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THREE-PHASE SQUIRREL-CAGE INDUCTION GENERATOR EXCITED BY CAPACITOR BATTERY

TRÓJFAZOWY GENERATOR INDUKCYJNY KLATKOWY WZBUDZANY BATERIĄ KONDENSATORÓW

Abstract

The generation of electrical energy in small power plants which use renewable energy sources is often implemented with the use of induction generators. This paper presents a proposal of an energy generation system which is constructed with the use of a three-phase self-excited squirrel-cage induction generator. The idea of this proposal consists of a control method of the generator rotor magnetic flux linkage via fully controlled power electronic switches. The energy produced by the induction generator is transferred to a DC link via an uncontrolled rectifier and a DC-DC chopper. The proposed solution allows us to generate energy with the use of a relatively simple and reliable electrical machine. Additional important advantages of this concept are a small number of controlled elements, and an easy control method.

Keywords: *self-excited cage induction generator*, *bi-directional switch*, *capacitor battery*

Streszczenie

Wytwarzanie energii w małych elektrowniach wykorzystujących odnawialne źródła energii jest często realizowane w oparciu o generatory indukcyjne. W artykule przedstawiono propozycję układu sterowania wzbudzeniem generatora indukcyjnego klatkowego. Idea rozwiązania polega na sterowaniu sprzężonego strumienia magnetycznego wirnika generatora dzięki baterii kondensatorów dołączonych do obwodu stojana za pośrednictwem łączników energoelektronicznych. Energia wytwarzana w generatorze jest przekształcana za pośrednictwem prostownika niesterowanego oraz przerywacza i dostarczana do obwodu DC. Rozwiązanie to pozwala wytwarzać energię za pomocą maszyny o względnie prostej i niezawodnej, a tym samym taniej konstrukcji uzupełnionej o dodatkowe układy energoelektroniczne. Zalety tej koncepcji to mała liczba elementów sterowanych i łatwe sterowanie.

Słowa kluczowe: *samowzbudny generator indukcyjny klatkowy*, *łącznik dwukierunkowy*, *bateria kondensatorów*

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1. Introduction

Cage induction generators are usually driven by wind, water or gas turbines which provide mechanical energy to the generator. In the simplest solution, the generator is directly connected to the power grid which, in turn, has to provide the reactive power which is necessary to excite the magnetic flux in the induction generator. The advantage of such a solution is simplicity and the ability to transfer from the generator mode to the motor mode and vice versa. Unfortunately, the main disadvantage is the restriction to only work in a very narrow range of angular speed changes. The second method of power generation, with the use of a squirrel cage induction generator, is an application of the PWM rectifier [1] or AC-AC dual active bridge converter [2–6], especially with a two or multilevel structure [7]. The fundamental advantage of these systems is the direct possibility of cooperation with an autonomous power grid in a wide range of rotational speed changes. On the other hand, an application of the AC-AC dual active bridge converter causes the complexity of the processing power both in terms of the topology and the control system. The induction generator can also be excited by the capacitor battery connected to the stator winding terminals [8]. In order to ensure a stable operation, the capacity of the battery should be continuously adjustable – the fulfillment of this condition is technically complicated. However, continuous adjustment of the battery capacity can be carried out by a series connection of capacitors and insulated gate bipolar transistors (IGBT) and their appropriate switching [9].

2. Topology of the energy generation system

The energy generation system with the self-excited cage induction generator and capacitor battery is shown in Fig. 1. The star-connected capacitors C_A, C_B, C_C of the excitation circuit are connected to the stator terminals A, B, C. Two capacitors are connected in series with two-direction fully controlled switches S_A and S_B. A three-phase diode rectifier

