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# Simulations and measurements on a self-excited induction generator

**Jozef Zuščak, Vladimír Kujan, František Janíček** *

Paper deals with the use of an induction machine in the role of a generator. Such an operational mode is called a self-excited induction generator SEIG. It does not require an external power source to create the excitation field, as is the case with traditional synchronous generators. Therefore, it is widely used in power plants with renewable energy as a primary source (wind, water, *etc* ). However, in terms of possible regulation and control of the electrical properties, the excitation process is extremely important. A mathematical model and simulation in Matlab are introduced. The excitation process was experimentally investigated in the laboratory of electric drives and the results are correlated with the expectations.

K e y w o r d s: SEIG, capacitor, load, saturation, excitation, voltage

## 1 Introduction

Increasing demands on electricity supply, coupled with declining machinery and storage battery prices, result in the expansion in the field of isolated (off-grid) power systems. Nowadays, two types of generators are predominantly used for off-grid power supply:

- generator with permanent magnets,
- inductive generator.

The main reason for this is that these machines do not need an external power source to generate the magnetic field of the rotor (excitation), which is needed for conversion of mechanical energy into electricity. This fact is very important. On the other hand, the lack of independent field regulation brings problems with current and voltage control. Especially if the generator is used in combination with a small wind turbine with poor speed control abilities. In this type of operation, undesirable voltage fluctuations can occur. Even the possibility of magnetic field loss resulting in a loss of power can be observed in case the load is increased behind a stable working point. We discuss these as well as other issues, focused on the SEIG, mainly due to its properties like: low unit price, brushless squirrel-cage rotor, low maintenance requirements, and operation without an external source of excitation.

## 2 Theoretical and mathematical background

Operation of the induction generator with a squirrel cage is possible only due to the presence of remanent magnetism in the rotor usually built from magnetically soft materials. Remanent (residual) magnetism is always present thanks to the previous operation of the machine. According to Faraday's law, the moving magnetic field of the rotor will induce voltage in the stator coils. This voltage depends on the excitation current and the speed of rotation. In our case, the excitation current is provided due to a capacitor bank connected to the stator windings.

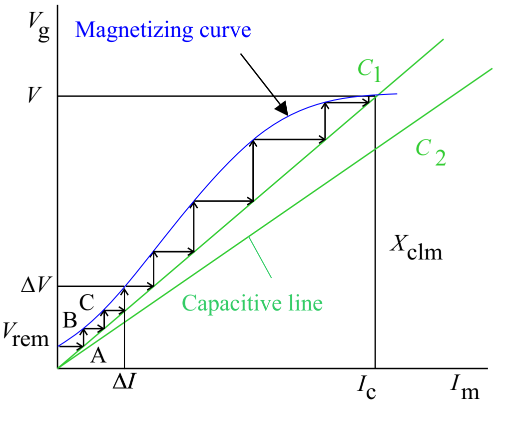


**Fig. 1.** Self-excitation process

The self-excitation, described in Fig. 1, is a long know process [6]. When the prime mover drives the rotor, the remanent magnetism in the rotor causes the induction voltage across the stator coils with frequency proportional to the speed of rotation. Due to this voltage the capacitor bank connected in parallel provides the stator current flow. The magnetic flux in the machine is raised with rising stator voltage and current. The process continues until the saturation point is reached where the voltage is stable.

The dynamic behaviour of SEIG can be mathematically described by six state equations, providing all currents and voltages can be describeds as

$$\begin{aligned} i(t) &= I(t)cos(\omega t + \phi) \\ v(t) &= V(t)cos(\omega t + \theta) \end{aligned} \tag{1}$$

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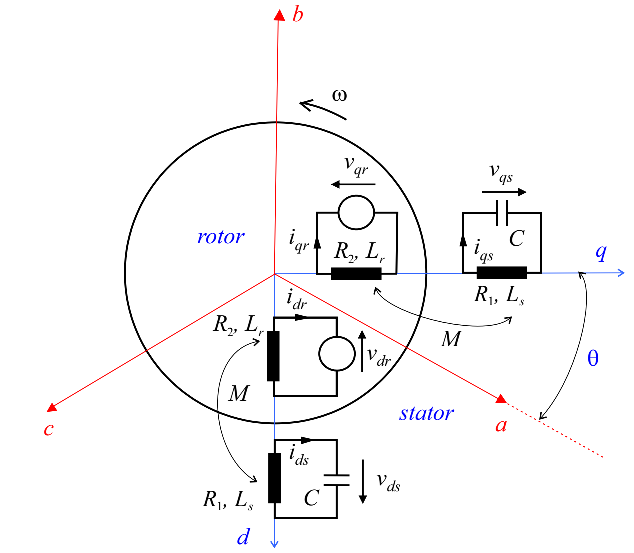


