of the internal yoke (sleeve and rotor shaft). The magnetic equivalent circuit model is recorded as a Matlab environment script. The calculations are made with the use of the nodal analysis method, with consideration of the non-linear magnetizing characteristics of ferromagnetic elements of the magnetic circuit.

Figure 3 shows machine's sectional views with fragments of the spatial permeance network which describe its geometry in a given plane, while figure 4 shows the diagram of the network which models the three-dimensional geometry of the machine for two pole pitches.

The formulated magnetic equivalent circuit model allows for the identification of the influence of fundamental construction parameters on the generated electromotive force. It is

characterized by a relatively short time of calculations in comparison with the FEM model, that allows for a quick identification of the influence of a given parameter on the induced voltage of the machine. However, owing to the used simplified assumptions, and to the absence of the correcting coefficients for this type of machine in the literature of the subject, the expected accuracy of calculations is lower than for a three-dimensional FEM model.
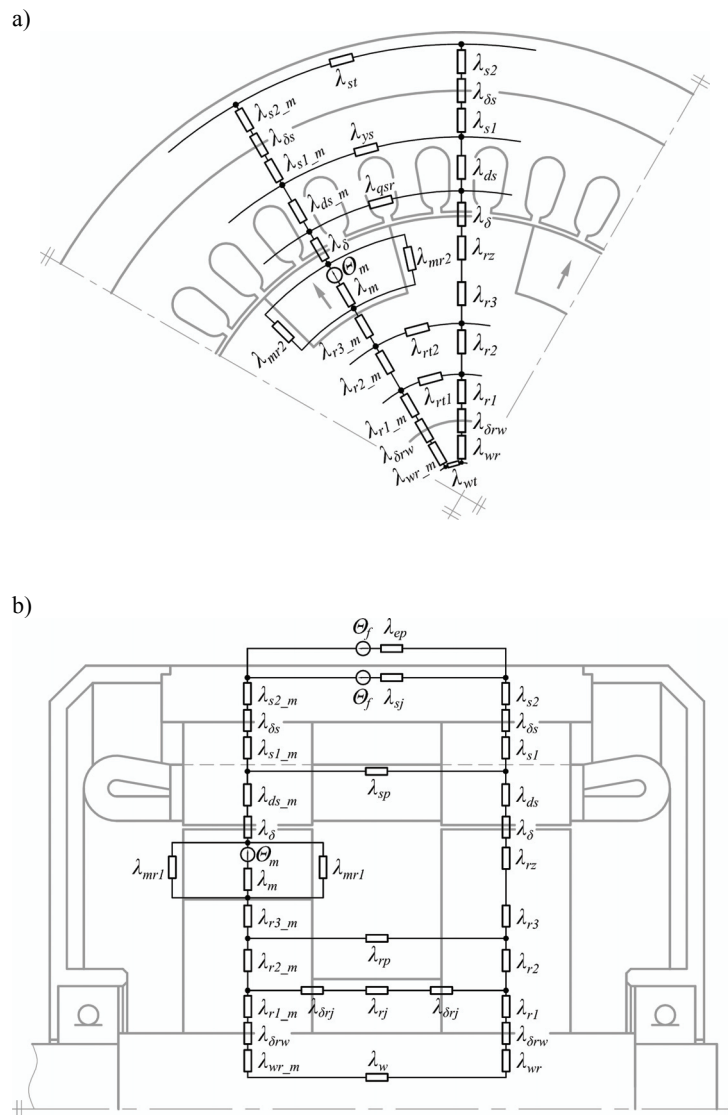