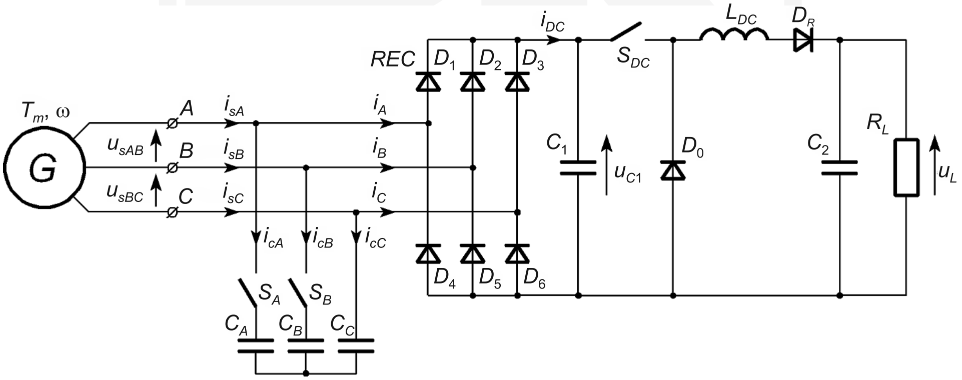

Fig. 1. System of energy generation with the self-excited cage induction generator and capacitor battery

REC with a capacitor C_1 on the output is also connected to the stator terminals. In addition, this circuit contains the fully controlled switch S_{DC}, the inductive choke L_D, the diode D_R, the reverse diode D_0 and the capacitor C_2 on the output of the system. The capacitor C_2 can form an integral part of the voltage source inverter that converts DC voltage to AC voltage. The resistor R_L represents the external load. It should be added that the items L_{DC}, D_R, D_0 and C_2 are not necessary if the load does not have a capacitive character. Bi-directional switches S_A and S_B can be constructed with the use of the IGBTs in one of two ways, as shown in Fig. 2.

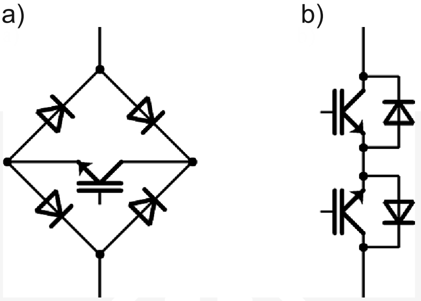

Fig. 2. The schemes of the bi-directional fully controlled switches: a) with a single transistor and a diode bridge; b) with two transistors connected in series in common emitter configuration

3. Description of the generator operation

The generator starts at a predetermined angular speed by the initial charge in the excitation circuit capacitors, or it can use the residual magnetism of the machine. In the second case, it is possible to consider additional shunting of the semiconductor excitation circuit switches at the initial stage of generator excitation. At the beginning, all switches are turned on. The required value of the capacity of the battery capacitors first of all depends on the generator's nominal parameters and on the generator's angular speed [8]. The lower the angular speed is, the higher the required battery capacity should be. Thus, the battery capacity is determined by the minimum angular speed of the induction generator. An increase in the angular speed causes an increase in the stator voltage. This condition occurs as long as the switches remain turned on. When the generator output voltage reaches the assumed value, the capacitor battery is disconnected. In the absence of passive power, both the magnetic flux of the generator and the magnitude induced voltage decrease. When the magnitude of the stator voltage drops to the specified value, the capacitor battery is turned on again, and in consequence, the magnitude of the stator voltage increases again. In practice, the frequency of such periodic switching of the transistors is in the range from several hundred hertz to a few-dozen kilohertz. The basis of correct operation is to ensure higher voltage of the capacitor C_1 with respect to the voltage of the capacitor battery. Otherwise, the two--direction switches would be damaged by the pulse current flow. The capacitor C_1 and one of the battery capacitors should be pre-charged in order to initialize the generator operation. During correct operation of the energy generation system, the voltage of the capacitor C_1 is always higher than the highest voltage of the battery capacitors. As long as the switches are turned on, the voltage of the capacitor C_1 is always equal to the maximum voltage of the capacitor battery. When the IGBTs are turned off, the voltages of the battery capacitors have a constant value. In turn, due to the inductive character the stator current, they cannot change their value abruptly. Hence, the currents i_A, i_B, i_C flowing to the rectifier *REC* remain different from zero. In view of the fact that the sum of the battery currents is always equal to zero, the current flowing to the capacitor C_1 does not change its value during the switching process. This capacitor is still charged, so its voltage increases and is higher than the maximum voltage of the capacitor battery. It is worth underlining that the capacitor can be discharging by the external load. To avoid this risk, the external load has to be periodically disconnected from the generation system. This process proceeds synchronously with respect to the switching of the capacitor battery with the use of the additional switch S_{DC} in the DC circuit. It is worth underlining that all IGBTs are turned on and turned off by means of a common signal.

