Krzysztof MAKOWSKI, Aleksander LEICHT

Wroclaw University of Technology, Chair of Electric Machines, Drives and Measurements

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Improving performance of a single-phase self-excited induction generator by modification of an excitation winding

***Abstract.** The paper deals with single-phase induction machine operating as a self-excited induction generator which may be used to generate electrical energy from non-conventional energy sources. Performance characteristics of the self-excited generator with capacitor connected to the both stator windings under load operating conditions are computed by field-circuit method. By changing number of turns and size of wires of the auxiliary stator winding, considerable improvement of performance characteristics of the generator were obtained with respect to no-load voltage and under load condition. Furthermore, an influence of corresponding changes in the excitation stator winding on voltage magnitude induced in excitation winding, winding currents and output power of the generator for two capacitor topology in the main stator winding have been presented. The obtained simulation results may be useful in designing the self-excited induction generator on the base of single phase capacitor induction motors.*

***Streszczenie.** Artykuł przedstawia jednofazową maszynę indukcyjną pracującą jako samowzbudny generator indukcyjny, który może być wykorzystany do wytwarzania energii elektrycznej z niekonwencjonalnych źródeł energii. Charakterystyki pracy samowzbudnego generatora indukcyjnego z kondensatorem podłączonym do obu uzwojeń stojana wyznaczone zostały za pomocą modelu polowo-obwodowego przy obciążeniu rezystancyjnym. Przez zmianę liczby zwojów i rozmiaru (średnicy) drutu uzwojenia pomocniczego stojana uzyskano znaczną poprawę charakterystyk generatora ze względu na wartość napięcia i prądu w uzwojeniu wzbudzenia generatora. Prezentowane wyniki uzyskane z symulacji mogą być wykorzystane w projektowaniu samowzbudnych generatorów indukcyjnych na bazie konstrukcji jednofazowych silników indukcyjnych. (**Poprawa charakterystyk pracy samowzbudnego jednofazowego generatora indukcyjnego przez modyfikację uzwojenia wzbudzenia**).*

Keywords: induction generator, single-phase, field-circuit modelling, performance characteristics, excitation winding
Słowa kluczowe: generator indukcyjny, jednofazowy, modelowanie polowo-obwodowe, charakterystyki pracy, uzwojenie wzbudzenia

Introduction

Small power self-excited single-phase induction generators (SPSEIGs), driven by wind turbine may be employed as an extra source of electrical energy at household. The self-excited induction generators compare favourably with synchronous, permanent magnet or DC generators as regards simplicity, durability, and low costs of manufacturing and maintenance. Theirs main disadvantages are unpredictable residual magnetism and weak voltage self-regulation [1, 2, 5, 7]. Field-circuit models of the induction generators can be found in recent papers [3,4,6]. No-load and load characteristics of the SPSEIGs may be inherently improved by a proper change of the magnetic circuit, windings and capacitor topology used in stator windings. The voltage regulation can also be improved with use of power electronics-based scheme [2].

The improvement of performance characteristics of the base model of induction generator (N_A=528, d=0.45mm, C_{ex}=30μF, C_{sh}=15μF, C_{se}=200μF) constructed on the base of single-phase induction motor (Tab. 1) has been presented for two capacitor topology in the load stator winding (Fig. 2).

Field-circuit model of the generator

The single-phase capacitor induction motor of 1.1kW, 230V employed for stand-alone generating operation has 4 poles and 30 skewed rotor bars. The ratings of the tested machine are listed in Table 1.

Table 1. Ratings of the single phase induction machine

Rated power	1.1 kW
Rated voltage	230 V
Rated current	7.5 A
Rated speed	1380 rpm
Run capacitor	30 μF
Frequency	50 Hz

Due to geometrical symmetry and electromagnetic periodicity, two-dimensional magnetic field computation of the generator was reduced to one pole pitch of the cross-section shown in Fig. 1. The finite element mesh of the generator comprises 25752 nodes forming 11244 second-order triangular and quadrangular elements. The time step for the FEM computation was 0.4 μs. The developed model of the generator accounted for nonlinear magnetizing characteristic of the magnetic core and skin-effect in the rotor bars [3, 8].