Fig. 3. Elements of the permeance network in: a) cross-section, b) axial section

5. Calculations results

Within the tests, a series of calculations were performed to determine the RMS value of the first harmonic of the voltage E induced in an armature coil consisting of a single turn (where $n = 1500$ rpm), depending on the excitation flux and the area of the cross-section of the external yoke (frame), where the cross-sectional area of the internal yoke (shaft and sleeve) is equal to the cross-sectional area of the external yoke.
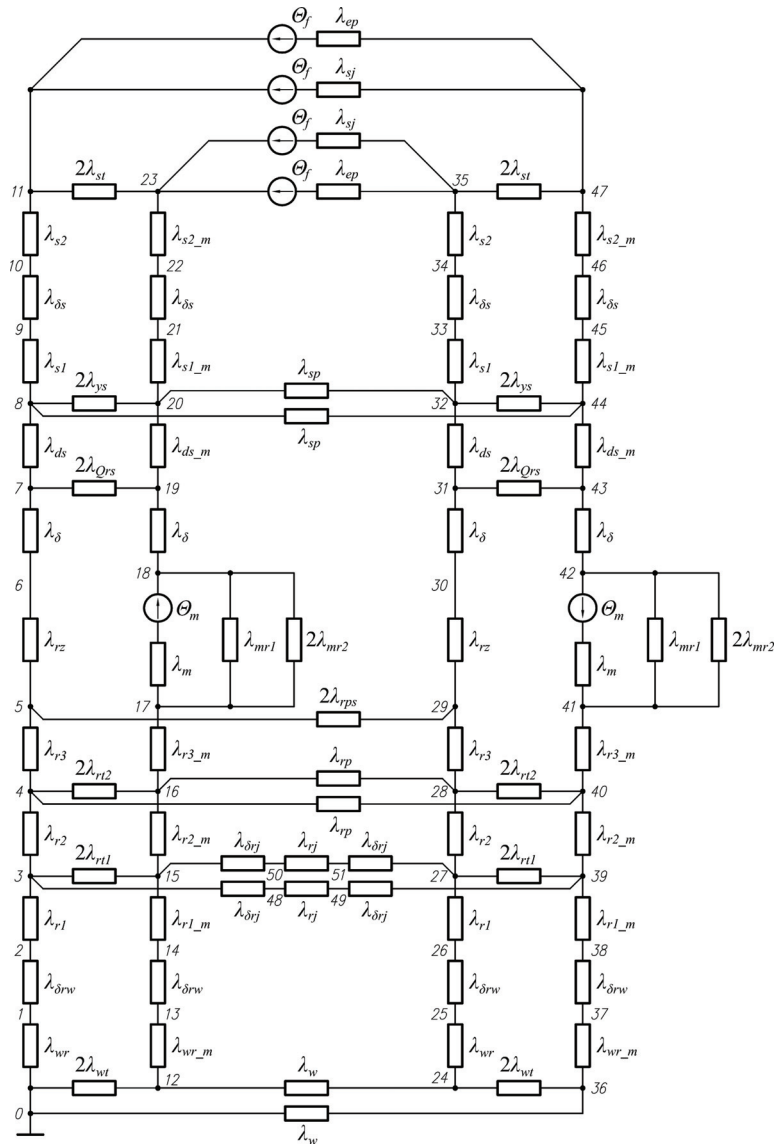

Fig. 4. Diagram of the permeance network

The change of the geometrical dimensions of the stator yoke have been specified with the parameter k_j, defined with the following relationship:

$$k_j = \frac{S_j}{S_z} = \frac{\pi\left(d_e^2 - d_{se}^2\right)}{4Qk_{Fe}b_{ds}l_s}.$$ (1)

This parameter expresses the ratio of the cross-sectional area of the external yoke S_j to the combined cross-sectional area of the teeth of one stator stack S_z, where d_e – external diameter of the machine's frame, d_{se} – external diameter of the stator stack, Q – number of stator slots, k_{Fe} – stack fill factor, b_{ds} – width of the stator tooth, l_s – length of the stator stack.

Figure 5a presents the relationship between the induced voltage E and the *mmf* of the excitation winding θ_e for two cross-sectional area of additional yokes. Moreover, the effective control range of this voltage is shown. Outside of this range, increase of the excitation *mmf* causes small increase of E or, in the case of relatively low reluctance of the additional yokes, the induced voltage decreases despite of the increase of *mmf*.
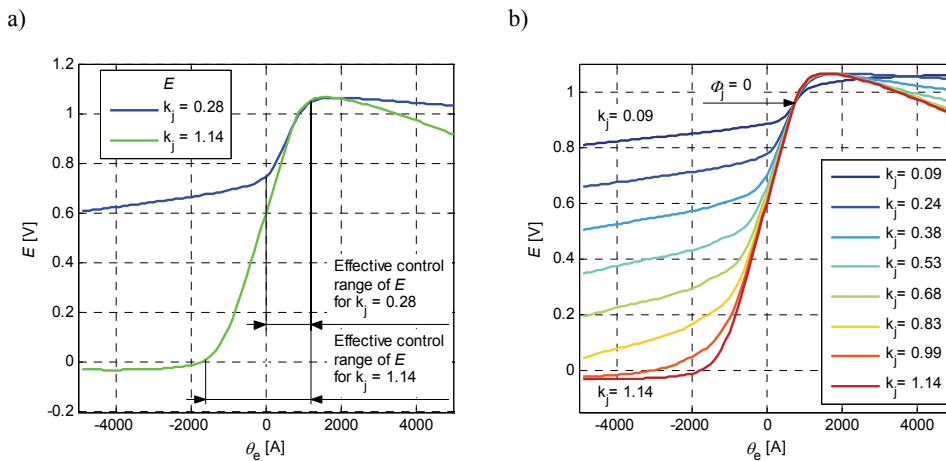
a)   b)