4. Parameter adjustment of energy generation system

The battery capacity depends on the parameters of the induction generator and operating conditions [8, 10]. This capacity can be determined with the use of the relationship:

$$C_A, C_B, C_C \geq \frac{1}{\omega_{\min}^2 L_m} \tag{1}$$

where:

$\omega_{\min} = 2\pi f_{\min}$; for the analysis, it has been assumed that the capacity is equal to 100 μF,
L_m – magnetizing inductance.

The capacitor C_1 of the DC circuit should be selected due to the amount of energy which is stored in this capacitor when the battery of the capacitors C_A, C_B, and C_C is disconnected from the energy generation system. The worst case occurs when the voltage of capacitor C_1 has its maximum admissible value and the stator currents are equal to the nominal value, whereas the DC output circuit is not loaded. Then, the total energy occurring in the magnetic circuit of the induction generator is transferred to capacitor C_1 causing an increase in its voltage. On this basis, capacity C_1 can be determined as follows:

$$C_1 \geq \frac{\frac{3}{2} L_s \cdot I_{s\max}^2}{u_{\max}^2 - u_{CN}^2} \tag{2}$$

where:

$u_{CN}^2, u_{\max}^2$ – the nominal and the maximum voltage of the capacitor C_1, respectively,
$I_{s\max}$ – amplitude of the stator current,
L_s – inductance of the stator phase.

To ensure a smooth waveform of the output voltage, the system is equipped with an output filter composed of the induction choke L_{DC} and the capacitor C_2. Parameters of the filter can be selected with a simplified method. The minimum value of the induction is determined by the admissible current of the S_{DC} switch at discharged capacitor C_2 (short circuit output) during one period of the switching in the worst case. This induction can be determined with the use of the relationship:

$$L_{DC} \geq \frac{U_{C1}}{f_{i\min} I_0 \delta I} \tag{3}$$

where:

U_{C1} – voltage of the capacitor C_1 at the time of turning on the switches,
$f_{i\min}$ – the minimum frequency of the switching,
δI – current growth of the induction choke L_{DC},
I_0 – initial current of the choke L_{DC} at the time of turning on the switches.

In a similar manner, the capacitance C_2 can be selected. The minimum value of the capacity is determined by admissible voltages of the capacitor whereas the DC output circuit is not loaded at the maximum possible current of the S_{DC} switch during one period of the switching in the worst case. On this basis, capacity C_2 can be determined as follows:

$$C_2 \geq \frac{L_{DC} I^2_{LDC\max}}{U^2_{C2\max} - U^2_{C20}} \tag{4}$$

where:

$I_{LDC\max}$ – the maximum current of the choke L_{DC} at the time of turning off the switches,
$U_{C2\max}$ – admissible voltage of the capacitor C_2,
U_{C20} – the initial voltage of the capacitor C_2.

Numerical calculations were carried out for a typical induction generator with nominal parameters: P_N = 3 kW; U_{sN} = 220/380 V; I_{sN} = 11.6/6.7 A; f_{sN} = 50 Hz; $\cos\varphi_N$ = 0.835; n_N = 1430 r/min.; p = 2. Parameters of the equivalent circuit of the induction generator have the following values: R_s = 2 Ω; $R_r^{/}$ = 1.42 Ω; $L_{\sigma s}$ = 12.2 mH; $L_{\sigma r}^{/}$ = 12.2 mH; L_m = 202 mH.

5. Numerical analysis of the system

A monoharmonic model in phase coordinates of the cage induction generator has been applied in numerical analysis [11]. This model takes into account only the basic harmonic of the magnetic field assuming linearity of the magnetic circuit. The matrix form of the equations which describe the model of the induction generator in phase coordinates has the following form:

$$\mathbf{U} = \mathbf{R} \cdot \mathbf{I} + \mathbf{L}_1 \frac{d}{dt}\mathbf{I} + p \cdot \omega \cdot \mathbf{L}_2 \cdot \mathbf{I} \tag{5}$$

where:

