

The Voltage Control System of Self-Excited Induction Generator

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Abstract – The novel voltage control system for self-excited induction generator (SEIG) is proposed. It is based on TRIAC-switched capacitor bank which is controlled according to the proposed algorithm considering the self-excitation borders of SEIG. Such system could be used in stand-alone power generating systems for feeding active and active-inductive load with high requirements to the value of generated voltage. It is given the principle of design and operation of such system, and experimentally verified the performance of this system.

Key words – induction generator, self-excitation, voltage control, TRIAC, capacitor bank, verification, design.

I. Introduction

Induction generators with self-excitation from capacitor bank are widely spread in modern stand-alone electric power systems. But voltage control and stabilization in such systems is not a simple task. Analyzing the prospective of different schemes of control systems that are given in [1, 2] it can be find that different approaches are used to design voltage control system. But not all of them are suitable for stand-alone systems, because they need the additional power supply for control system operation and are not-suitable for a wide power-range because of capacitance constraints and can not be multipurpose for high power induction generators (50 kW or higher). In [3] is approved the expediency of application of thyristor switched capacitor bank to control the SEIG's terminal voltage to use both for low-power stand-alone generators, and for large power generating plants, and which provide a reliable and smooth voltage regulation. Based on that was designed the system of voltage regulation based on TRIAC-switched capacitor bank wich is controlled according to the algorithm [4,5] considering the self-excitation borders of SEIG.

II. SEIG Model

A standard mathematical model of induction generator stator and rotor circuits in the arbitrary coordinate frame is described by two nonlinear vector differential equations [4, 5].

$$\begin{aligned} \frac{d\Psi_S}{dt} &= U_S - R_S i_S - \omega_e J \Psi_S, \\ \frac{d\Psi_R}{dt} &= -R_R i_R + (n_p \omega - \omega_e) J \Psi_R, \end{aligned} \quad (1)$$

where $J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$, $\Psi_S = [\Psi_{SF} \quad \Psi_{SG}]^T$,

$\Psi_R = [\Psi_{RF} \quad \Psi_{RG}]^T$ – vectors of stator and rotor flux

linkages, $i_S = [i_{SF} \quad i_{SG}]^T$, $i_R = [i_{RF} \quad i_{RG}]^T$ – vectors of stator and rotor currents, $U_S = [U_{SF} \quad U_{SG}]^T$ – a vector of stator voltage, R_S i R_R – are the resistances of stator and rotor, n_p – number of pole pairs, ω – angular rotor velocity, i ω_e –the angular velocity of arbitrary coordinate frame F-G.

The resistive loads which are connected in parallel with capacitors to the stator windings are shown in Fig 1.

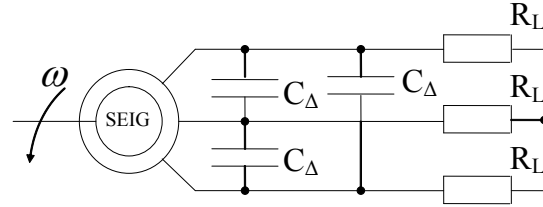


Fig. 1. Connection of loads to SEIG

For equivalent replacement capacitors triangle on the star is enough to triple their capacity $C = 3C_{\Delta}$. Then the fragment of generator phase equivalent circuit of the capacitor and the load will look like in Fig. 2.

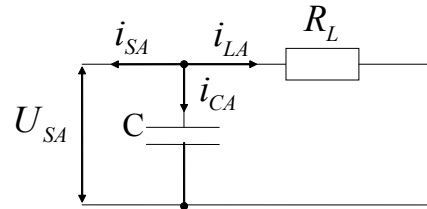


Fig 2. Fragment of generator phase equivalent circuit of the capacitor and the load

Index "A" marked projection vectors corresponding to the axis A in the fixed coordinate system A-B of stator.