**Fig. 2.** Park transformation of SEIG with capacitors on stator terminals

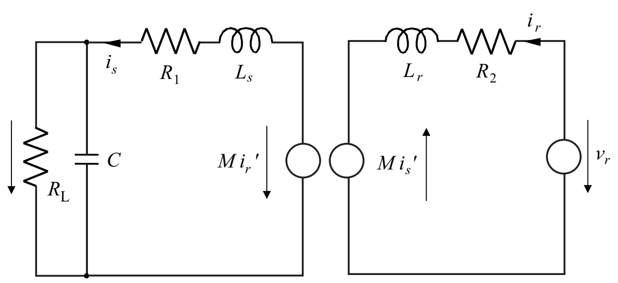


**Fig. 3.** Equivalent circuit diagram

where amplitudes $I(t), V(t)$ are time dependent until the saturation is reached and $\omega$ - is rotation speed of the prime mover, [1]. Using standard complex representation in equations of the equivalent circuit in Fig. 3: $i(t), v(t) \to \mathcal{J}(t)e^{j\omega t}, \mathcal{V}(t)e^{j\omega t}$, after the separation into $d$ and $q$ -frames, $\mathcal{J} = I_d + jI_q$ and $\mathcal{V} = V_d + jV_q$, still with time dependent amplitudes – although we omit the explicit notation for brevity – after some manipulation, the following equations were formulated

## 3 Measurments on induction generator

For simulation and evaluation of the results, several laboratory measurements were performed on a test induction machine:

- Coil resistance test
- No-load test
- Locked rotor test
- Magnetization curve test

First, equivalent circuit, Fig. 3, parameters need to be determined, to be used in simulations. Inductances $L_r, L_s$ and the mutual inductance $M$, resistances $R_1, R_2$ of stator and rotor windings, and initial amplitude $V_r$ due to remanent induction. The losses in the core were neglected in presented calculations and the load $R_L$ (not indicated in Fig. 2) was considered to be purely ohmic (no capacitive nor inductive) in this approach.

### *3.1 Parameters of equivalent circuit*

Induction machine plate information: $P = 2.2$ kW, wound rotor, $n = 1400$ rpm, $U = 380/220$ V, (Y/D), $I = 5/8.6$ A (Y/D).

The $I - V$ method was used to measure the resistances of the stator $R_1 = 2.935\ \Omega$ and rotor $R_2 = 0.145\ \Omega$ windings.

The no-load test, similar to the open circuit test on a transformer, was performed to determine the parameters $R_{\rm Fe}$ and $X_{\rm m}$ of the equivalent circuit. In this test, Fig. 4, the machine is running free at the rated voltage and the rated frequency without load. The slip is nearly equal to zero and the machine will rotate at almost synchronous speed. This causes the equivalent rotor impedance to be theoretically infinite and the resulting data will give information about the stator and magnetization branch of the equivalent circuit. The actual machine was powered from an induction regulator (booster) to provide a precise sinus rated voltage.

The locked rotor test is very similar to the short circuit test on a transformer. The rotor is locked to prevent rotation and regulated voltage is applied to the stator to achieve the rated machine current, Fig. 4 ($n = 0$). The slip in this condition is equal to unity since the rotor is standstill.

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \\ V_{ds} \\ V_{qs} \end{bmatrix} = K \begin{bmatrix} R_1L_r & -\omega M^2 & R_2M & -\omega ML_r & L_r & 0 \\ \omega M^2 & R_1L_r & \omega ML_r & -R_2M & 0 & L_r \\ R_1M & -\omega M & R_2L_s & -\omega M^2 & M & 0 \\ -\omega ML_s & -R_1M & \omega L_sL_r & R_2L_s & 0 & -M \\ 1/CK & 0 & 0 & 0 & 0 & 0 \\ 0 & 1/CK & 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} I_{ds} \\ I_{qs} \\ I_{dr} \\ I_{qr} \\ V_{ds} \\ V_{qs} \end{bmatrix} +$$

$$\begin{bmatrix} M & 0 \\ 0 & M \\ -L_s & 0 \\ 0 & -L_s \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} V_{dr} \\ V_{qr} \end{bmatrix}, \quad \text{with:} \quad K = \frac{1}{M^2 - L_sL_2} \tag{2}$$