$$\mathbf{U} = \begin{bmatrix} u_a \\ u_b \\ 0 \\ 0 \end{bmatrix}, \quad \mathbf{I} = \begin{bmatrix} i_a \\ i_b \\ i_c \\ i_d \end{bmatrix}, \quad \mathbf{R} = \begin{bmatrix} 2R_s & -R_s & 0 & 0 \\ -Rs & 2R_s & 0 & 0 \\ 0 & 0 & 2R_r^{/} & -2R_r^{/} \\ 0 & 0 & -2R_r^{/} & 2R_r^{/} \end{bmatrix}$$

$$\mathbf{L_1} = \begin{bmatrix} 2L_s & -L_s & 2L_m & -L_m \\ -L_s & 2L_s & -L_m & 2L_m \\ 2L_m & -L_m & 2L_r & -L_r \\ -L_m & 2L_m & -L_r & 2L_r \end{bmatrix}, \qquad \mathbf{L_2} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & \sqrt{3}L_m & 0 & \sqrt{3}L_r \\ -\sqrt{3}L_m & 0 & -\sqrt{3}L_r & 0 \end{bmatrix}$$

The equation of the electromagnetic torque is given by:

$$T_e = \sqrt{3}pL_m(i_U i_M - i_W i_K) \tag{6}$$

where:

i_U, i_V, i_W – the stator phase currents,
i_K, i_L, i_M – the rotor phase currents.

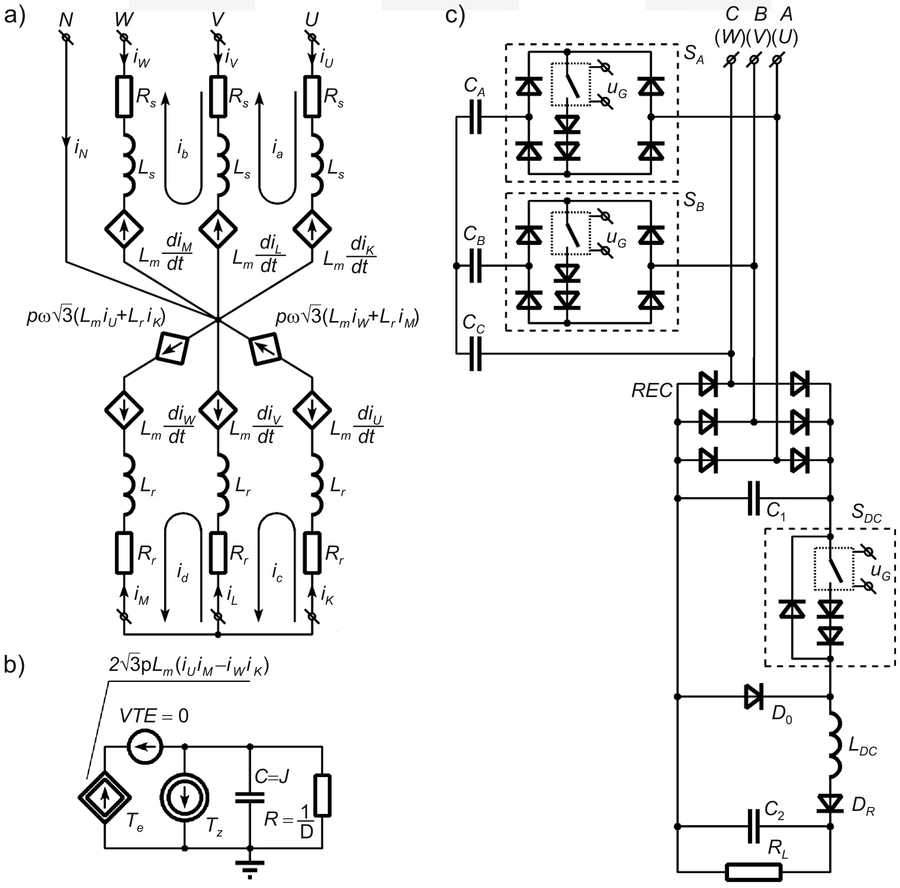

Fig. 3. Numerical model of the three-phase squirrel-cage induction generator: a) the equivalent circuit of the voltage equations; b) a replacement scheme of the motion rotary equation; c) the equivalent circuit of the external system connected to the induction machine

On the basis of equations (5) and (6), an electric equivalent circuit (Fig. 3) was built and this circuit was implemented in the IsSPICE simulation program. Transistors: S_A, S_B, S_{DC} were modeled on the basis of the model of the voltage-controlled switch. All switches are controlled by means of a common signal u_G. This model takes into account the basic parameters such as the static resistance of the transistor at blocking-bias and the resistance forward-bias. The optional neutral wire *N* is not used in this case.