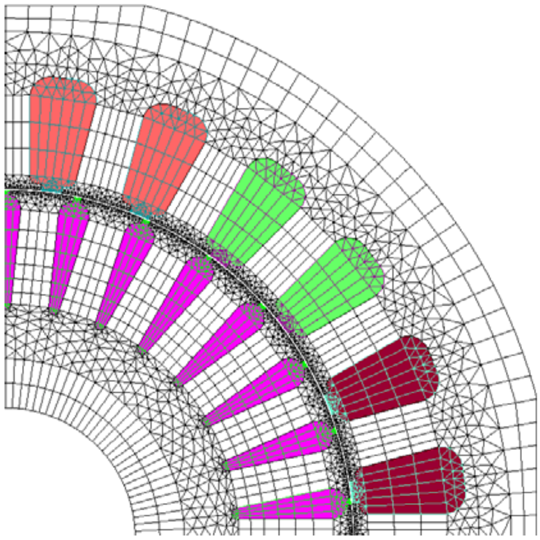

Figure 1. FE mesh of 2D field-circuit model of the SPSEIG

The 2D magnetic field in the induction generator is determined by the equations:

$$(1)\ \mathrm{curl}(\nu \cdot \mathrm{curl}\boldsymbol{A}) = \begin{cases} \boldsymbol{J}_\mathrm{S} & \text{in stator windings} \\ \boldsymbol{J}_\mathrm{b} - \sigma \cdot \partial \boldsymbol{A} / \partial t & \text{in rotor bars} \\ 0 & \text{in air, iron core and shaft} \end{cases}$$

where $\boldsymbol{A}[0,0,A(x,y,t)]$ is the magnetic vector potential, $\boldsymbol{J_s}[0,0,J_s(x,y,t)]$ – the current density in the stator slots, $\boldsymbol{J_b}[0,0,J_b(x,y,t)]$ – the current density in the rotor bars ν – reluctivity of magnetic material, σ – electric conductivity. The above field equations coupled with voltage equations of stator and rotor windings were solved simultaneously to obtain voltages and currents induced in the stator and rotor. Having the variables ***A*** and ***J*** computed, the other quantities of electromagnetic field as magnetic flux, magnetic induction (flux density), etc. may be determined taking into account the magnetization characteristic of iron sheets of magnetic core of the generator.

Performance characteristics

Steady-state performance characteristics of the SPSEIG were computed for two topology of the load stator winging: with parallel connected capacitor to the terminals (the shunt capacitor C_{sh}) and short-shunt connection (the shunt capacitor C_{sh} and series capacitor C_{se}), as shown in Fig. 2.

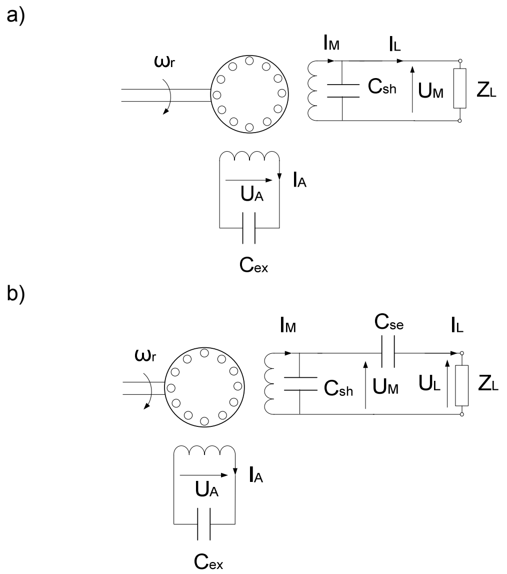

Fig. 2 Capacitor topology in the load stator winding: a) shunt connection, b) short-shunt connection

For comparison of performance characteristics it was assumed that for the both analyzed capacitor configuration, the terminal voltage is nominal (230V) for synchronous rotor speed at no-load operation. It obviously needed selection of adequate capacitors connected (in series or parallel) to the stator windings.

Load characteristics of the single-phase self-excited induction generator for decreased number of turns in the excitation stator winding (N_A), different diameters of the wires (d) and capacitors connected to the load stator winding are presented in Figures 3-6.

