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Experimental Validation of Hybrid Excited Permanent Magnet Synchronous Generator

Streszczenie. *Prądnice wzbudzane magnesami trwałymi mają prostą budowę i najwyższą sprawnością ze wszystkich maszyn elektrycznych. Te zalety zadecydowały o szerokim ich zastosowanie np. w elektrowniach wiatrowych małej mocy. Wadą tych prądnic jest bark regulacji napięcia, co dyskredytuje je do zastosowań na skalę energetyczną, gdyż nie ma możliwości regulacji współczynnika mocy cosφ. W artykule przedstawiono wyniki badań modelu prądnicy synchronicznej z magnesami trwałymi o mocy 5.5 kW z podwójnym wzbudzeniem: magnesami trwałymi i elektromagnetycznym. Wyniki potwierdzają, że prądnica ze wzbudzeniem hybrydowym ma wysoką sprawność i ma pełne właściwości regulacyjne* ***(Weryfikacja doświadczalna prądnicy z magnesami trwałymi ze wzbudzeniem hybrydowym)****.*

Abstract*. Permanent magnet (PM) excited generators are characterised by simple design and highest efficiency of all electric machines. The greatest drawback of these generators is lack of voltage control. It disqualifies this type of generator for large-scale usage in power engineering industry. The paper presents investigating results of a model of PM synchronous generator rated at 5.5 kW, with double excitation: one made with permanent magnets, the other electromagnetic.*

Słowa kluczowe: prądnica synchroniczna z magnesami trwałymi, generator synchroniczny, prądnice ze wzbudzeniem hybrydowym.
Keywords: AC generator, permanent magnets generator, hybrid synchronous generator, electromagnetic excitation.

Introduction

Comparison of electric machines with PM excitation to other electric machines shows that they are characterized by [1, 2, 4, 7]:

- highest efficiency,
- highest power density (power per volume ratio).

The simplest design is the PM generator with magnets surface-mounted on the rotor. This type of generator is widely used mostly in wind power plants [5]. The construction has proved itself to be reliable and is more and more commonly used. However, this particular design, i.e. rotor surface mounting of permanent magnets determines machine's output parameters. The voltage vs. load current curve shape is not satisfactory.

The current paper is devoted to synchronous generator with two excitation circuits [6, 9, 10, 11, 13, 14, 22, 23]: PM excitation and electromagnetic excitation – this is so called hybrid excitation. The excitation circuits are parallel to each other. The basic excitation is effected by permanent magnets, while additional excitation is electromagnetic in nature. Its goal is to stabilize generator's voltage-current curves.

Physical model of the generator

A physical model of synchronous generator with hybrid excitation was designed using elements of standard electric machines. The rotor was designed and built separately [10]. The rotor consists of two parts. The basic part which runs for c. 90% of overall stator iron length, contains permanent magnets, while the other (additional) part lying along c.10% of stator iron length, is electromagnetically excited.
Fig.1 shows a photo of the rotor at assembly process.

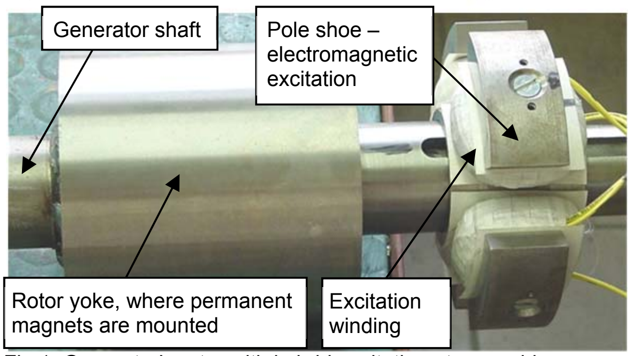

Fig.1. Generator's rotor with hybrid excitation at assembly process.

Principal dimensions of magnetic circuit were:

- Outer stator laminations diameter - 208 mm
- Inner stator laminations diameter – 134 mm
- Active length of stator laminated core L_{Fe} – 149 mm
- Number of stator slots – 36
- Number of turns connected in series per phase – 162.

