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Performance characteristics evaluation of a single-phase self-excited induction generator by a field-circuit model

***Abstract**. The paper concerns the field-circuit evaluation of the steady-state performance of a self-excited single-phase induction generator. For the performance computation the field-circuit model of the generator was implemented using Flux2D software package. The steady-state operation of the generator was simulated for different capacitor topologies in the stator windings. An influence of the capacitor configurations in the main stator winding on terminal voltage and stator winding currents under resistive and resistive-inductive load of the generator at constant rotational speed was investigated.*

***Streszczenie.** Artykuł przedstawia polowo-obwodowe wyznaczanie charakterystyk samowzbudnego jednofazowego generatora indukcyjnego w stanie ustalonym. Do wyznaczenia charakterystyk wykorzystano model polowo-obwodowy generatora opracowany w środowisku pakietu Flux2D do obliczeń elektromagnetycznych maszyn elektrycznych. Przeanalizowano pracę generatora w stanie ustalonym dla różnych konfiguracji kondensatorów w uzwojeniu głównym i pomocniczym stojana wyznaczając napięcie i prąd w uzwojeniach generatora przy obciążeniu rezystancyjnym i rezystancyjno-indukcyjnym dla stałej prędkości obrotowej turbiny. (**Wyznaczanie charakterystyk pracy samowzbudnego jednofazowego generatora indukcyjnego za pomocą modelu polowo-obwodowego**).*

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

Introduction

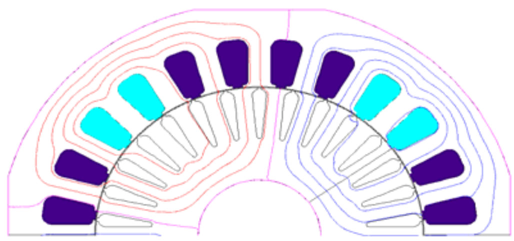
The single-phase induction machine operates as the single-phase self-excited induction generator (SPSEIG) when the rotor of the machine is driven by turbine at the main and auxiliary stator windings electrically separated and with capacitors connected to the auxiliary winding (excitation winding) or/and in the main stator winding (load winding). Self-excited single-phase induction generators, driven by small wind or hydro turbine may be successfully utilised as a supplementary or sole power source of electrical energy at household or in remote areas. Considerable interest in induction generator was observed in last two decades when renewable energy sources became alternative to conventional sources [1-5]. Most of the papers deal with three-phase SEIG, while a single-phase induction machine may also be a viable solution [1,5]. Application of a field-circuit FEM model of the generator, combining the magnetic field equations with the voltage equations of windings, allows precise determination transient and steady-state characteristics, as it accounting for phenomena associated with electromagnetic fields such as saturation of the magnetic core or self-excitation of the magnetic flux [2,3, 6].

Through the residual magnetism in the rotor core and saturation, a self-excitation phenomenon occurs in the induction generator. Its intensity depending on residual flux density left there from previous operations of the machine, rotor speed and capacitances in the excitation and load stator windings.

The paper presents the two-dimensional finite element evaluation of steady-state performance of the single-phase, self-excited induction generator.

Field-circuit model of the generator

The two-dimensional FEM model for the generator with cross-section and electric circuit is shown in Fig. 1. In the model, the magnetic field in windings, the iron core and air-gap is solved by 2D FEM and coupled with voltage equations of stator windings and rotor windings (or rotor bars). The stator winding of the generator is unsymmetrical, single-layer two-phase copper winding: main winding (dark violet in Fig. 1) is the output winding of the generator with terminals to which the resistive load R_L is connected, while the auxiliary winding (cyan in Fig. 1) operates as the excitation winding with the capacitor connected to its terminals. The rotor cage is made of aluminum and consist of bars connected by short-circuit rings in both ends of the rotor core. Through the geometrical symmetry and electromagnetic periodicity of the generator, computation of two-dimensional field was reduced to the 2 pole pitches of the cross-section. This field-circuit model allows for nonlinear magnetizing characteristic, field harmonics and eddy currents in the rotor bars. The field-circuit computation of the SPSEIG dealt with steady-state examination of the single-phase four poles induction machine which ratings are listed in Table 1.



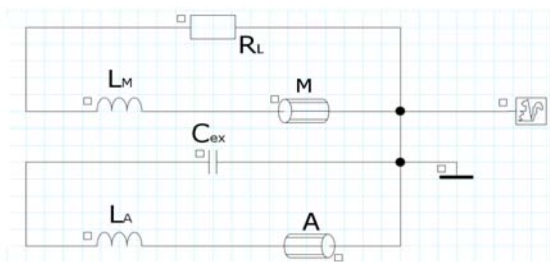


Fig.1. Field-circuit model of the single-phase induction generator

Table 1. The ratings of the tested machine

Rated power	1.1 kW
Rated voltage	230 V
Rated current	7.5 A
Rated speed	1380 rpm
Efficiency	0.70
Power factor	0.96
Frequency	50 Hz

The second order finite element mesh consisting of triangular and quadrilateral elements, includes around 22000 nodes. Part-view of the meshed geometry is shown in Fig.2. The boundary conditions are set as zero magnetic flux on the outer surface of the stator core and the inner surface of the rotor core and symmetry constrains were set on the periodic boundary. The shaft is modeled as non-conductive and non-magnetic medium.