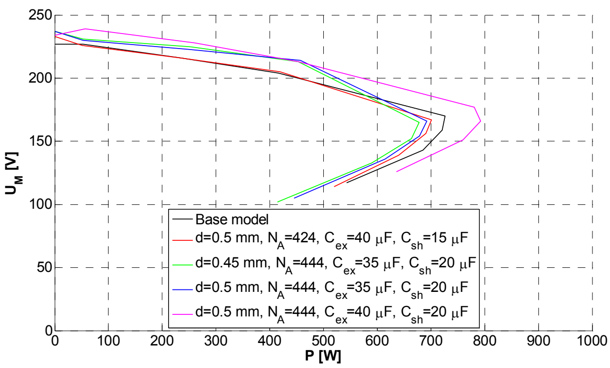

Fig. 3. Terminal voltage (U_M) versus output power of the SPSEIG with shunt capacitor in load stator winding

As it result from Figs. 3-6, series connected capacitor (C_{se}) together with shunt capacitor (C_{sh}) allows loading the generator up to its nominal power and ensures good stability of the terminal voltage at rated value of output power. With only parallel connected capacitor in the load winding (C_{sh}) the maximum output power of the generator is reduced by (30-40)%.

Voltages and currents of the stator windings at no-load, the current density (J_A), the stator slot fill factor (k_Q) of the excitation winding and the turns ratio of stator windings (a) of the tested generator are listed in Table 2. It should be noted that for no-load operation of the generator there is flow of the current through the shunt capacitor C_{sh} parallel connected to the load stator winding.

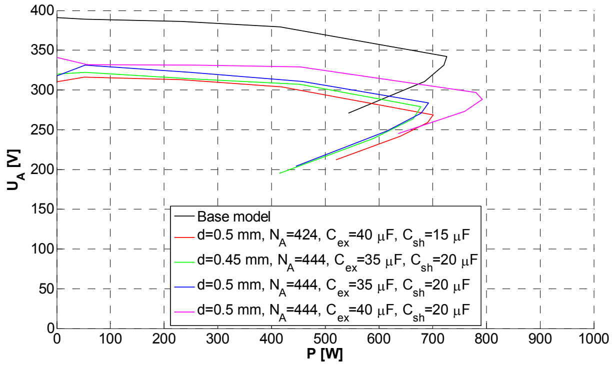

Fig. 4. Voltage of excitation stator winding (U_A) versus output power of the SESPIG with shunt capacitor in load stator winding

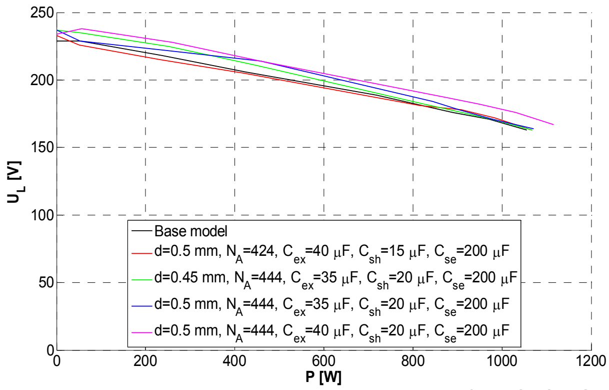

Fig. 5. Terminal voltage (U_L) versus output power of the SPSEIG with short-shunt capacitors in load stator winding

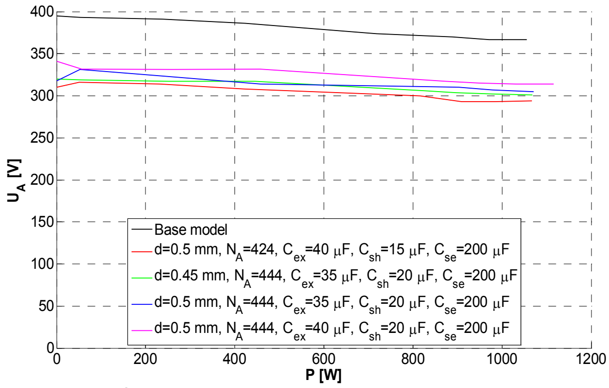

Fig. 6 Voltage of excitation stator winding (U_A) versus output power of the SESPIG with short-shunt capacitors in load stator winding

Validation of the simulation method

For experimental validation of the field-circuit model used for performance simulation of the single-phase self-excited induction generator, operating characteristics of the base model were measured using the test setup described in [3]. Load characteristics of the generator with shunt capacitor in the main stator winding presented in Figs. 7, 8 show that the generator operates stably for resistive load up to the about 50% of the machine rated power.

