A single-phase induction motor operating as a self-excited induction generator[*]

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Abstract: The purpose of the paper is the investigation of possibility of utilization of a single-phase induction machine, designed and normally operating as a single-phase capacitor induction motor, as a self-excited single-phase induction generator, which can be used to generate electrical energy from non-conventional energy sources. The paper presents dq model of the self-excited single-phase induction generator for dynamic characteristics simulation and steady-state model based on double revolving field theory with two phase symmetrical components – a forward and backward revolving field for performance of the generator under resistive load. Excitation and load characteristics obtained by simulation showed considerable influence of method of capacitor configuration in the load stator winding on terminal voltage, current and output power of the generator under load. An specific construction of the stator windings together with capacitor requirements to obtain nominal output power at desired self-regulating terminal voltage over the operating range will be the aim of further research.

Key words: induction generator, single-phase, circuit modelling, self-excited, induction motor

1. Introduction

Self-excited single-phase induction generators (SPSEIGs), driven by small wind turbine or hydro turbine may be successfully utilised as an additional or reserve source of electrical energy at household or in remote areas. For supplying single-phase loads of power up to 10 kW single-phase self-excited induction generators or three phase self-excited induction generators with single-phase output may be used. Excitation capacitors should have regulated capacitance to secure self-excitation and stability of output voltage of generator during load

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changes. Considerable interest in induction generator was observed in last two decades when renewable energy sources became alternative to conventional sources [1-8]. Self-excited induction generators have advantages like simplicity, durability and low costs of manufacturing and maintenance when compared to synchronous, permanent magnet or DC generators. Theirs main disadvantages are unpredictable residual magnetism, necessary for self-excitation, and weak voltage self-regulation [1, 4]. Output characteristics of the SPSEIGs may be improved with proper design of the magnetic circuit, windings and adequate choice of capacitors. The operation range of the SPSEIGs can also be expanded with use of a simple power electronics-based scheme, such as reported in [3]. A single-phase induction motor may operate as the SPSEIG if the rotor of the machine is driven with synchronous speed or higher with the main and auxiliary stator windings electrically separated and when the capacitor is connected across the auxiliary winding (excitation winding) or/and in the main stator winding (load winding). Due to residual magnetism in the magnetic core of the machine, self-excitation phenomenon occurs. Its intensity depends on residual flux density left after preceding operation of the machine, rotor speed, and values of capacitances connected in the excitation and load windings.

The paper presents an influence of different capacitor topologies and number of turns of stator windings on steady-state and self-excitation performance characteristics of the SPSEIG. The considered machine is an off-the-shelf single-phase induction machine designed for motor operation. The steady-state calculations were performed with the use of analytical circuit model based on double revolving field theory, while the transient analysis was done with the use of *dq* model.

2. Steady-state model of the generator

A steady-state model of the SPSEIG which was used for simulation is based on double revolving field theory and two-phase symmetrical components method – the elliptic field in the machine's airgap is decomposed into two waves progressing in opposite directions: a forward and backward revolving field, each associated with an induction machine equivalent circuit [9, 10]. The equivalent circuit of considered generator is given in Figure 1 and is similar to the equivalent circuit of the single-phase induction motor, where the load impedance $\mathbf{Z}_{LM}$ replaces supply voltage.

R_M and X_{lM} are the resistance and leakage reactance of the main winding, R_A and X_{lA} are the resistance and leakage reactance of the auxiliary winding, referred to the main winding. Respective rotor parameters, also referred to the main stator winding are denoted as R_r and X_{lr}. X_{CA} denotes reactance of the excitation capacitor in the auxiliary winding.

Autonomous induction generator operates in general at variable frequencies, thus phase impedances are adjusted for the per unit operating frequency denoted as F. Also, slip was replaced with per unit rotor speed v. Magnetizing reactance X_m is affected by magnetic saturation (Fig. 2).

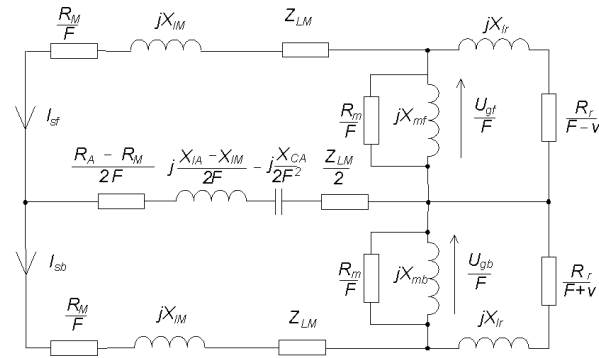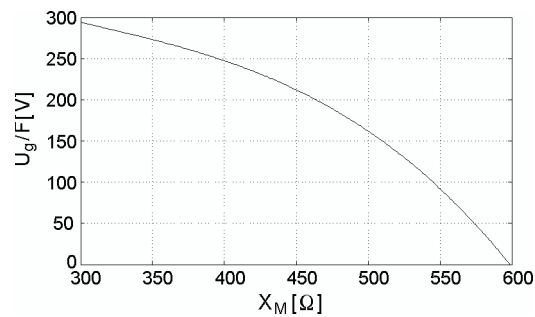Fig. 1. Equivalent circuit of a single-phase self excited induction generator