Electromagnetic calculations of the physical model

Electromagnetic calculations of hybrid excitation generator have been run by superposition method. The calculation model included two separate machines: PM excited machine and machine with electromagnetic excitation. The calculations have been conducted by two methods: circuit-fleld method [3, 13, 15, 16, 17, 18, 19, 20] (FEM 2D) and analytical method.

A. Generator with PM excitation

Magnetic circuit of PM generator has been modeled with the help of FEMM software. A series of simulations have been run and optimum solution (design) has been selected. The selection criteria have been: air gap equal to 1 mm and maximum magnetic flux density in the teeth equal to 1.9 T.

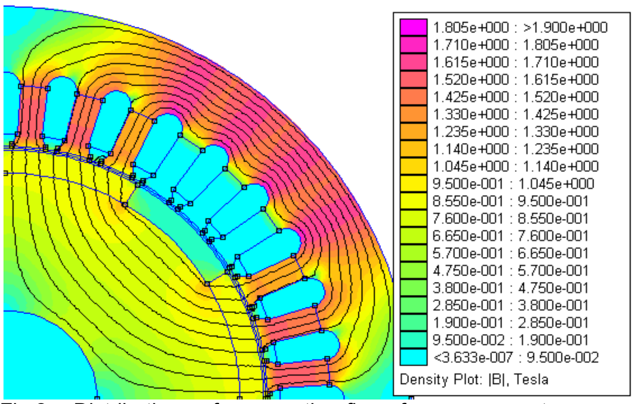

Fig.2. Distribution of magnetic flux for permanent magnet generator, (the value of first harmonic of flux density in air gap is 0.931 T).

Distribution of flux density of fundamental harmonic in the air gap under one pole pair has been found [12]. Basing on flux density and its fundamental harmonic's distribution, fundamental harmonic of generator's rotational electromagnetic force (e.m.f.) at no load has been calculated as follows:

$$E_{1RMS} = \sqrt{2} \cdot A_{mp_1} \cdot l_{PM} \cdot \omega_{el} \cdot \frac{D-\delta}{1000 \cdot 2} \cdot N_S \cdot q \cdot \frac{k_{u1}}{a_g} \cdot k_s \qquad (1)$$

where: A_{mp1} – fundamental harmonic of flux density in the air gap, l_{PM} – PM length, ω_{el} - angular speed, D – stator's inner diameter, δ - air gap width, N_S – number of conductors connected in series in the slot, q – number of slots per pole and phase, k_{u1} – winding coefficient, a_g – number of parallel branches, k_s – skew coefficient.

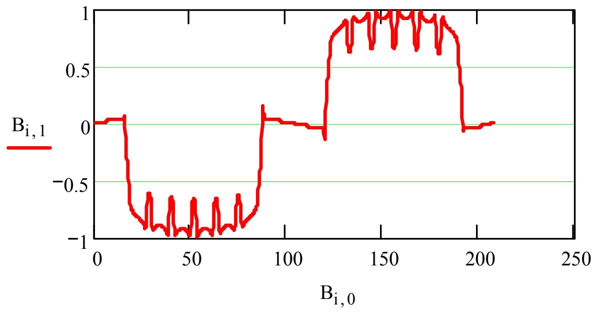

Fig. 3. Distribution of magnetic induction in the air gap (for the PM excitation).

Voltage RMS-value at 50 Hz has been found to be 429 V.

The field-circuital methods used in analysis is founded on running FEM 2D simulations in order to obtain flux density distribution in the machine air gap. On this basis and using Eq. (1) the RMS-value of 1st harmonic of voltage induced in no-load state has been calculated. Next, taking into account design data (machine dimensions) parameters of the equivalent scheme have been calculated: windings' resistances, main inductance and leakage inductances (assuming that Xq≈Xd). Then, being provided with value of no-load RMS voltage and solving equivalent scheme for a given load type, the characteristics presented further in this work have been obtained.