Then according to first Kirchhoff's law

$$i_s + i_c + i_L = 0, \quad (2)$$

where $i_s = [i_{SA} \quad i_{SB}]^T$, $i_c = [i_{CA} \quad i_{CB}]^T$, $i_L = [i_{LA} \quad i_{LB}]^T$ vectors of currents in the fixed coordinate system A-B of stator.

Since, $i_c = C \frac{dU_S}{dt}$, then the coordinate system A-B

$$-C \frac{dU_S}{dt} = i_s + i_L, \quad (3)$$

where $U_S = [U_{SA} \quad U_{SB}]^T$ - is the vector of stator in the fixed coordinate system A-B, R_L - load resistance, C – value of capacitor.

III. TRIAC Switched Capacitor

The equivalent circuit of the single-phase TRIAC switched capacitor is shown in Fig. 3.

TRIAC has a small value of inductance in series with the capacitor, which can be limited the surge current of this circuit.

According to the Second Kirchhoff's law voltage U_T can be described by the following expression:

$$U_T = U_m \sin(\bar{\omega}t + \varphi) = L \frac{di}{dt} + \frac{1}{C} \int idt. \quad (4)$$

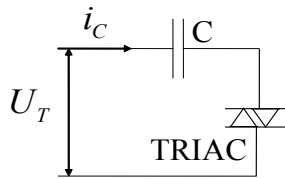


Fig 3. The equivalent circuit of the single-phase TRIAC switched capacitor

On condition when the initial current is zero ($i=i(0)=0$) and the initial voltage of the capacitor is zero ($U_c=U_c(0)=0$) the solution of the Equation 4 is :

$$i = I_m \cos(\bar{\omega}t + \varphi) - I_m \cos \bar{\omega}t \cos \omega_0 t + \frac{\omega_0 C}{1 + \omega^2 LC} \cdot \left(\left[\omega^2 LC^2 - 1 \right] U_c + U_m \sin \varphi \right) \sin \omega_0 t, \quad (5)$$

where $\omega_0 = \sqrt{LC}$ is the oscillation frequency and I_m is the maximal steady state current. In order to reach the steady state value of the current Equation 5 has to satisfy the next conditions:

$$U_c = \pm \frac{U_m}{1 - \omega^2 LC} \quad (6)$$

$$\varphi = \frac{\pi}{2}.$$

This means that the principal requirements specified in [6] are performed and the current equation could be written as:

$$i = I_m \cos(\omega t + \frac{\pi}{2}). \quad (7)$$

IV. Voltage control

A problem of voltage control and stabilization could be solved in different ways; they are velocity, capacitance, and the load impedance. In the most of applications, the velocity of SEIG is rarely controllable (wind- and hydro-generators). Therefore the load and the capacitance are fully controllable. In this paper we will deal with the control by the change of the value of capacitance according to the changes of the load connected to the SEIG using the TRIAC-switched bank of capacitors. The load characteristics of SEIG in case of the constant velocity are presented in Fig. 4, where U_{SEIG} is the terminal voltage of the generator, I_{load} is the load current, proportional to the active power of the load.

These characteristics are dropping and if the dip of the voltage reaches some minimum value (self-excitation border) the SEIG fails to generate voltage (voltage collapses). In this scenario, additional capacitances should be switched into a circuit to increase the voltage magnitude of the SEIG.

Also it is important to stabilize the voltage magnitude within the borders ($U_{max}-U_{min}$) to ensure the operability of the connected consumer. Consequently it is necessary to select the value of the capacitors in the bank to provide the required quality of the generator voltage stabilization.

Usually, in such kind of systems, the addition of the auxiliary capacitors is stepwise like C, 2C, 4C etc. This provides the ability to get more steps with different capacitance without acquiring extra number of capacitors in the bank.