Fig. 2. Magnetization curve of the considered machine

The conditions under which the generator self-excites (resonance conditions) are determined by the relation:

$$\mathbf{I}_{sf} \cdot \mathbf{Z}_t = 0. \tag{1}$$

Since $\mathbf{I}_{sf}$ cannot be zero under steady-state self-excitation, the resonance conditions are derived by equating real and imaginary parts of total impedance of the equivalent circuit, $\mathbf{Z}_t$, to zero [10]. Those equations yield unknown values of X_m and F for given rotor speed v and load impedance $\mathbf{Z}_{LM}$ which can be evaluated using Matlab software. For given X_m and F, corresponding value of airgap voltage U_g may be determined from the magnetizing characteristics. Using equivalent circuit, forward and backward components of stator currents, $\mathbf{I}_{sf}$ and $\mathbf{I}_{sb}$ are computed, and finally, main and auxiliary winding currents $\mathbf{I}_M$, $\mathbf{I}_A$ and voltages $\mathbf{U}_M$, $\mathbf{U}_A$ are calculated from the following relations (*a* denotes machine's auxiliary-to-main turns ratio) [9]:

$$\mathbf{I}_M = \mathbf{I}_{sf} + \mathbf{I}_{sb}, \tag{2}$$

$$\mathbf{I}_A = \frac{j \cdot (\mathbf{I}_{sf} + \mathbf{I}_{sb})}{a}, \tag{3}$$

$$\mathbf{U}_M = \mathbf{I}_M \cdot \mathbf{Z}_{LM}, \tag{4}$$

$$\mathbf{U}_A = \frac{-\mathbf{I}_A \cdot jX_{CA}}{F^2}.$$ (5)

3. Dynamic model of the generator

The dq model of the SPSEIG was formulated under following assumptions:
• air-gap is uniform,
• only fundamental harmonic magnetic field is considered,
• core loss and skin-effect in rotor bars are neglected,
• magnetizing inductance is subject to saturation,
• resistances and leakage inductances are constant,
• generator is driven at constant speed.

Using flux linkages as state variables, a set of nonlinear differential equations mapping dynamics of the generator may be written as follows:

$$\frac{d\psi_{ds}}{dt} = u_{dM} - \frac{R_M}{L_{lM}}(\psi_{ds} + \psi_{dm})$$

$$\frac{d\psi'_{qs}}{dt} = u'_{CA} - \frac{R'_A}{L'_{lA}}(\psi'_{qs} + \psi_{qm})$$

$$\frac{d\psi'_{dr}}{dt} = -\frac{R'_r}{L'_{lr}}(\psi'_{dr} + \psi_{dm}) + \psi'_{qr}\omega_r$$ (6)

$$\frac{d\psi'_{qr}}{dt} = -\frac{R'_r}{L'_{lr}}(\psi'_{qr} + \psi_{qm}) - \psi'_{dr}\omega_r,$$

$$\psi_{dm} = \frac{-L_m}{L_{lM}L'_{lr} + L_m(L_{lM} + L'_{lr})}\left(L'_{lr}\psi_{ds} + L_{lM}\psi'_{dr}\right)$$

$$\psi_{qm} = \frac{-L_m}{L'_{lA}L'_{lr} + L_m(L'_{lA} + L'_{lr})}\left(L'_{lr}\psi'_{qs} + L'_{lA}\psi'_{dr}\right),$$ (7)

$$\psi_m = \sqrt{\psi^2_{dm} + \psi^2_{qm}}.$$ (8)

Nonlinear dependence $L_m = f(\psi_m)$ was determined using so-called normal magnetizing curve for induction machines [11] and was approximated by the 2nd order polynomial as follows:

$$L_m = -0.5816\psi^2_m + 0.09305\psi_m + 1.894.$$ (9)

Having determined the flux linkages, the stator currents are calculated as:

$$i_{dM} = -\frac{\psi_{ds} + \psi_{dm}}{L_{lM}}$$

$$i'_{qA} = -\frac{\psi'_{qs} + \psi_{qm}}{L'_{lA}}.$$

(10)

The voltage across the main stator winding (load winding) may be calculated using the expressions:

$$u_{dM} = R_L \cdot i_{dM} \quad \text{or} \quad u_{dM} = \frac{1}{C_{Msh}} \int i_{dM}\, dt$$

(11)

and the voltage across the excitation winding is given by:

$$u'_{CA} = \frac{1}{C_A} \int i'_{qA} dt.$$

(12)