The calculations of the second part of electromagnetic circuit (additional excitation winding) have been conducted in a similar manner.

Calculations of electromagnetic circuit of the generator with PM excitation have also been run by circuit method (analytical calculations by RMxprt). Calculated RMS-value of voltage's fundamental harmonic, at 50 Hz, is equal to 425V.

"RMxprt" software is a commercial type tool manufactured by Ansoft company and aimed at running electromagnetic calculations of standard rotational electrical machines. This RMXprt calculations are done baseing on standard equivalent scheme. The material type data may be selected from accessible database or original data be be introduced by the user (eg. magnetization curves of steel, laminations of permanent magnets parameters). The equivalent scheme parameters are calculated on the basis of design dimensions of the machine, input by the user.

Calculations of electromagnetic parameters of machine with permanent magnets and machine with additional excitation winding have been defined in similar way.

B. Generator with electromagnetic excitation

Stator iron shape has not been changed, and therefore in modeling generator with salient poles same shapes have been adopted as in the case of PM generator. Next, distribution of flux density in the air gap has been calculated and, basing on Eq. 1, e.m.f. value at no-load conditions has been found.

Voltage RMS-value (fundamental harmonic) at 50 Hz and m.m.f of 550 Ampere-turns (excitation current 1 A, number of turns at one pole 275) has been calculated to as 48 V.

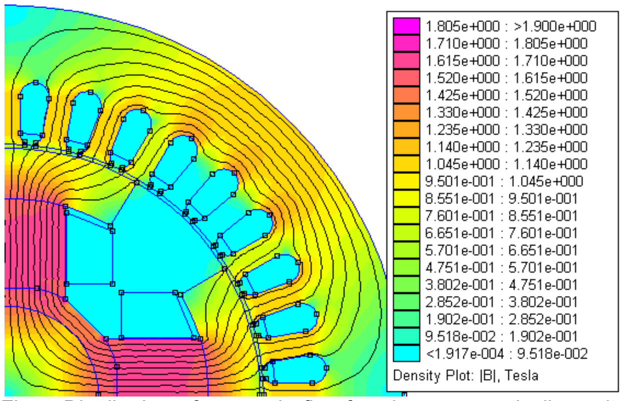

Fig.4. Distribution of magnetic flux for electromagnetically excited salient pole generator, (the value of first harmonic of flux density in air gap is 0.642 T)

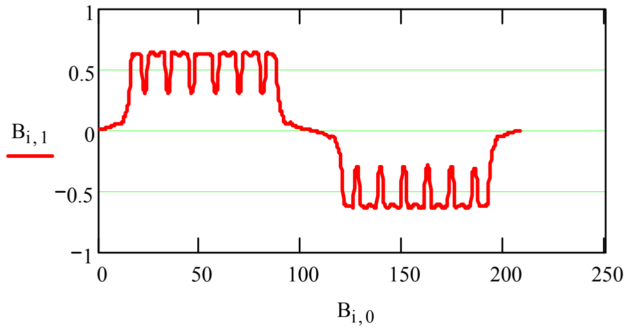

Fig. 5. Distribution of magnetic induction in the air gap (for the electromagnetic excitation).

Calculations of electromagnetic circuit of the generator with electromagnetic excitation have also been run by circuit method. When machine is excited at m.m.f. equal to 550 Ampere-turns, RMS value of voltage's fundamental harmonic, at 50 Hz, is equal to 26V. The divergence in calculation results is 60% and requires further investigation.

C. Resultant machine with hybrid excitation

The calculated no-load voltage of the machine with hybrid excitation by circuit-field method is equal to 477 V, and by circuit method is 451 V. The results diverge by 6%. Comparison of rotational voltage calculation results conducted by two different methods (field-circuit and circuit) shows that circuit method is quite sufficient and, which is important, is simpler and faster.