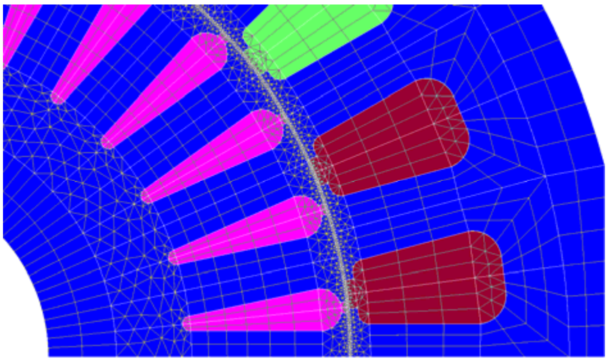
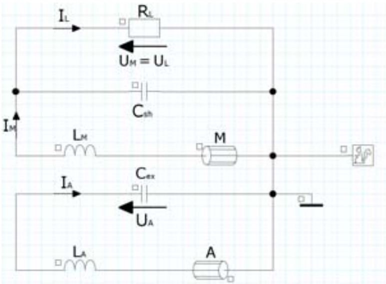
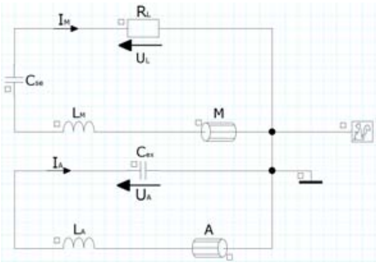


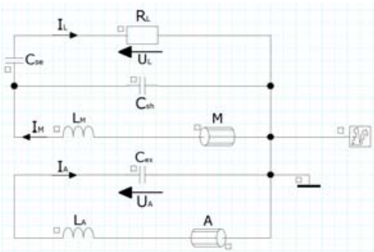
Fig.2. FE mesh of the computational domain of the generator



a)



b)



c)

Fig.3. Electric circuits of the generator model with: shunt (a), series (b) capacitor and short-shunt connection (c)

Using vector potential formulations for magnetic field, the 2D quasi-static magnetic field in different parts of cross-section of the induction machine can be determined by the equation:

(1)

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

where: A[0, 0, A(x,y,t)] is the magnetic vector potential, J_s[0, 0, J_s(x, y, t)] – the current density in the stator slots, ν – reluctivity of the magnetic material, σ – electric conductivity, (in the laminated iron core the conductivity is set to zero).

The excitation capacitor C_{ex} parallel connected to the auxiliary winding (A) (Fig.1.) provides the reactive power necessary for self-excitation. The resistor R_L connected to the main winding (M) of the generator represents the resistive load or internal resistance of the voltmeter, if no-load conditions are considered. The inductances L_M and L_A denote the end-winding inductances of the stator.

The capacitors in the stator windings

Investigations of performance of the SPSEIG were conducted for different topologies of the capacitors in the load stator winding, i.e. with the shunt or/and series capacitors connected to the terminals or without capacitance in the load winding. The connection diagrams of the circuit part of the model for considered capacitor topologies are shown in Fig. 3. In the cases of the basic capacitor topology (shown in Fig.1) and with shunt capacitor, the load voltage is equal to the terminal main winding voltage, otherwise is the difference between the main winding voltage and voltage across the capacitor C_{se} .

Performance characteristics under restive load

The load characteristics of the tested generator for different capacitor configurations are presented in Figs. 4, 5. In all studied cases, the capacitors capacitances were selected in such a way that it develops the no-load terminal voltage about 230 V at the prime mover speed n = 1620 rpm and their values are listed in Table 2.

Table 2. Capacitances for different capacitor topologies

Topology	C_{ex} [μF]	C_{se} [μF]	C_{sh} [μF]
Excitation capacitor	30	-	-
Series capacitor	30	200	-
Shunt capacitor	25	-	15
Short-shunt connection	25	200	15

The single-phase induction machine as a self-excited induction generator has inherently poor voltage regulation. The shunt capacitor C_{sh} allows moving a burden of self-excitation from the auxiliary to main stator winding. The SPSEIG operates then with lower auxiliary winding current I_A (Fig. 5b). This is advantageous, as the auxiliary winding is designed to work with currents much smaller than the main stator winding. Introduction of series capacitor C_{se} in the main winding allows loading the generator with more active power. However, the value of the series capacitor is relatively large, and the use of few parallel-connected, smaller capacitors would be needed to build a capacitor battery of 200 μF. As the capacitance requirement is mostly influenced by parameters of stator winding, a redesign of the machine's windings is necessary.