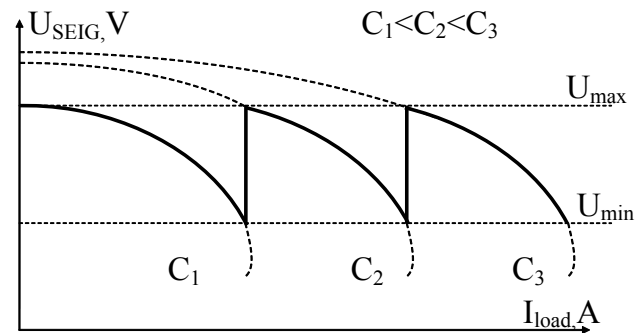


Fig. 4. The load characteristics of SEIG with TRIAC switched capacitors

V. Voltage control system of SEIG

For reliable work and voltage stabilization the control system has to provide the ability to respond rapidly to changes in the output voltage of the generator and the high quality of voltage regulation.

Switched capacitor bank should have several stages with different capacities that need to be connected or disconnected depending on the voltage at the output of the generator. Control device switched capacitor bank must do a quick switch to the battery and at the same time to switch the capacitor when the voltage across it is zero, which ensure the absence of current surges, when switching the system, and would provide durable and high-quality voltage stabilization. One example of a system that meets the requirements set is offered on; Fig.5 shows the functional diagram of such system.

The voltage control system consists of SEIG, the six blocks of three-phase capacitors, one of them is static and permanently connected to the stator windings for self-excitation and others are connected through TRIAC keys. TRIACs are controlled by using Phase TRIAC Control blocks (PTC), depending on the current state of TRIAC key and control signals coming from the Logic Control Unit. The Logic Control Unit generates control signals which are in varying sequences (a total of 32 levels of control) connect the AC capacitors on the generator bus, thus regulating the reactive current or SEIG, depending on the load or velocity of the prime mover. Formation pulse control is based on information received from the Voltage Sensor. The operating algorithm of Voltage Sensor and Logic Control Unit stabilizes the output voltage of SEIG according to the load changes.

Phase TRIAC Control blocks (PTC) provide the control of TRIAC switches that connect the appropriate power capacitors. To reduce excessive currents during switching the capacitor was developed a device that ensures the inclusion of TRIACs at the times when the voltage on the capacitor section that connects is consistent in magnitude with the corresponding phase voltage of the generator.