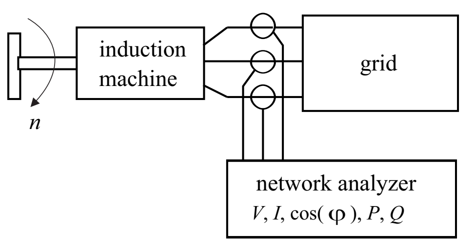


**Fig. 4.** No-load and locked ($n = 0$) rotor test

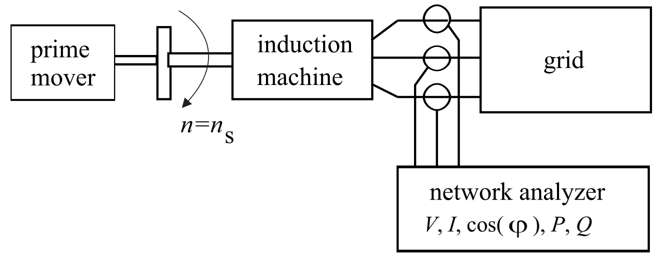


**Fig. 5.** Magnetizing curve test

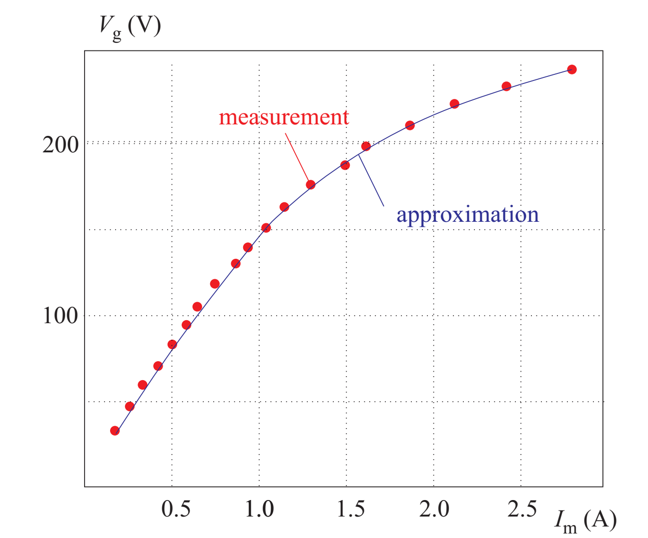


**Fig. 6.** Measured magnetization curve of the induction machine

If one can say that the impedance of the shunt branch of the equivalent circuit is much higher than that of the longitudinal branch of the circuit, neglecting the excitation branch allows to determine parameters $X_1, X_2$, $L_s$ and $L_r$ from the measurements. Practical test was performed with reduced voltage using an induction regulator (booster).

Results of measurement and the evaluated parameters are summarized in Tab. 1.

**Table 1.** No-load and locked rotor test

| | no-load | locked rotor | |
|---|---|---|---|
| $U_{LL}$ | 380 | 124 | V |
| $I_L$ | 2.057 | 5.0 | A |
| $P$ | 280 | 616 | W |
| $Q$ | 1330 | 904 | VAr |
| $\cos(\varphi)$ | 0.206 | 0.56 | - |

After the parameters of equivalent circuit were determined, a measurement giving information about the magnetization curve – $L_m = f(I_m)$ dependence was needed. In this case, Fig. 5, the rotor shaft is driven by a DC dynamometer at constant synchronous speed of 1500 rpm. The slip becomes equal to the zero and the rotor resistance reaches infinity

$$s \to 0 \quad \text{hence} \quad R_2' \frac{1-s}{s} \to \infty.$$

## 4 Simulation of SEIG

Matlab script was written to simulate the self-excited induction machine operation based on (2). Then, parameters of the equivalent circuit calculated from no-load and locked rotor tests were collected.