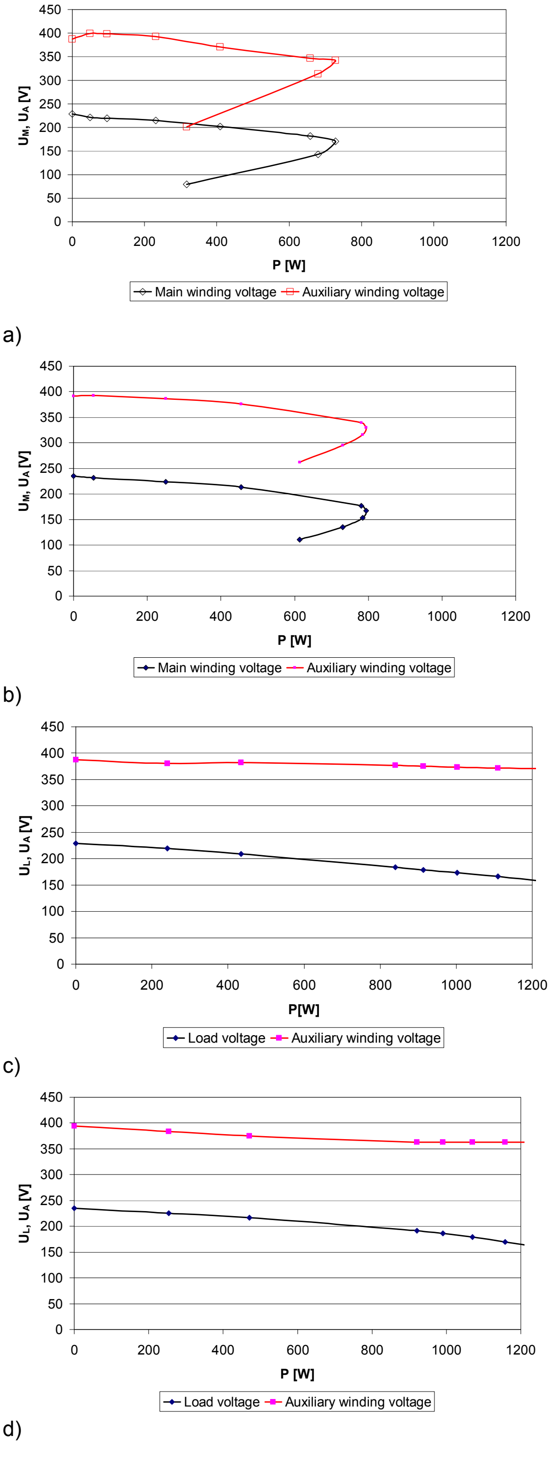


Fig.4. Voltages of main and auxiliary windings of the generator: without capacitor (a), with shunt capacitor (b), with series capacitor (c) and with short-shunt connection (d) in the main winding, versus resistive output power