4. The excitation and regulation capacitor topologies

Computations of performance characteristics of the SPSEIG with excitation capacitor C_A in the auxiliary winding were performed for three configurations in the load stator winding, i.e. without capacitor, with parallel capacitor and with series connected capacitor, as shown in Figure 3.
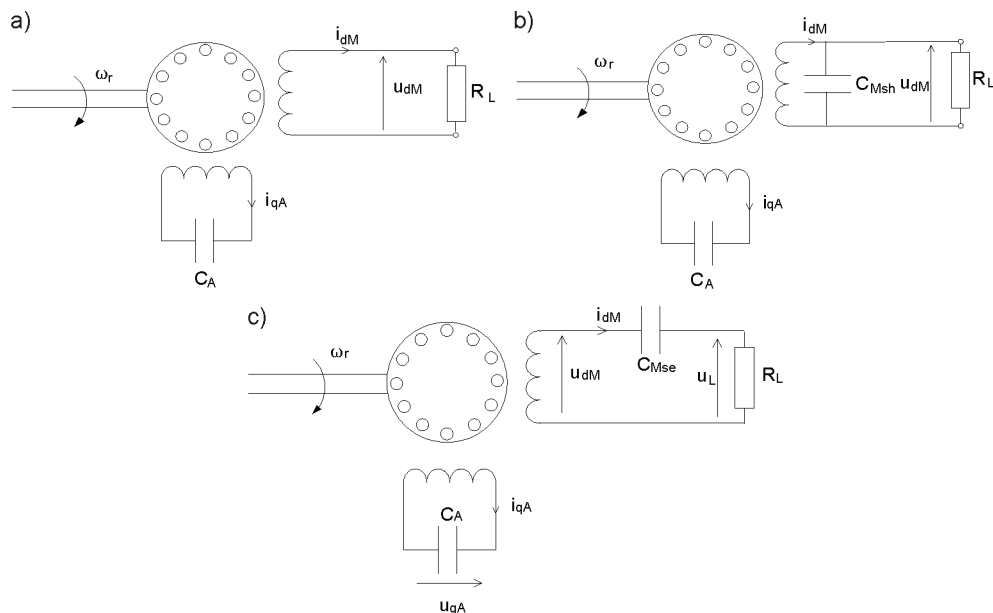

Fig. 3. Generator with excitation capacitor and: a) without capacitor in the load winding,
b) with parallel capacitor in the load winding, c) with series capacitor in the load winding

5. Steady-state performance characteristics

The load characteristics of the SPSEIG without and with series and shunt capacitor in the load winding are presented in Figure 4. In order to make comparison of performance characteristics it was assumed that for each analyzed configuration, the terminal voltage has nominal value of 230 V for synchronous rotor speed at no-load operation. It required selection of adequate specific value of capacitor connected in series or parallel to the stator windings. The ratings and winding parameters of the tested machine are listed in Table 1.

Table 1. Ratings and parameters of the tested machine

Rated power	0.09 kW
Rated voltage	230 V
Rated current	0.9 A
Rated speed	2840 rpm
Efficiency	0.55
Power factor	0.9
Frequency	50 Hz
Stator windings resistances R_M/R_A	48.3 Ω / 156.8 Ω
Stator winding leakage inductances L_{lM}/L_{lA}	59.3 mH / 210.1 mH
Rotor cage resistance R_r	39.2 Ω
Rotor cage leakage inductance L'_{lr}	160.2 mH

It may be observed from Figure 4 that load characteristics of the generator depend on value of capacitance and method of connection of capacitor to the load stator winding. The series connected capacitor allows loading the generator up to its maximum power and ensures good stability of the terminal voltage at rated value of output power. The parallel connected capacitor in the load winding brings about reduction of induced voltage in the exciting stator winding but at the same time causes decrease of maximum output power by about 40%.