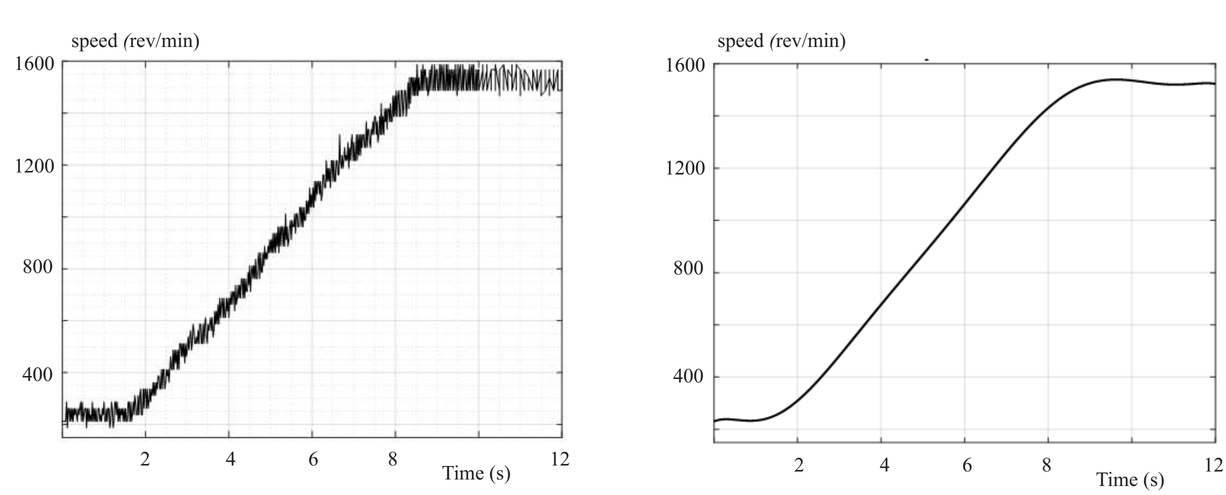


**Fig. 7.** Speed *vs* time: (a) – measured, and (b) – simulated

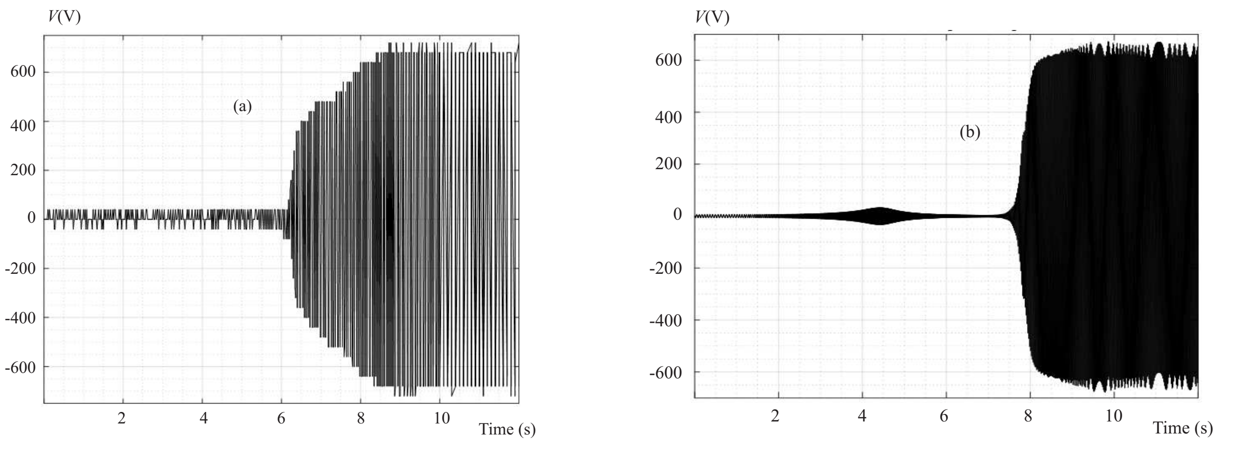


**Fig. 8.** Measured voltage build up on SEIG: (a) – measured, and (b) – simulated

Equivalent circuit parameters: $R_{Fe} = 22\,\Omega$, $L_m = 332$ mH, $R_1 = 2.935\,\Omega$, $R_2 = 0.145\,\Omega$, $L_1 = L_2 = 45.39$ mH.

A positive torque or speed was used to represent the "prime mover" (DC motor of the dynamometer). The initial value of stator terminal voltage was found, too. This voltage is related to the magnetic remanence in the core, hence the magnetization curve (Fig. 6) was determined. Using 1:1 transformation ratio ($L_1 = L_2$) of machine windings, made the modelling and calculations somewhat simpler.