Lab tests results

Lab tests of the model generator have been conducted in the similar way as the calculations, i.e. for three different models.

Fig.6 shows comparison of results of induced voltage vs. rotational speed for PM excited machine at no-load. Different curves show calculated and measured values.

Fig.7 shows induced voltage vs. excitation current curves at 1500 rpm (results of calculations and tests), for generator with electromagnetic excitation. When excitation current is equal to 1 A (and MMF is 550A), the measured induced rotational voltage value is 37 V. The calculation error of this voltage with field-circuit calculation method is (+10%), and with circuit method is (-25%). Both these methods clearly require further elaboration. Field-circuit 2D method does not take into account leakage flux, which runs along a closed path through rotor yoke beneath permanent magnets. This flux causes rotor pole saturation, which is neglected during the calculations, and therefore the inaccuracies are too high.

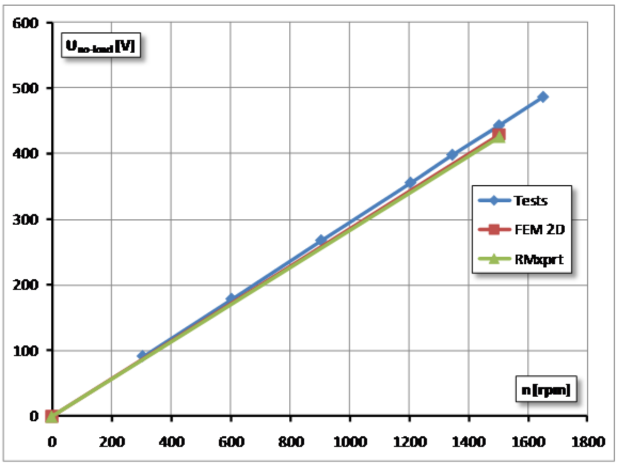

Fig. 6. Characteristics of no-load voltage for permanent magnet generator vs rotation speed.

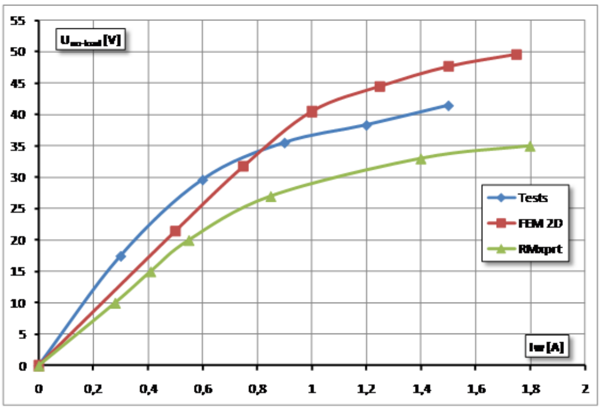

Fig. 7. Characteristics of no-load voltage for generator vs excitation current.

Table 1 shows comparison of lab tests and circuit method calculation results for generator with hybrid excitation.

Table 1.

Parameter	Unit	Calculations	Lab tests
$P_{electric}$	W	5500	5525
$P_{mech.}$	W	6101	6220
U	V	431	443
I	A	10.1	10.6
cosφ	-	0.935	0.935
η	%	90.3	88.8
f	Hz	50	50

Fig.8 shows generator's load characteristics for two different generator designs (where Iex - excitation current):

- Generator with PM excitation only, i.e. Iex.=0,
- Generator with additional excitation control I_{ex}=variab.≠0.

Fig.8 shows a series of control characteristics for generator with hybrid excitation. The positive values of excitation current are adopted, when directions of permanent magnets' MMF and excitation winding's MMF are identical. Negative current value means that MMF directions are opposite.

Fig.9 presents measured voltage vs. generator load curves for two cases:

- generator loaded, Iex=0
- generator loaded, hybrid excitation.

Generator efficiency curves for identical two cases as before are shown in Fig.10.