A single-phase induction machine designed to operate as a motor can be used as induction generator, however it's performance may not be satisfactory. The parameters of the motor differ from those of the generator for good performance. Among other parameters, the magnetizing characteristic and stator windings need to be modified. Figure 5 shows the magnetizing characteristics for different number of stator winding turns, while the Figure 6-8 presents the effects of variation of the winding turns on the load characteristics. In this figures, N_M and N_A denote the number of turns in the main (load) and auxiliary (excitation) winding, and a is the auxiliary-to-main turns ratio. The calculations were performed for all the capacitor topologies presented in Figure 3. The capacitor capacitances were selected to maintain the no-load nominal voltage for the base winding configuration ($N_M = 840$, $N_A = 1252$, $a = 1.56$) and was maintained for the other configurations.
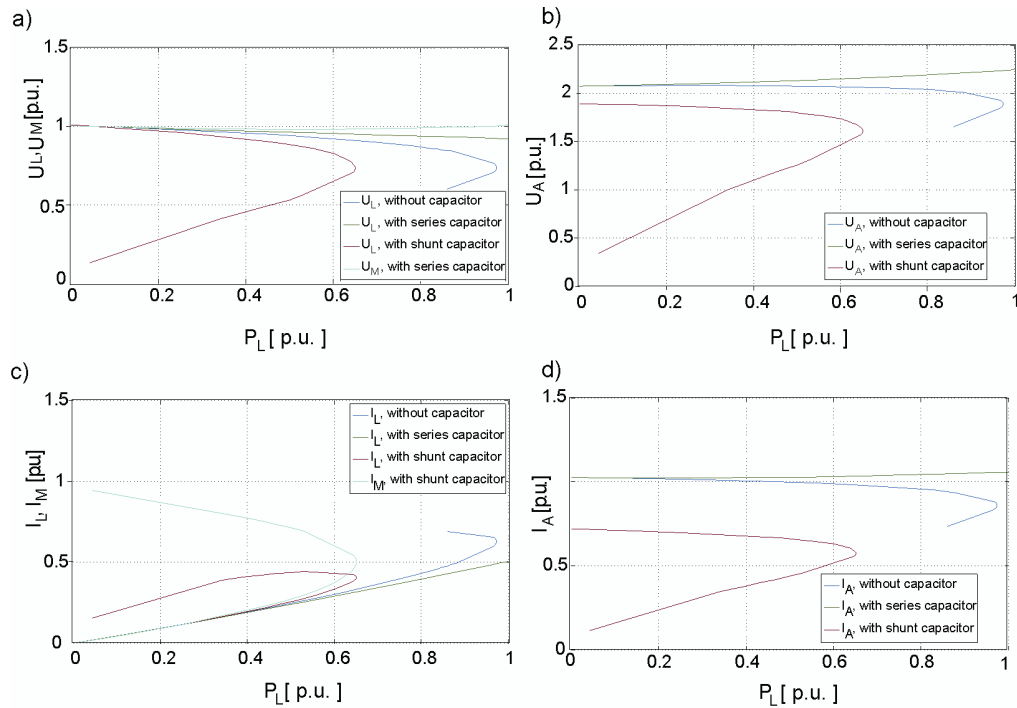
a)

b)

c)

d)

Fig. 4. Load characteristics of SPSEIG at unity power factor load for different configurations of load stator winding: a) terminal/load voltage; b) auxiliary winding voltage; c) main winding/load current; d) auxiliary winding current
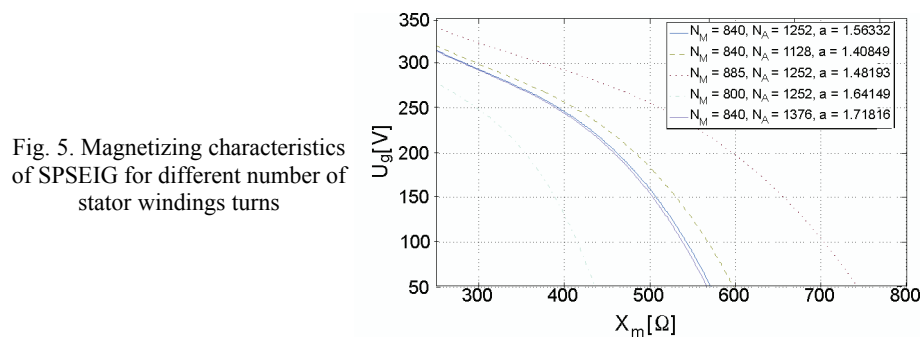

Fig. 5. Magnetizing characteristics of SPSEIG for different number of stator windings turns