The stable operation of the proposed energy generation system requires the use of an adjustment control unit which takes into account the following parameters: u_{sAB}, i_{sA}, ω, f_s, u_{DC} (Fig. 4). Initial validation of the correctness of the energy generation system has been performed for the scalar control with an assumed rotor magnetic flux linkage Ψ_r^r. The output signal m_a from the controller is proportional to the relative conduction time of the switches, and this signal is used for the switching of the IGBTs.

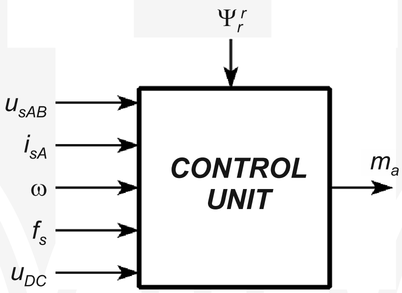

Fig. 4. The control unit of the squirrel-cage induction generator

Numerical calculations were carried out for the assumed angular speed which was equal to 157 rad/s. The switching frequency of IGBTs was fixed at 1 kHz. The other operating parameters did not exceed the nominal values. The generation system was controlled due to the relative magnetic flux linkage Ψ_r^r. This flux changes its value from zero to the maximum relative value which is equal to 0.8 at about 1.2 sec., and next, the magnetic flux has a constant average value until 3 sec. when the load resistance rises three times. The main task is maintaining the load voltage on the constant value equal to 675 V. As a result, the magnetic flux decreased. At 5 sec. the load resistance returned to the previous value. Figure 5a shows some chosen waveforms of the energy generation system from the start point to the steady state and operating of the proposed system after disturbance. In turn, Figure 5b presents analogous waveforms during the stable operation.

Figure 6 presents three chosen static characteristics of the squirrel-cage induction generator system as a function of the load power at the assumed angular speed equal to 157 rad/s, while the load voltage was equal to 250 V.