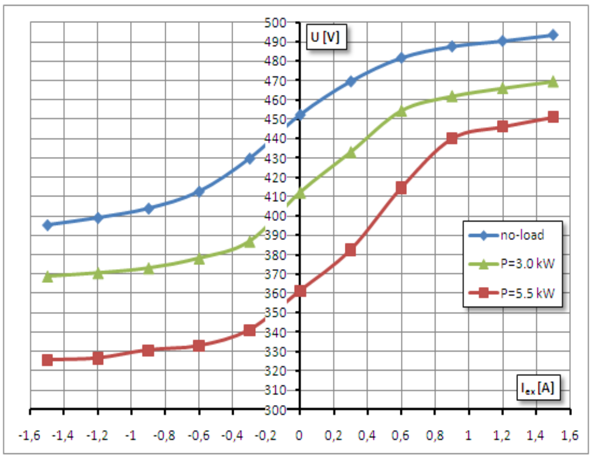

Fig.8. Characteristics of voltage for salient-pole and permanent magnet excited generator (n = 1500 obr/min, cosφ = 0,94)

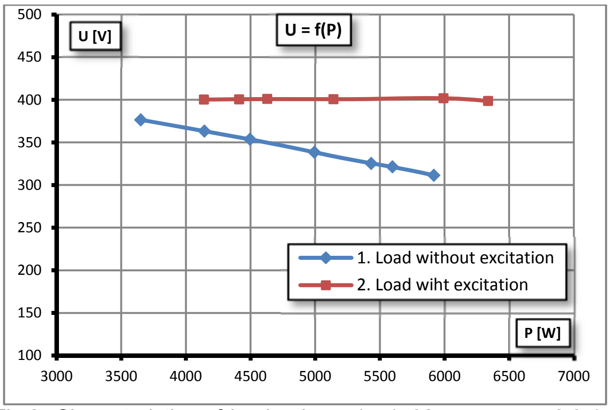

Fig.9. Characteristics of load voltage (n=1500 rpm, cosφ=0.94) vs output power

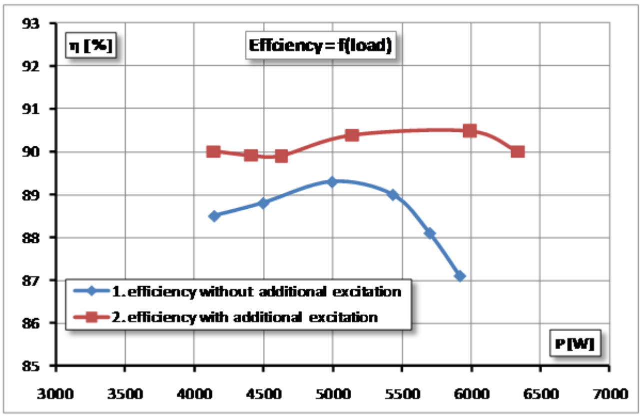

Fig.10. Characteristics of load voltage (n=1500 rpm, cosφ=0.94) vs excitation current

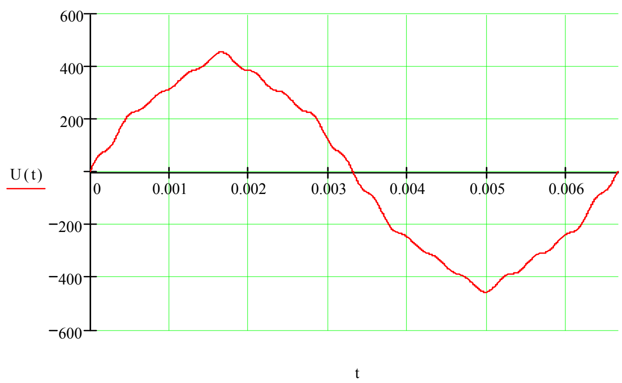

Fig.11. Characteristics of no-load voltage for without excitation.

Fig. 11 shows measured no-load voltage waveform generated without participation of additional electromagnetic excitation. The diagrams for waveforms measured with additional excitation are not presented, since their shapes are similar.