We use the forward Euler method for solving system of differential equations (2). The results of simulation

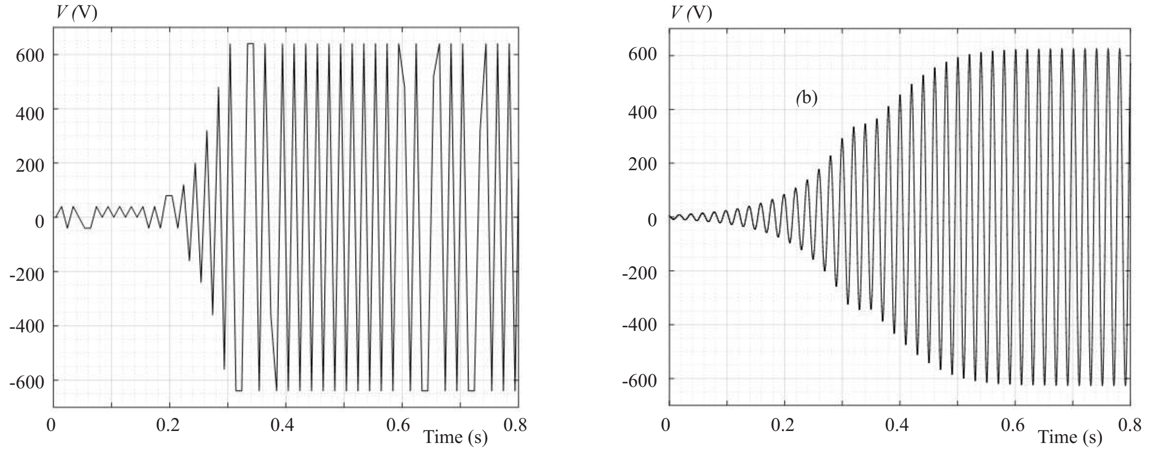


**Fig. 9.** No-load voltage of SEIG, after reaching the over synchronous speed: (a) – measured, and (b) – simulated

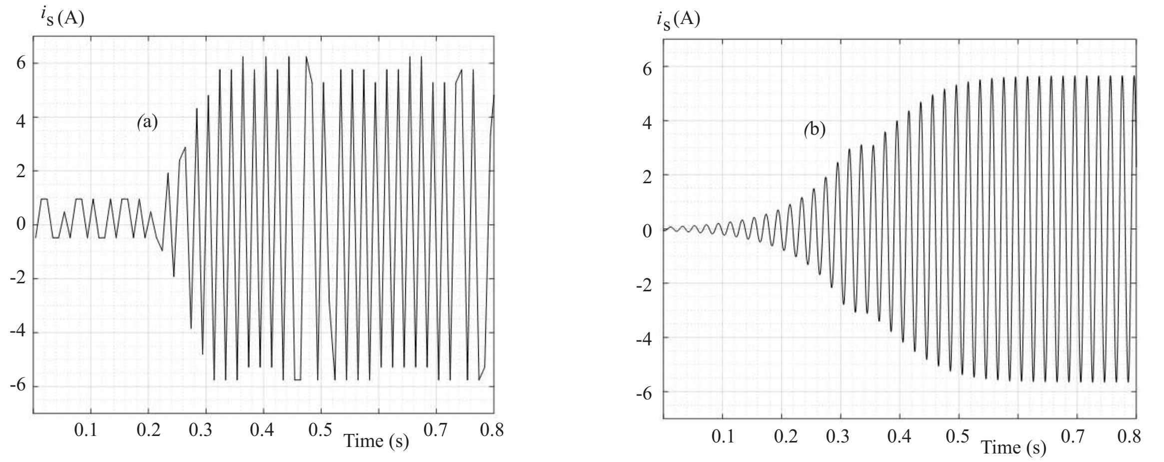


**Fig. 10.** No-load current of SEIG, after reaching the over synchronous speed: (a) – measured, and (b) – simulated

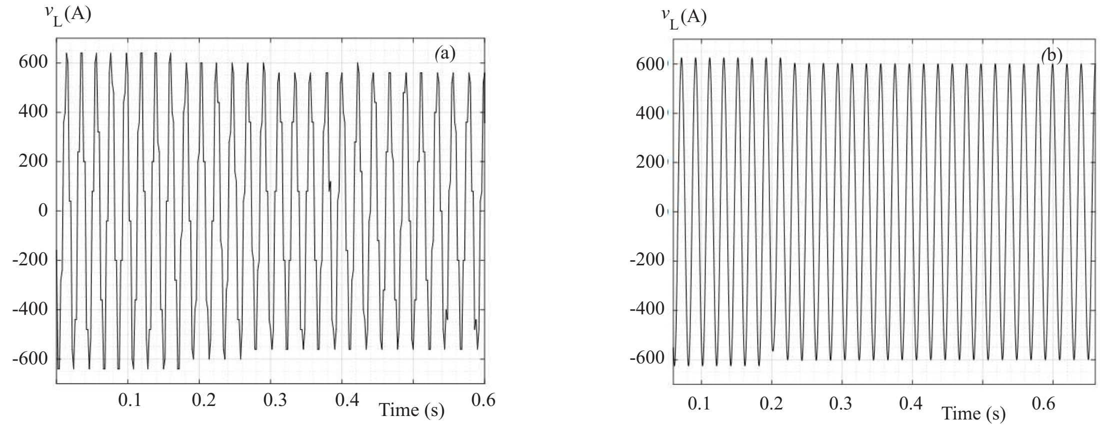


**Fig. 11.** Voltage on SEIG at a load of 250 $\omega$: (a) – measured, and (b) – simulated

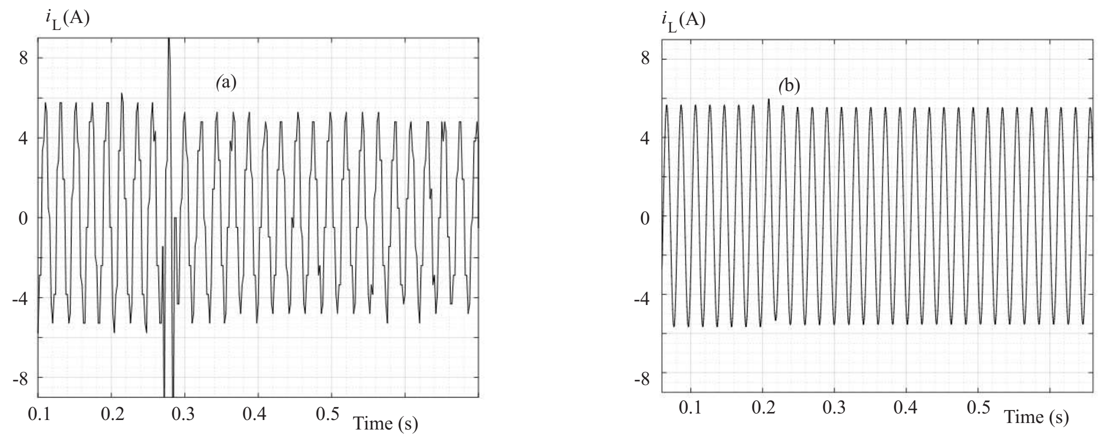


**Fig. 12.** Stator current at a load 250 $\omega$: (a) – measured, and (b) – simulated

at different conditions, namely with increasing load are compared below.

### *4.1 Results of measurements and simulation on SEIG at no-load condition*

No-load self-excited induction generator tests were performed. The capacitor bank with three 50 $\mu$F capacitors in wye connection was applied across the terminals of the investigated induction machine, Fig. 5. The self excitation process was achieved at a speed slightly above the synchronous speed.

At first we let the capacitor bank connected and the rotation speed was linearly increased until a full voltage was observed (Fig. 7). As shown in Fig. 8, the self-excitation was achieved at $t = 6.5$ s and the full voltage was reached at $t = 9$ s. This moment and the rotation speed when self-excitation begins depend on the remanent magnetism and capacitance of the connected capacitor bank. In Fig. 7(b) is the simulation result of interpolated speed and in Fig. 8(b) is the simulated voltage course.

In the subsequent experiment the machine was running at synchronous speed of 1500 rpm with the capacitor bank connected but in no-load condition. The voltage build-up can be observed on the oscillogram, Fig. 9. The phase-to-phase voltage stabilized at a value according to the magnetization curve and applied reactive power from the capacitors. The value of the voltage reached slightly above 600 V. In Fig. 10 one can see the peak value of the current reaching approximately 6 A.

In Fig. 9 and Fig. 10 we can see the simulation results with the same initial parameters as in the experiment.