The magnetizing characteristics give suggestion about requirements of the excitation capacitor. When the saturated value of X_m is low, the machine needs higher value of capacitance. Lowering the number of turns of the auxiliary winding lowers the voltage U_A, which is beneficial, but it worsens the terminal voltage regulation and the higher value of the capacitance is required. Better results were obtained by increasing the number of turns in the main stator winding – the required capacitance is lower and it results in better voltage regulation. However, the voltage in auxiliary winding rises.
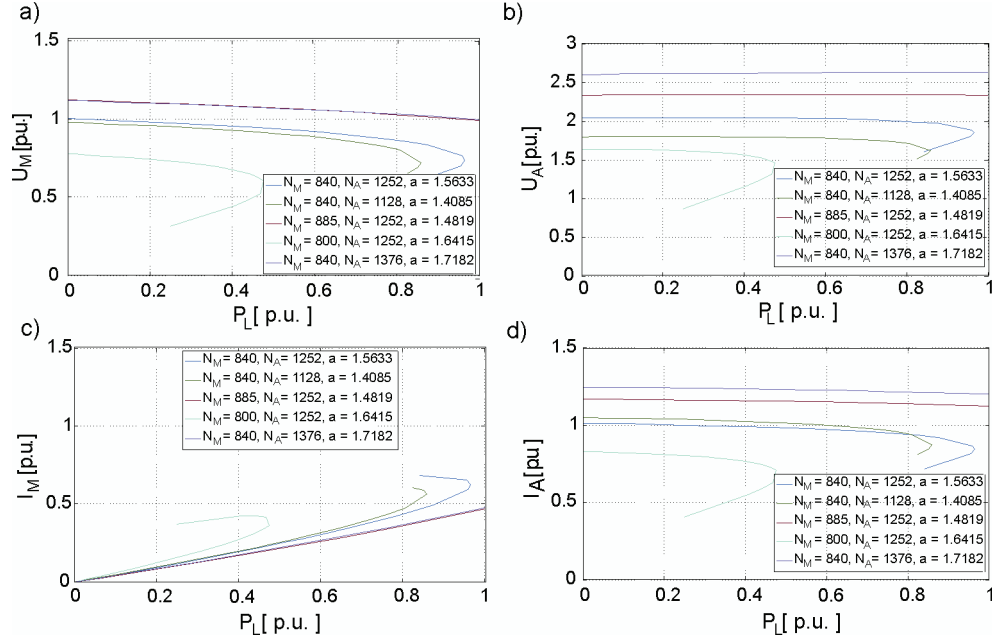
Fig. 6. Load characteristics of SPSEIG at unity power factor load for different stator winding
configurations, for the topology shown in Figure 3a: a) terminal voltage;
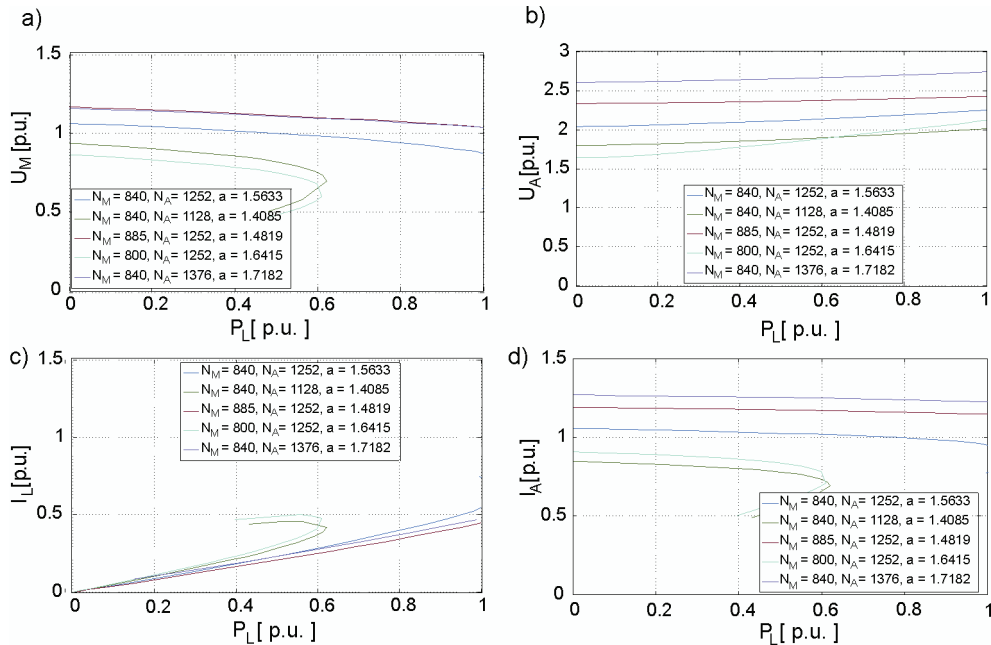b) auxiliary winding voltage; c) main winding current; d) auxiliary winding current

Fig. 7. Load characteristics of SPSEIG at unity power factor load for different stator winding
configurations, for the topology shown in Figure 3b: a) terminal voltage;
b) auxiliary winding voltage; c) main winding current; d) auxiliary winding current
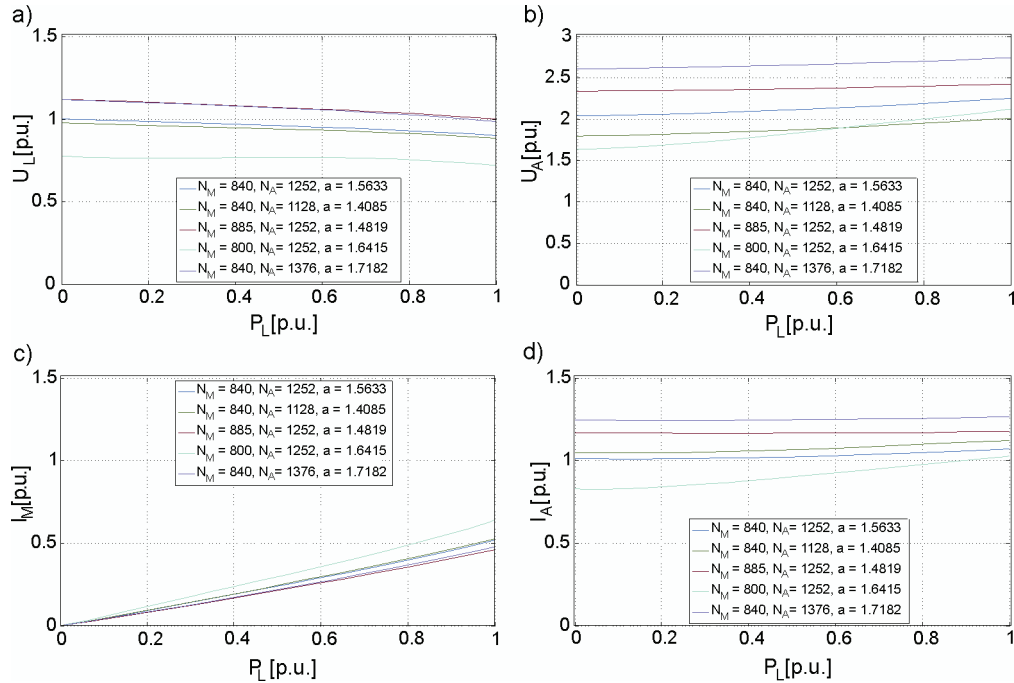
Fig. 8. Load characteristics of a SPSEIG at unity power factor load for different stator winding configurations, for the topology shown in Figure 3c: a) load voltage; b) auxiliary winding voltage; c) main winding current; d) auxiliary winding current