Table 2. Parameters of the generator at no-load and n = 1620 rpm for different numbers and sizes of excitation stator winding

C_{ex} = 30 µF, C_{sh} = 15 µF, N_A = 528, a = 1.44	d [mm]	2 x 0.45mm
	U_M [V]	227
	U_A [V]	391
	I_M [A]	1.16
	I_A [A]	3.82
	J_A [A/mm^2]	12.01
	k_Q [%]	80
C_{ex} = 40 µF, C_{sh} = 15 µF, N_A = 424, a = 1.15	d [mm]	2 x 0,5 mm
	U_M [V]	233
	U_A [V]	310
	I_M [A]	1.14
	I_A [A]	4.25
	J_A [A/mm^2]	10.82
	k_Q [%]	78.8
C_{ex} = 35 µF, C_{sh} = 20 µF, N_A = 444, a = 1.21	d [mm]	2 x 0.45mm
	U_M [V]	237
	U_A [V]	320
	I_M [A]	1.55
	I_A [A]	3.84
	J_A [A/mm^2]	12.08
	k_Q [%]	67.2
C_{ex} = 35 µF, C_{sh} = 20 µF, N_A = 444, a = 1.21	d [mm]	2 x 0,5 mm
	U_M [V]	237
	U_A [V]	318
	I_M [A]	1.55
	I_A [A]	3.78
	J_A [A/mm^2]	9.63
	k_Q [%]	82.5
C_{ex} = 40 µF, C_{sh} = 20 µF, N_A = 444, a = 1.21	d [mm]	2 x 0,5 mm
	U_M [V]	234
	U_A [V]	341
	I_M [A]	1.61
	I_A [A]	4.43
	J_A [A/mm^2]	11.29
	k_Q [%]	82.5

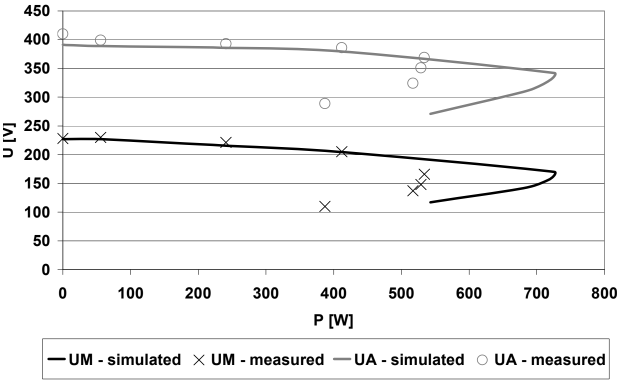

Fig. 7. Voltages versus output power of the SPSEIG with shunt capacitor in load stator winding

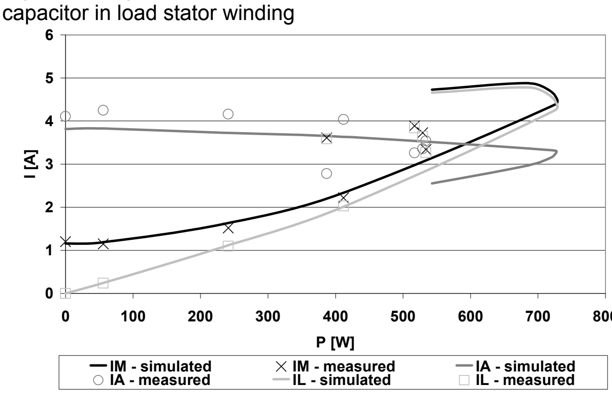

Fig. 8. Currents versus output power of the SPSEIG with shunt capacitor in load stator winding

Load range of the SPSEIG may be extended by applying the short-shunt capacitor topology, e.g. the capacitor 200 µF connected in series with the main stator winding and then the generator may be loaded up to the rated power when load is purely resistive (Figs. 9, 10).