### *4.2 Simulation and measurement with with resistive load*

In this series of measurements we have connected a resistive load on stator terminals, Fig. 11 and Fig. 12. A voltage drop and slip increase can be observed with an increasing load on the generator. This happens because the electromagnetic torque rises and decelerates the rotor shaft speed. We were able to change the load (wye connected rheostats) in range from 250 $\Omega$ to 30 $\Omega$ in each phase.

When the resistive load of 250 $\Omega$ was connected to the stator terminals (0.6 s), switching transient phenomena causing spikes during 1 or 2 periods could be observed. After next few periods the operating point shifted (magnetization curve) and new values of the voltage (Fig. 11) and current (Fig. 12) appeared.

Resistive load of 50 $\Omega$ applied on the stator terminals (0.15 s) caused the voltage, Fig. 13(A), and current, Fig. 14(a), to drop rapidly, although a new equilibrium

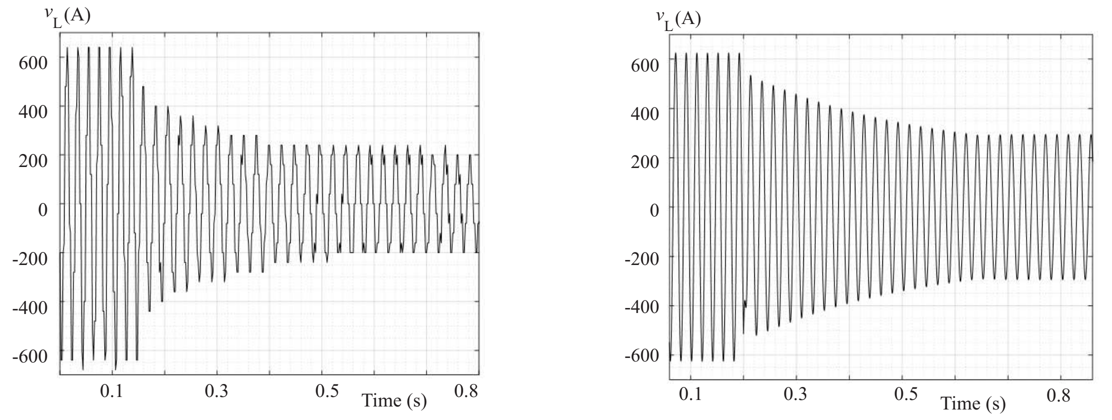


**Fig. 13.** Measured voltage build up on SEIG: (a) – measured, and (b) – simulated

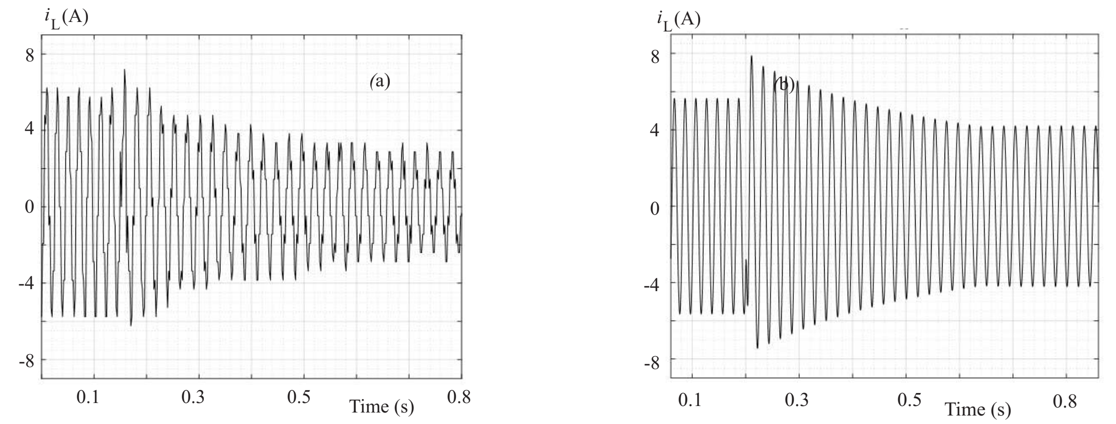


**Fig. 14.** Measured voltage build up on SEIG: (a) – measured, and (b) – simulated

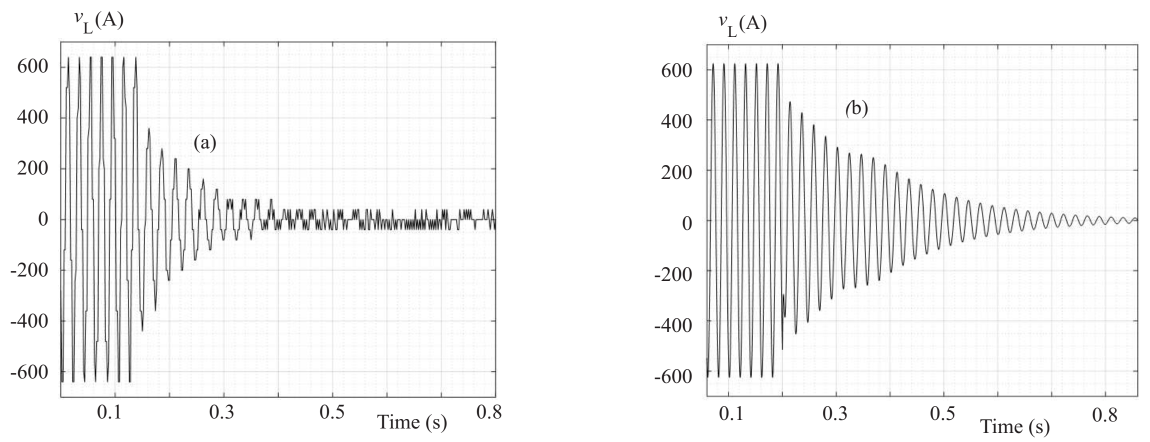


**Fig. 15.** Measured voltage build up on SEIG: (a) – measured, and (b) – simulated

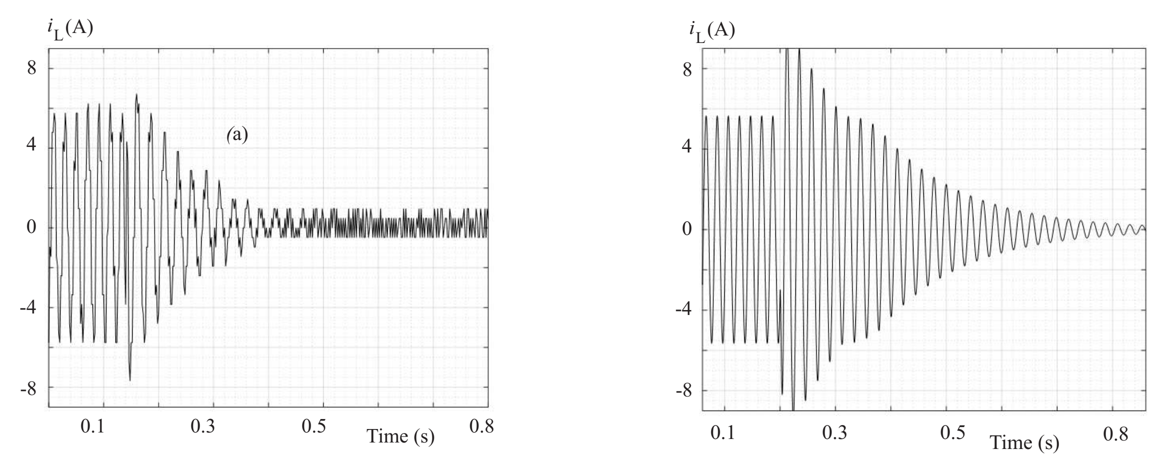


**Fig. 16.** Measured voltage build up on SEIG: (a) – measured, and (b) – simulated

was reached. The peak value of the phase-to-phase voltage is about 250 V and the phase current decreased from approximately 6 A to 3 A, which is well below the rated values.

Overloading of the machine with a load of $30\,\Omega$ clearly resulted in an unstable state when the machine excitation was lost due to a lack of reactive power supplied from three 50 $\mu$F capacitors.

## 5 Conclusion

Even if the induction machine itself is one of the oldest and most known machinery, its use in SEIG's role is of importance only in the recent years. This article presented partial results of a more complex study of the properties of SEIG in terms of its use in off-grid renewable power plants. We have investigated the self-excitation process using external capacitor banks and outlined the behaviours of the generator in variable (resistive) load conditions.

Experiments as well as simulations were proposed to compare and evaluate the measurement methods used and confirmed good correlation. However, further work is needed to be able to present more a comprehensive look on the research results such as regulation and control properties of SEIG.

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