Fig. 5. No-load characteristics for different cross-sectional area of the additional yokes: a) including definition of the effective control range of induced voltage, b) for wide range of k_j

Figure 5b presents the relationship between the induced voltage E and the *mmf* θ_e of the excitation winding for different values of coefficient k_j. It is worth mentioning that the permeance of additional yokes determines the effective control range of the induced voltage E, as well as its value at zero field winding *mmf*. Moreover, the no-load characteristics for different k_j meet in one point, which corresponds to zero flux in additional yokes. The location of this point in respect to $\Phi_j = 0$ does not depend on the permeance of additional yokes, but on the parameters of the magnetic circuit of individual machine segments, and especially on the thickness of the main air-gap and on the height of magnets and their coercivity. At this point, machine segments may be considered as separate machines.

The thickness δ of the main air-gap has fundamental influence on the value of the *mmf* in the field winding that is necessary for obtaining full effective control range of the electromotive force *E* (Fig. 6a). Increasing this air-gap thickness leads to the necessity of increasing the *mmf*, as well to decreasing of maximum *E* value. Increasing the value of the required *mmf* also is necessary in cases of increased reluctance of additional yokes in their unsaturated state caused, for example, by the increase of thickness of technological air-gaps between the stator stack and stator additional yoke (Fig. 6b). In this case, the slope of the $E = f(\theta_e)$ characteristic rises, while the maximum value of *E* remains unchanged. These curves meet at the point corresponding to $\Phi_j = 0$.

The curve of the no-load operation $E = f(\theta_e)$ has a clear maximum, which is a characteristic phenomenon in inductor machines [2] (Fig. 7b). The reason for this is the saturation of the stator teeth located opposite to the ferromagnetic rotor tooth, which occurs as the excitation *mmf* θ_e increases. This causes a lower increase of the flux in this zone than the resulting from *mmf* increase, weakening of the flux in the zone of the permanent magnet (Fig. 7a). As a consequence, the difference between these fluxes decreases, and so does the induced voltage which depends on it.

The control of the electromotive force in discussed machine is performed by changing the flux in the ferromagnetic rotor tooth zone (Fig. 7a) [8], caused by the change of *mmf* of the excitation coil, for nearly constant flux in the permanent magnet zone. This is performed analogously to an inductor machine, and for this reason discussed machine is also called a hybrid excitation inductor generator [11].

Based on the calculated magnetizing characteristic shown on Figure 8, it is possible to state that a hybrid machine, as compared to an inductor machine, produces twice the electromotive force. This means double the power from the same load current.
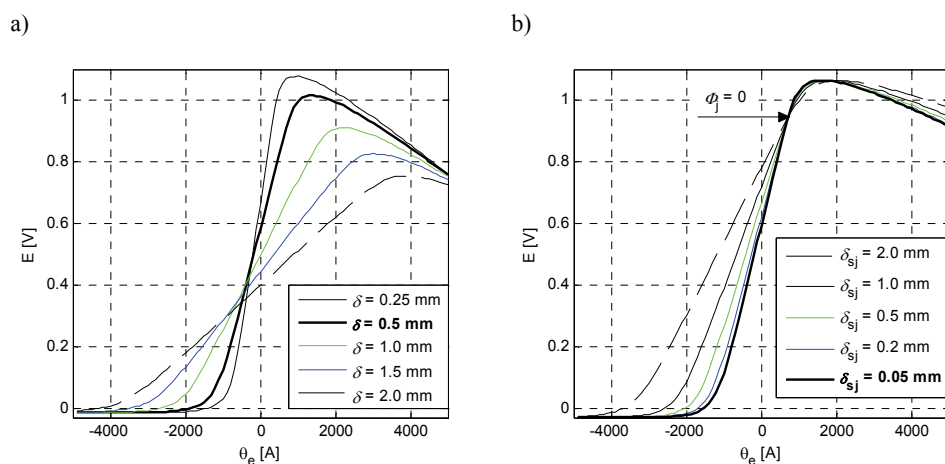
a)   b)