6. Self-excitation of the single-phase induction generator

Simulations of dynamic operation of the SPSEIG was limited to self-excitation process with excitation capacitor C_A in the auxiliary winding for three basic configurations in the load winding as shown in Figure 3. As in the Section 5, the excitation capacitor C_A across the auxiliary winding was such selected that no-load terminal voltage across the main winding reaches about 230 V (the nominal value) at steady-state. The voltage and current waveforms of the generator excited at no-load operation and after application of 50% rated load are shown in Figures 9-11.

It is seen that the load stator winding with capacitor connected in series with load improved stability of the terminal voltage under load. The results showed enormous sensitivity of the terminal voltage to load: switching about 50% of nominal resistive load of the generator brings about the terminal voltage drop by several percent. Increasing magnetizing inductance L_m (Fig. 12) by increasing the number of turns of the load winding (M) has profitable impact on self excitation of the generator and stability of voltage under resistive load. Changing number of turns of the excitation winding even by (5-10)% does not effect visibly on magne-

tizing inductance L_m. However, increasing the number of turns of the excitation winding (A) brings about considerable increase of the voltage and current in the excitation winding.
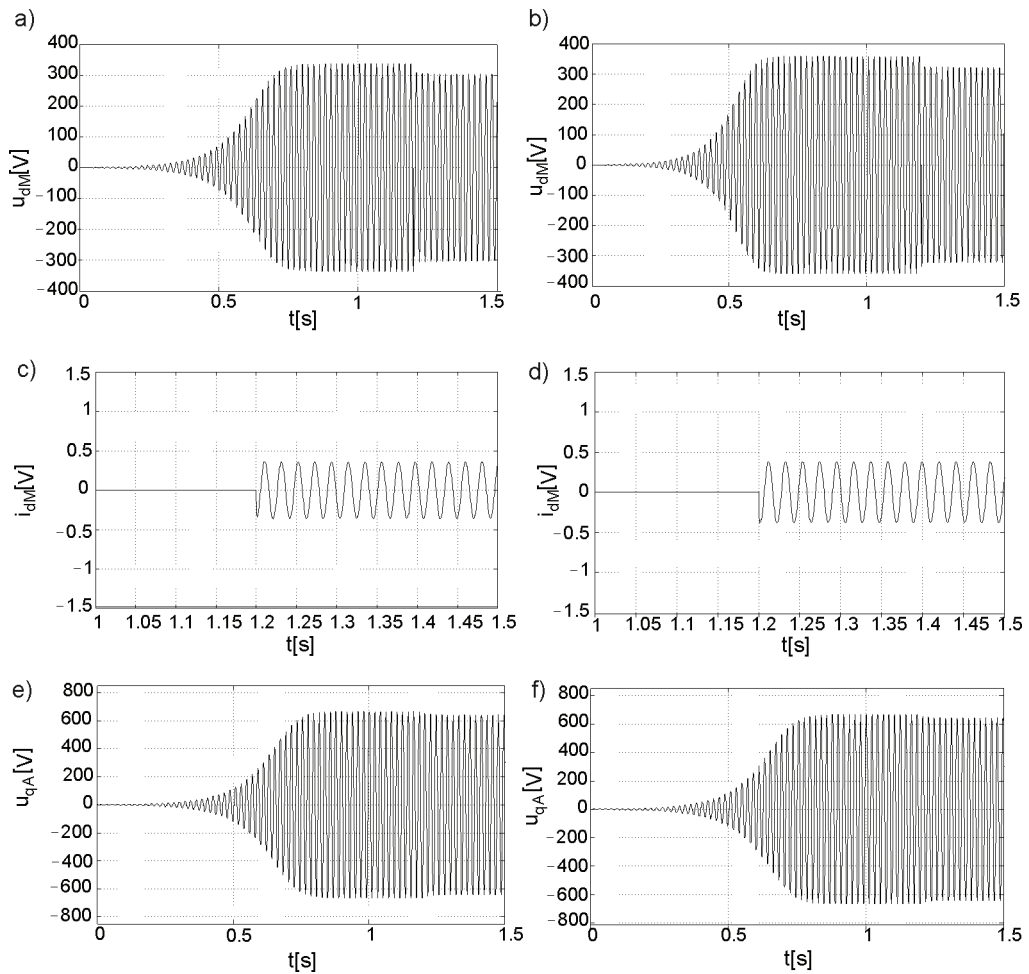