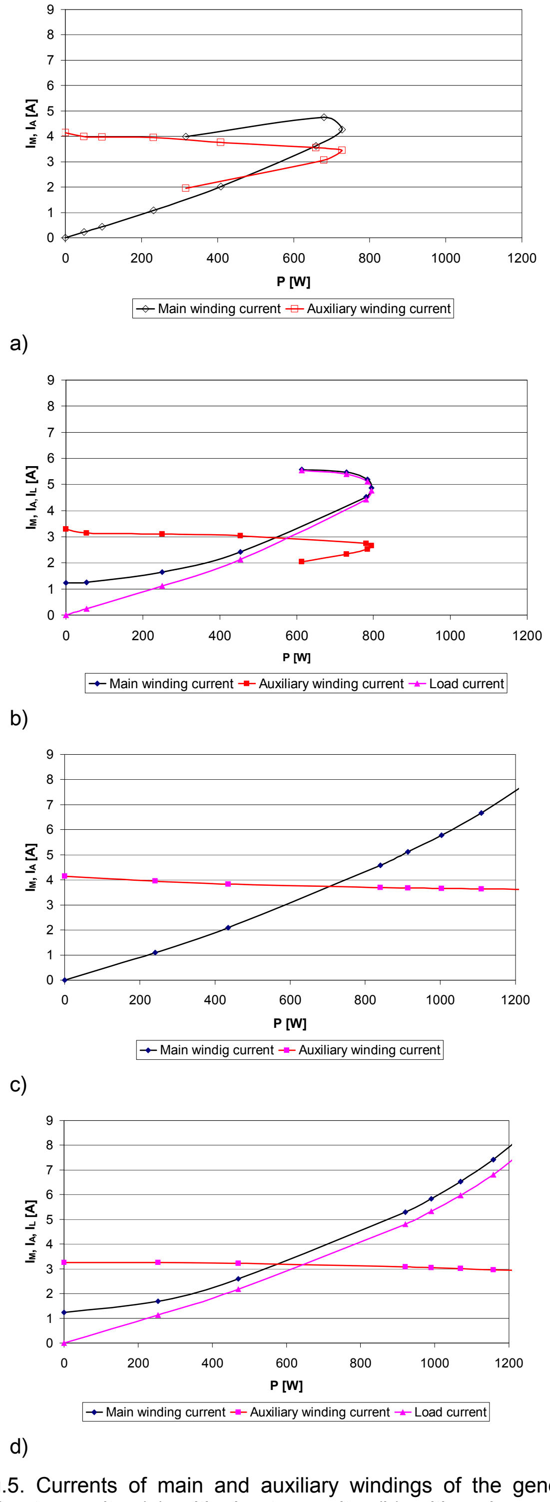


Fig.5. Currents of main and auxiliary windings of the generator: without capacitor (a), with shunt capacitor (b), with series capacitor (c) and with short-shunt connection (d) in the main winding, versus resistive output power

The capability of the generator may be improved by using one more capacitor connecting in series to the main stator winding capacitor C_{se}. Such capacitor topology allows more stable operation, however necessity of using three different capacitors may be a disadvantage.

Under resistive load corresponding to rated output power at the speed mover equal to 1620 rpm only the short-shunt capacitor configuration in the main stator winding ensures self-regulation of the terminal voltage of the generator, i.e. the terminal voltage remains at required level (Fig.4d).

Simulation results presented in Figs. 4b, 5b show that the SPSEIG with shunt capacitor in main winding may operate stably with resistive load up to approximately 50% of the machine's rated power, while with the resistive-inductive load, the range of stable operation significantly decreases with decreasing power factor of the load (Fig. 6).

Load range of the SPSEIG may be easily extended by applying the short-shunt capacitor topology (Fig. 7), where the generator is loaded up to the rated power when load is purely resistive. For resistive-inductive load output power of the generator, as in previous case, considerably decreases as power factor decreasing.

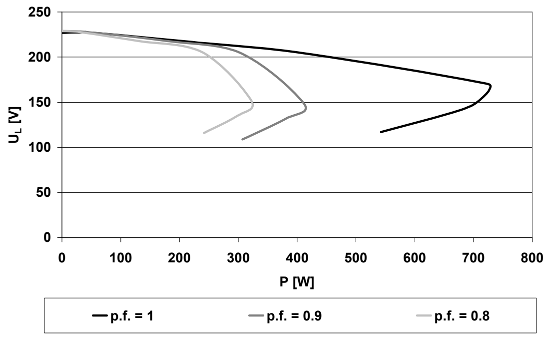


Fig. 6. Terminal voltage (U_L) versus output power of the SPSEIG with shunt capacitor for different power factors

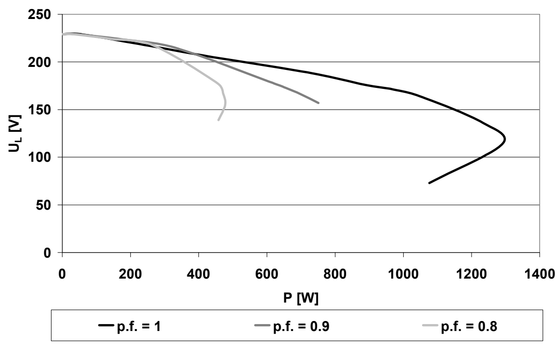


Fig. 7. Terminal voltage versus output power of the SPSEIG with short-shunt capacitor connection for different power factors

Conclusions

The aim of the paper was to present the simulation study of the single-phase self-excited induction generator at steady-state conditions of operation. Performance characteristics of the generator was investigated by exampled cases of varying topologies of capacitors connected to the main stator winding. The effects of the capacitor capacitance at constant prime-mover speed on the excited terminal voltages in the generator were investigated by the circuit–field model accounting for complex geometrical construction and nonlinear magnetizing characteristic of the iron core. The results showed possible employment of the tested induction machine as self-excited induction generator in range of speed from 1500 to 1680 rpm to ensure the terminal voltage under no-load and resistive load equal to 230V ±10%. The single-phase induction machines are usually design to operate as induction motors at desired output torque and efficiency, therefore for the machines in working order as self-excited induction generators, redesign of stator windings construction are necessary. Further investigations on terminal voltage under load condition will be performed concerning specific design of the both stator windings including different auxiliary-to-main winding turns ratio.

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