Fig. 6. The influence of air-gaps thickness on the no-load characteristics: a) main air-gap thickness δ, b) technological air-gap thickness δ_{sj}; (nominal values in bold)
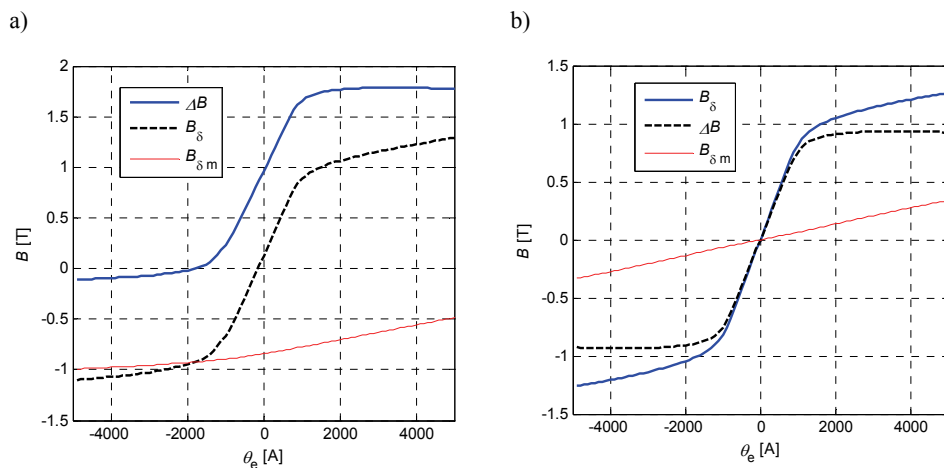
a)

b)

Fig. 7. Characteristics of the maximum values of flux density $B_{\delta m}$ in the air gap in the magnet zone and the maximum values of flux density B_δ in the ferromagnetic rotor tooth zone, and its difference ΔB: a) in a hybrid excitation machine, b) in an inductor machine (where $B_{\delta m}$ – flux density in the rotor slot zone)
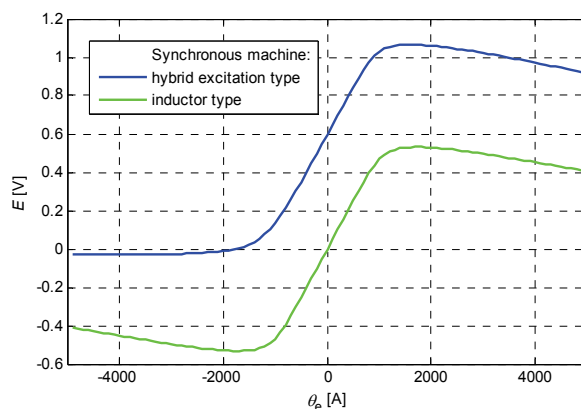

Fig. 8. Comparison of the no-load characteristics of the hybrid excitation machine and the inductor machine

6. Conclusions

The presented unipolar hybrid excitation synchronous machine (Fig. 1) shows features characteristic to the machines that served as the initial base for proposed construction. This means that it is characterized by the existence of a maximum of no-load characteristic $E = f(\theta_e)$ caused by the presence of the permanent component of flux density in the air-gap – like an inductor generator. Moreover, it is characterized by a high value of induced voltage at zero *mmf* of the field winding, just like a permanent magnet synchronous machine.

One important construction parameter determining the effective control range of electro-motive force of this machine is the additional stator and rotor yokes cross-sectional area. This creates new possibilities for adapting the operating parameters of the machine. By selecting, for example, yokes of a smaller cross-sectional area, it is possible to build a machine of high induced voltage for $I_f = 0$ and with a narrow control range of E, for which only field streng-thening will be effective. The application of yokes with larger cross-sectional areas ($k_j > 1$) increases the overall diameter of the machine, but allows for a broader range of effective con-trol of electromotive force.

The fundamental constructional parameter which influences the required value of field winding *mmf*, necessary for obtaining full range of effective control of electromotive force, is the thickness δ of the main air-gap, and a secondary parameter is the thickness of techno-logical air-gaps between the magnetic circuits of machine segments and the additional stator and rotor yokes.

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