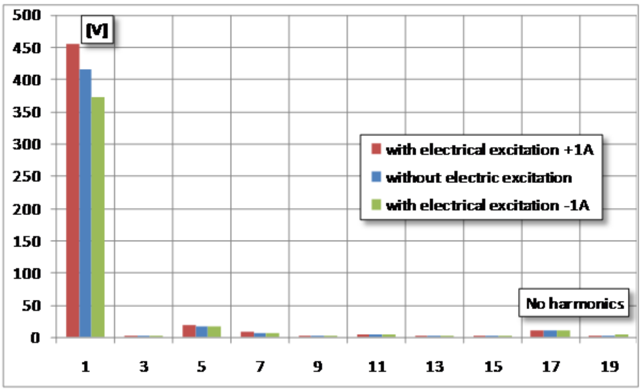

Fig.12. Amplitudes of voltage harmonics generated for operation without electric excitation and with electrical excitation +1A and with electrical excitation -1A.

Fig. 12 show harmonic spectra for no-load voltage for following operational conditions: operation with no extra excitation, with compound excitation and additional excitation current equal to (+1 A) and with compound excitation and additional excitation current equal to (-1 A). Lab tests indicate that THD content in no-load induced voltage varies depending on generator mode of operation. With generator running idle with no extra excitation THD was equal to c. 7%, with compound excitation and additional excitation current of 1 A THD dropped to c.6.2% and with additional excitation current of (-1 A) THD rose to c.8.3%.

Conclusions

Synchronous machine with two different excitation sources located at a common shaft (rotor) has been modeled. It is a complex machine from the engineering viewpoint and, even more so, from design and calculation standpoint.

Analyzing results of investigation of the physical model of the synchronous generator with hybrid excitation, the following conclusions may be drawn:

- The proposed and applied superposition method seems to be correct for machine design calculations,
- Electromagnetic calculation results of PM excited machine correspond to the lab tests results,
- Electromagnetic calculations for machine excited by electromagnets are widely divergent from lab tests results for both calculation methods. The different sources of this discrepancy can be discussed:
  - ➢ Actual magnetization curve differing from one adopted in the calculations. Basing on flux density distribution it has been assumed for calculations' sake that saturation of electromagnetic circuit will be attained at excitation current equal to c. 0.9÷1 A (with 550 turns connected in series per one pole), while lab tests show that saturation is reached when at current equal to c. 0.5 A. Divergence of calculation results from test results increases as saturation grows. In no-load voltage calculation and for excitation current 0.6 A (which corresponds to linear part of magnetization curve) the discussed error does not exceed 20% (Fig. 7).
  - ➢ Rotor core with wound excitation winding is characterized by similar axial and radial dimensions (the pole width is approximately equal to its length). During FEM 2D simulations it has been assumed that m.m.f. acts in the axial direction only. This assumption (simplification) causes calculation error, since it does not take into account the magnetic flux entering the stator outside rotor ends.
  - ➢ Rotor core with wound excitation winding is in direct contact with surface-mounted magnets. This type of design makes a perfect bypass for some portion of excitation magnetic flux. This "escaped" flux saturates rotor core instead of participating in energy conversion. Brief for design has been that 6.5 mm wide passage between these two cores should be quickly saturated by main flux (flux due to PMs operation) and would not make it possible for some of the flux produced by electromagnetic winding to "escape". Still, even from process engineering viewpoint, rotor core thickness at this particular point could not be less than 4÷5 mm.
- Characteristics shown in Fig.8 prove that at constant power and (n =1500 rpm, cosφ = 0.94) voltage may be changed in the range of ± 15%,
- Output characteristics shown in Fig.9 prove that voltage is kept nearly constant while load varies widely (even when rated power is exceeded), i.e. voltage variability $\delta U\% \approx 0$ %,
- Additional electromagnetic excitation used in PM generator results in higher generator efficiency (Fig. 10).
- Since additional excitation winding does not greatly contribute to principal voltage generation, it seems that calculation using superposition methods is sufficient.