Fig. 9. No-load/load terminal voltage, load current and auxiliary winding voltage during self-excitation for generator without capacitor in load winding (Fig. 3a); a, c, e $N_M = 840$, $N_A = 1252$, $a = 1.56$; b, d, f $N_M = 885$, $N_A = 1252$, $a = 1.48$

7. Conclusions

In the paper, the steady-state and self-excitation characteristics of the single-phase induction generator with different configuration of load stator winding was presented. The results showed enormous sensitivity of the terminal voltage to method and value of capacitance

connected in the load stator winding. The influence of the number of turns of the stator windings was examined. It was shown that number of turns of stator windings of the single-phase induction machine operating as an autonomous generator at constant speed should be chosen to ensure good terminal voltage regulation and to decrease the voltage in the auxiliary (excitation) winding. The single-phase induction machine operating as a generator should be designed to work with the auxiliary winding voltage higher than the nominal value. Investigations on specific construction of the generator windings to obtain maximum output power at desired self-regulating terminal voltage (to remain the terminal voltage at required level) over the operating range will be the aim of further research.
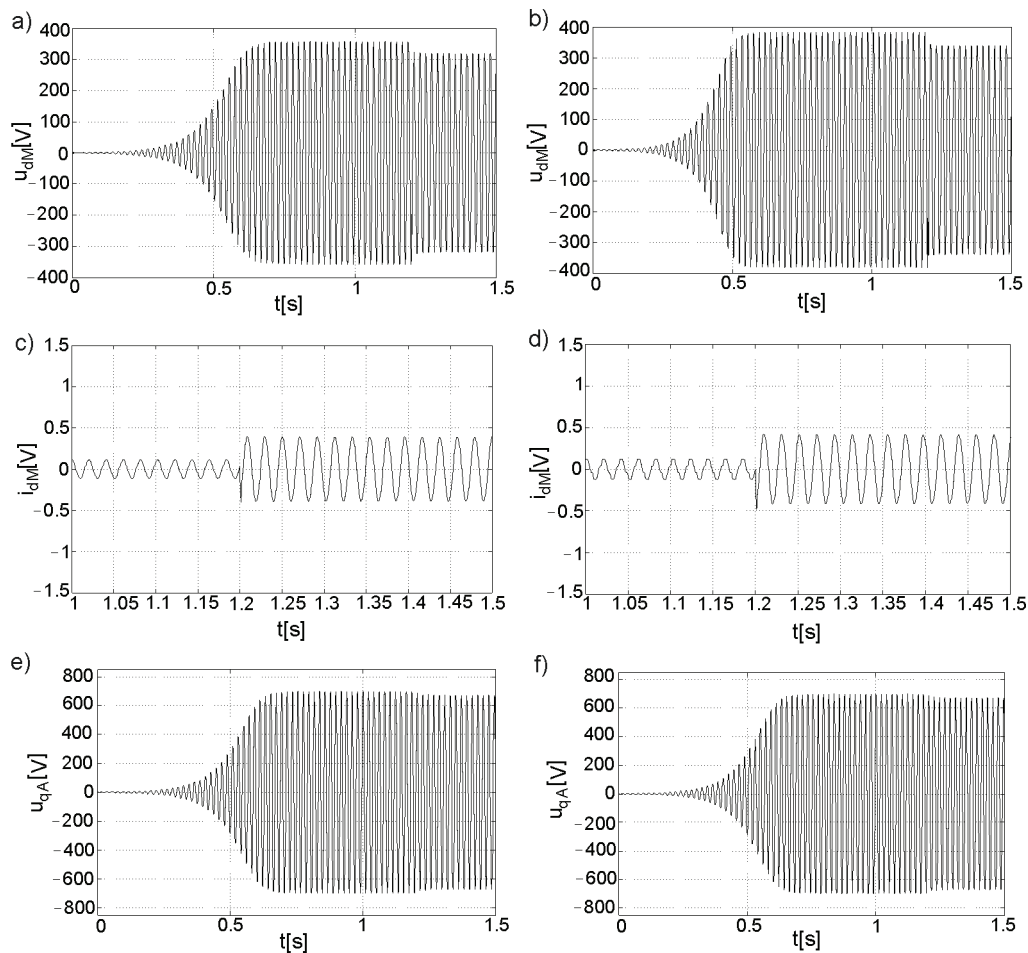