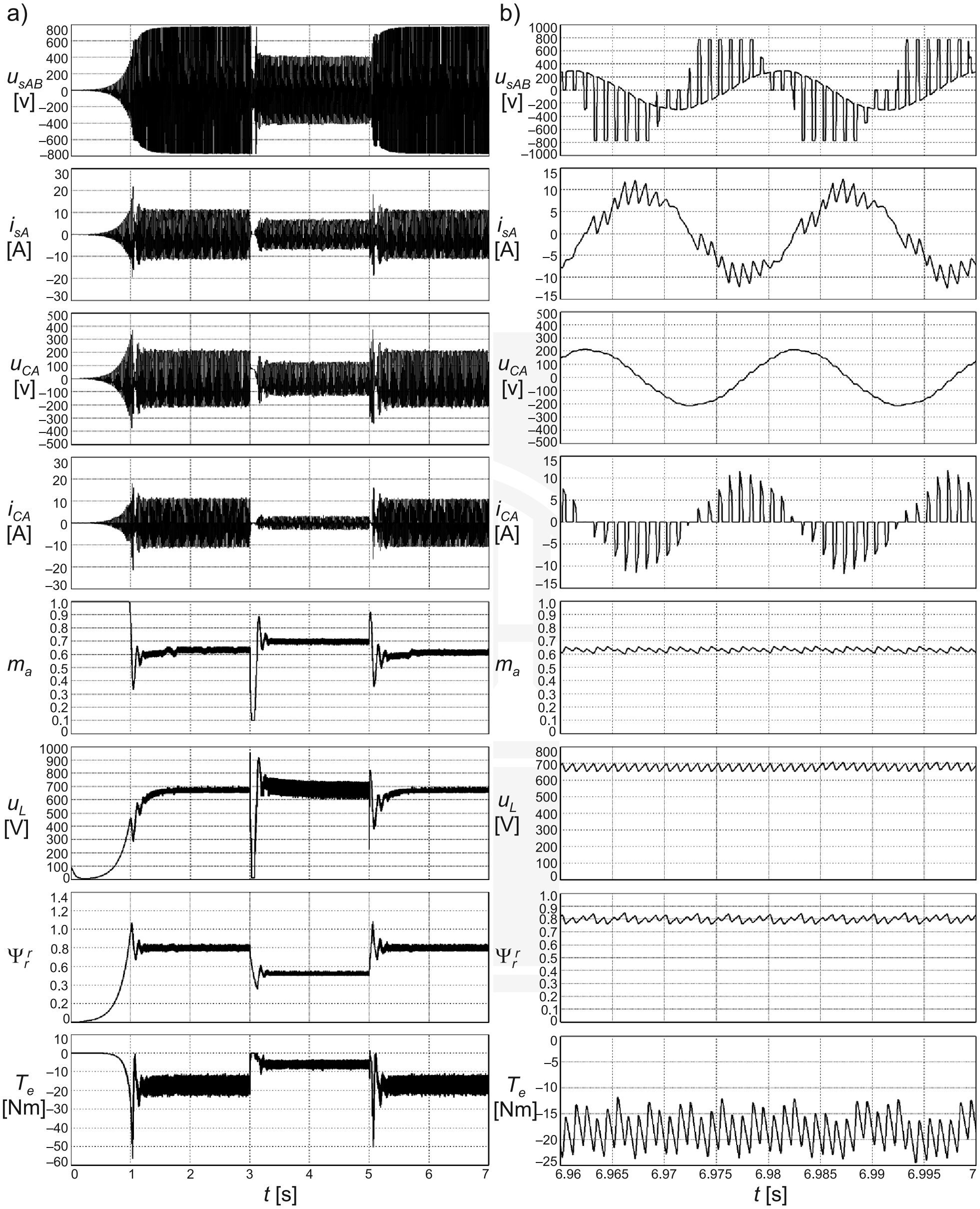

Fig. 5. Waveforms of chosen variables of the system of energy generation for: a) start-up of the generator and its transient states; b) zoomed in of a stable operating area

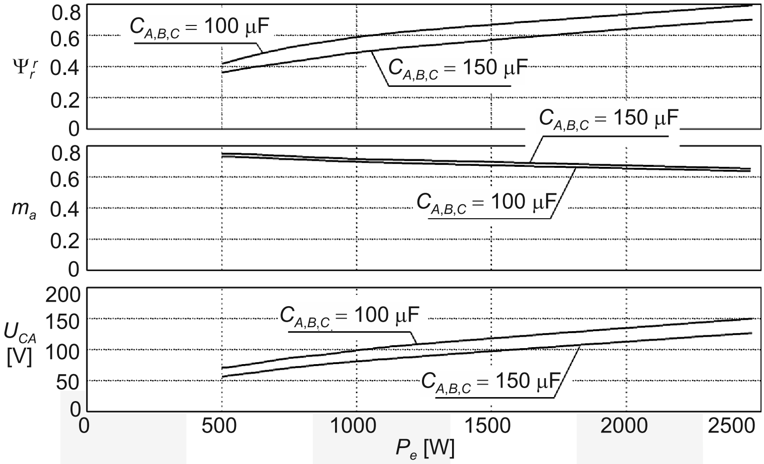

Fig. 6. Characteristics of the rotor magnetic flux linkage Ψ_r^r, the deep modulation coefficient m_a, and the rms voltage U_{CA} of the capacitor C_A for the assumed operating parameters

6. Conclusions

Analysis of numerical calculation results allows us to state the correctness of the proposed energy generation system. This system has several advantages in comparison with existing solutions; the most important feature to the application of the cheapest and reliable squirrel-cage induction machine. The proposed system has only three IGBTs in its simplified version. It is necessary to stress that the DC output voltage can be boosted up, and all IGBTs are switched with the use of only one control signal. The proposed energy generation system can operate in a wide range of angular speed; this is very important in cases of using renewable energy sources. Additionally, unlike the PM generators, the magnetic flux of the induction generator can be decreased safely when the angular speed is too high. It is understood that validation of the correctness of the proposed energy generation system requires comprehensive research with the use of the laboratory stand.

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