In order to properly model a complex electromagnetic circuit consisting of PM excitation system and additional electromagnetic coil wound round iron core, it is indispensable to conduct FEM 3-dimensional simulations. However, creation of the model as well as subsequent calculations requires much labour and huge computational power.

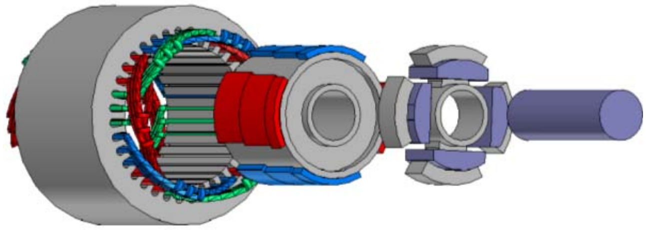

Fig.13. Model 3D synchronous generator with hybrid excitation

Fig.13 shows initial 3D model of generator with hybrid excitation. Preliminary calculations have been run with this model and some exemplary results are given in Table 2.

Table 2. Some exemplary results

Circuit-field Method 2D [V]	Analytical method [V]	Circuit-field Method 3D [V]	Lab tests [V]
PM excitation			
429	425	441	443
Electromagnetic excitation 0,5 A			
43	18	17,7	28
Electromagnetic excitation 1 A			
81	26	26	38
Total voltage with excitation 0,5 A			
472	443	453	471
Total voltage with excitation 1 A			
510	451	470	481

Table 2 shows summary of 2D field-circuit, analytical and 3D simulation calculation results [3] as well as lab tests results of idle-running generator.

Investigation of selected calculation and lab tests results presented in Table 2 leads to conclusion that 3D analysis is most precise. This conclusion could be easily foreseen, since it is not possible to assess two different excitation circuits in 2D analysis. The accuracy of analytical or FEM 2D analysis in geometrically complex devices is therefore not sufficient, even though these calculations are faster. That is why design of hybrid machines must be done with help of FEM 3D methods.

Acknowledgments

The research published in this paper had the financial support in year 2012 as scientific grant from Polish government - Grant no. N N510 214738.