Fig. 10. No-load/load terminal voltage, main winding current and auxiliary winding voltage during self-excitation for generator with parallel capacitor in load winding (Fig. 3b);
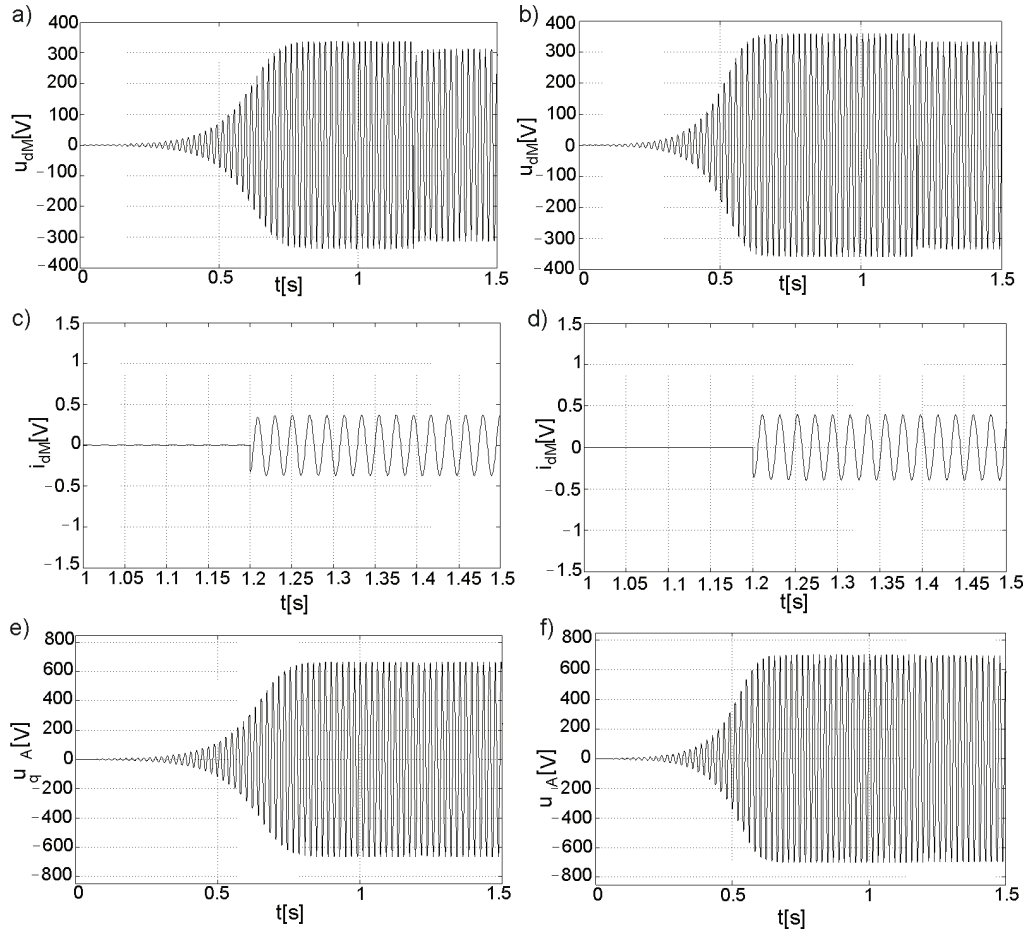a, c, e $N_M = 840$, $N_A = 1252$, $a = 1{,}56$; b, d, f $N_M = 885$, $N_A = 1252$, $a = 1.48$

Fig. 11. No-load/load terminal voltage, load current and auxiliary winding voltage during self-excitation
for generator with series capacitor in load winding (Fig. 3c);
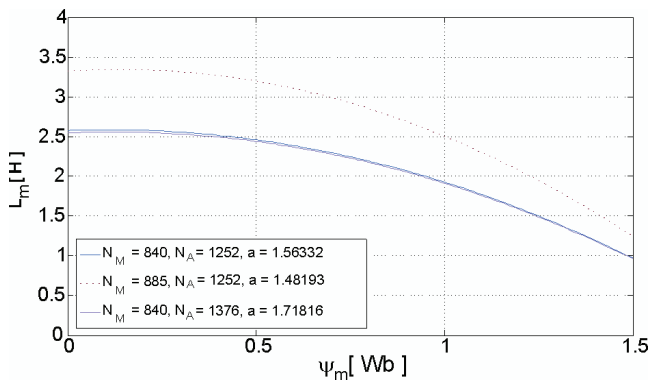a, c, e N_M = 840, N_A = 1252, a = 1.56; b, d, f, N_M = 885, N_A = 1252, a = 1.48

Fig. 12. Magnetizing characteristics
of a SPSEIG for different number of
stator windings turns

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