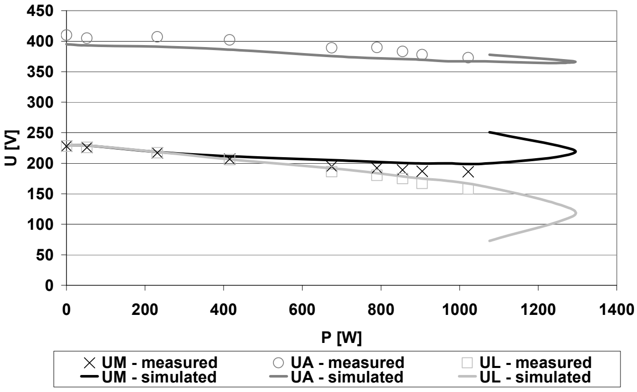

Fig. 9. Voltages versus output power of the SPSEIG with short-shunt capacitor topology in load stator winding

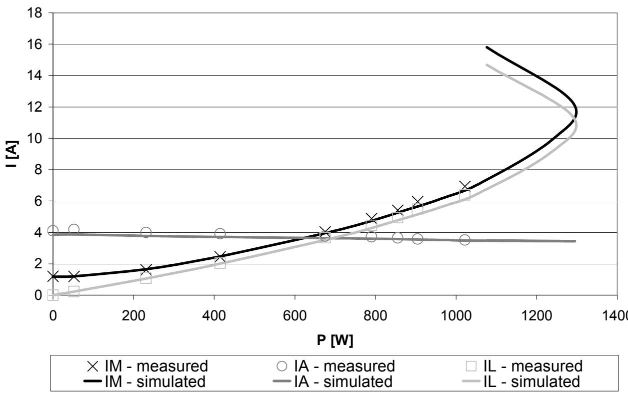

Fig. 10. Currents versus output power of the SPSEIG with short-shunt capacitor topology in load stator winding

It should be noticed very good agreement of the simulation characteristics with experimental ones in the range of stable operation of the generator.

Conclusions

The calculation of performance characteristics of the single-phase self-excited induction generator were carried out by applying the 2D field-circuit modeling. To expand output power of the generator up to the nominal power of the machine, the short-shunt capacitors should be employed. The decrease of number of turns of the excitation winding causes profitable reduction of voltage magnitude in the auxiliary stator winding. The increase in size of wires of the excitation winding, brings about decrease of current density and working temperature of the excitation winding.

***Authors**: Krzysztof Makowski, Prof. of Wroclaw University of Technology, Chair of Electrical Machines, Drives and Measurements, Poland, e-mail: krzysztof.makowski@pwr.edu.pl*

Aleksander Leicht, Ph.D, Wroclaw University of Technology, Chair of Electrical Machines, Drives and Measurements, Poland, e-mail: aleksander.leicht@pwr.edu.pl

REFERENCES

[1] Elder, J.M.; Boys, J.T.; Woodward, J.L.; The process of self excitation in induction generators, Electric Power

Applications, IEE Proceedings B, vol.130, no.2, pp.103-108, March 1983.
[2] Ojo, O.; Omozusi, O.; Jimoh, A.A.; Expanding the operating range of a single-phase induction generator with a PWM inverter, Industry Applications Conference, 1998. Thirty-Third IAS Annual Meeting. The 1998 IEEE, vol.1, no., pp.205-212 vol.1, 12-15 Oct 1998.
[3] Makowski K., Leicht A.; Analysis of self-excitation and performance characteristics of a single-phase self-excited induction generator by field-circuit method, COMPEL, The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, Vol. 35, No. 1, pp. 200-224, 2016.
[4] Cherl-Jin Kim, Kwan-Yong Lee, A Study on the Modeling and Design of Single Phase Induction Generators, KIEE International Transactions on Electrical Machinery and Energy Conversion Systems, Vol. 5-B, No. 4, pp. 331-336, 2005
[5] Murthy S.S., Singh B., Sandeep V.; Design-based computational procedure for performance prediction and analysis of single-phase self-excited induction generator, Electric Power Applications, IET , vol.7, no.6, pp.477,486, July 2013
[6] Tudorache T., Melcescu L., Paturca S.V.; Finite Element Analysis of Self-Excited Induction Generator for Isolated Small Power Wind Turbines, International Conference on Clean Electrical Power, 2007. ICCEP '07, pp.656-661, 21-23 May 2007
[7] Kumbhar G.B., Kulkarni S.V., Escarela-Perez R., Campero-Littlewood E.; Applications of coupled field formulations to electrical machinery, COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering, Vol. 26, Iss. 2, pp. 489-523, 2007
[8] Flux 2D v. 11.1, User guide, CEDRAT, France, 2011