REFERENCES

[1] Glinka T.: *„Electrical machines excited with permanent magnets"*, copyright by Silesian University of Technology, Poland, Gliwice 2002.
[2] Bernatt J.: *„Electrical and magnetic circuits of electrical machines excited with permanent magnets"*, copyright by Research And Development Centre Of Electric Machines „Komel", Poland, Katowice 2010.
[3] Gieras J.F., Wing M.: *„Permanent Magnet Motor Technology Design and Applications*", second edition, Marcel Dekker INC, New York 2002.
[4] Bernatt J., Gawron S.: *„New construction of 2-pole permanent magnet synchronous generator",* copyright by Research And Development Centre Of Electric Machines „Komel", Poland, Katowice, ZP-M E No 88/2010.
[5] Bernatt J., Gawron S., Król E.: *„Small windmills – construction and exploitation experience*", copyright by Research And Development Centre Of Electric Machines „Komel", Poland, Katowice, ZP-M E No 72/2005.
[6] Gawron S: *„Prądnica synchroniczna z magnesami trwałymi z możliwością dowzbudzania",* Przegląd Elektrotechniczny (Electrical Review) nr 01/2008.
[7] Rossa R., Król E.: *"Modern electric machines with permanent magnet*". Przegląd Elektrotechniczny (Electrical Review) nr 12/2008.
[8] Rozycki A.: "*Development of the machine construction high-temperature superconducting electric. Part II. Synchronous generators, induction motors and DC machines*", Przegląd Elektrotechniczny (Electrical Review) nr No 12/2008.
[9] Gawron S.: *„ Permanent magnet synchronous generator with low output voltage variability",* copyright by Research And Development Centre Of Electric Machines „Komel", Poland, Katowice, ZP-M E No 84/2009.
[10] Bernatt J., Gawron S.: "*The synchronous generator with permanent magnets and with by excitation Winding"*. Proceeding ICEM, Roma 2010.
[11] Bernatt J., Gawron S, Dukalski P.: "*Modeling 3D of generator with hybrid excitation*", International Aegean Conference on Electric Machines and Power Electronics & Electromotion, 08-10 September 2011, İstanbul, Turkey, IEEE Xplore Digital Library.
[12] Thelin P., Soulard J., Nee H.P., Sadarangani C.: *"Comparison between Different Ways to Calculate the Induced No-Load Voltage of PM Synchronous Motors using Finite Element Methods"*, PEDS'01, Bali, Indonesia, Oct. 2001.
[13] Dou, Y.; Guo, Y.; Zhu, J.: "*Study of a Hybrid Excitation Synchronous Generator Using Three-Dimensional Magnetic Field Finite Element Analysis*", Magnetics Conference, 2006. INTERMAG 2006. IEEE International, Digital Object Ident.: 10.1109/INTMAG.2006.375781, Publication Year: 2006 , Page(s): 198 – 199
[14] Kapinos J.: *„Synchronous generator with hybrid excitation*". XV International Symposium on Electric Machinery in Prague, ISEM'2007, 5-6 Sep 2007, Prague, pp.72-79.
[15] Thelin P., Soulard J., Nee H.P., Sadarangani C. "*Comparison between Different Ways to Calculate the Induced No-Load Voltage of PM Synchronous Motors using Finite Element Methods*", PEDS'01, Bali, Indonesia, Oct. 2001.
[16] Zhang Hongjie, Li Qingfu: *„Theory and Desing of Hybrid Excitation Permanent Magnet Synchronous Generators*". IEEE ICEMS 2001, vol.2, pp898-900, 2001.
[17] Chao-hui Zhao, Yang-guang Yan: *„A Review of Development of Hybrid Excitation Synchronous Machine*". IEEE ISIE 2005, pp857-862, 20-23 June 2005.
[18] Zhuoran Zhang, Yangguang Yan, Shanshui Yang, Zhou Bo, *„Principle of Operation and Feature Investigation of a New Topology of Hybrid Excitation Synchronous Machine*", IEEE Transactions on Magnetics, vol. 44, NO. 9, September 2008.
[19] Fu Xinghe, Zou Jibin: "*Numerical Analysis on the Magnetic Field of Hybrid Exciting Synchronous Generator"*, IEEE Transactions on Magnetics Volume: 45, Issue: 10, publication year: 2009, pages: 4590 – 4593.
[20] Xia Yonghong, Wang Shanming, Ma Mingyuan, Hao Liangliang, Qiu Ami, Huang Shaogang: "*Basic principles of hybrid excitation PM synchronous generator utilizing harmonic for excitation*", Electrical Machines and Systems (ICEMS), International Conference on publication year: 2010 , pages: 1010 – 1013.
[21] Kamiev K., Nerg J., Pyrhonen J., Zaboin V., Hrabovcova V., Rafajdus P.: "*Hybrid excitation synchronous generators for island operation*", Electric Power Applications, IET Volume: 6 , Issue: 1, Digital Object Identifier: 10.1049/iet-epa.2010.0226, Publication Year: 2012 , Page(s): 1 – 11.
[22] Fu Xinghe, Zou Jibin: "*Design and analysis of a novel Hybrid Excitation Synchronous Generator*", ICIEA 2008. 3rd IEEE Conference on Industrial Electronics and Applications, publication year: 2008 , pages: 2074 – 2077.
[23] Mingji Liu; Yang Ji; Li Li; Zhongqin Cai: "*Research on the modeling and simulation of coordinate structure hybrid excitation synchronous generator with AC excitation*", Electrical and Control Engineering (ICECE), 2011 International Conference on Digital Object Identifier: 10.1109/ICECENG.2011.6057276 Publication Year: 2011, Page(s): 3616 – 3619.

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