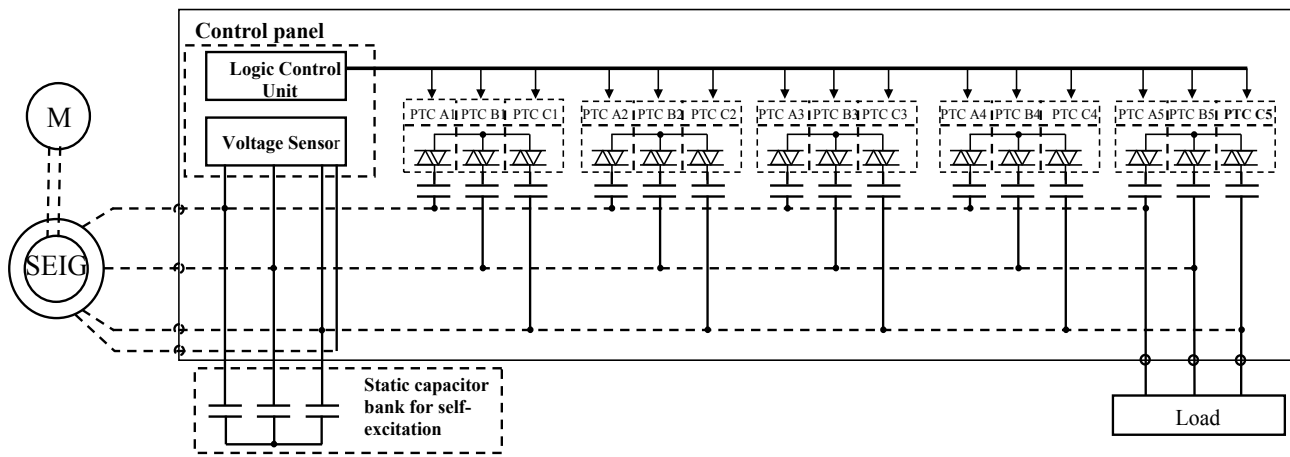


Fig. 5. Functional diagram of voltage control system of SEIG

PTC includes a voltage feedback of TRIAC and current feedback of TRIAC with inhibited blocking oscillator. The moment of TRIAC's inclusion is determined by the voltage feedback which is realized using a diode rectifier, key transistor and optic-isolation.

VI. Experimental Results

The experimental verification of designed operating algorithm and the voltage control system was performed on existing laboratory stand for the study of operation of SEIG [7]. It consists of three-phase induction motor (AIPM63B4Y3, with rated values 370W, 380V, 50 Hz, and 1450 rpm) which was used for experiments as SEIG. The following parameters of the generator were determined experimentally $R_s=27 \Omega$, $R_r=17.9 \Omega$, $L_{\sigma s}=L_{\sigma r}=0.08266 \text{ H}$, $n_p=2$, $L_{MAX}=1.03115 \text{ H}$, $L_{M0}=0.6345 \text{ H}$. The SEIG was coupled to another induction motor (4AM80B3Y3, with rated values 2.2KW, 380V, 50 Hz, and 2800 rpm) controlled through the frequency converter ABB ACS140 feeding the stator winding. The higher value of the motor's power and the slip compensation function in the ACS140 provided velocity stabilization at desired levels during experiments. The load was Y-connected. Collection of the experimental data was performed using ACS140's monitoring system and a system for tests of electric drives providing voltage and current measurements with visualization compatible with MATLAB.

The experiments were carried out for both connection of the induction generator windings in star and delta and for different value of load resistance. Experiment for SEIG voltage stabilization for star connection with a load resistance of 400 ohms was set at a voltage of approximately 80% of the nominal, because of the lack of established nominal values of a TRIAC switched capacitance.

Fig. 6 presents the transients of linear voltage of SEIG with windings switched in delta for load change from 200 Ω to 180 Ω . The generator operates with load of 200 Ω , voltage of the SEIG U_{SEIG} is 223 V, at time of 1.5 s

the load changes to 180 Ω , and at the moment of time 3 s the voltage U_{SEIG} decreases to 184 V. At time 3.4 s the voltage control system begin to switch the capacitors and the voltage starts to increase until at time 4.5 s it reaches the value of 225 V.

Fig. 7 presents the transients of linear voltage of SEIG with windings switched in star for load change from 400 Ω to 380 Ω . The generator operates with load of 400 Ω , voltage of the SEIG U_{SEIG} is 325 V, at time of 2 s the load changes to 380 Ω , and at the moment of time 3 s the voltage U_{SEIG} decreases to 315 V. At time 4 s the voltage control system begin to switch the capacitors and the voltage starts to increase until at time 5 s it reaches the value of 315 V. Precision of voltage regulation can be increased by the accurate selection of container capacitors steps in the serial system and by increasing the number of levels of the TRIAC-switched capacitor bank.

The system performance matches the characteristics of commercially manufactured voltage control systems for generators.

Conclusion

SEIG's have proven to be reliable and inexpensive devices for generating electrical energy to supply electric power for consumers in remote areas and for stand-alone power plants.

There are different ways to control the voltage of the SEIG, but not all of them are suitable for the wide range of load power and kind of loads.

The voltage control system for stand-alone SEIG which uses the proposed algorithm for switching the capacitors in the bank is workable.

The accuracy of voltage stabilization can be improved by increasing the number of levels of the TRIAC-switched capacitor bank and more accurate selection of the capacitance of bank levels when designing the system for a particular generator of a specific power. Performance of the system allows its use in stand-alone power systems with SEIGs to support sustainable voltage value for consumers.

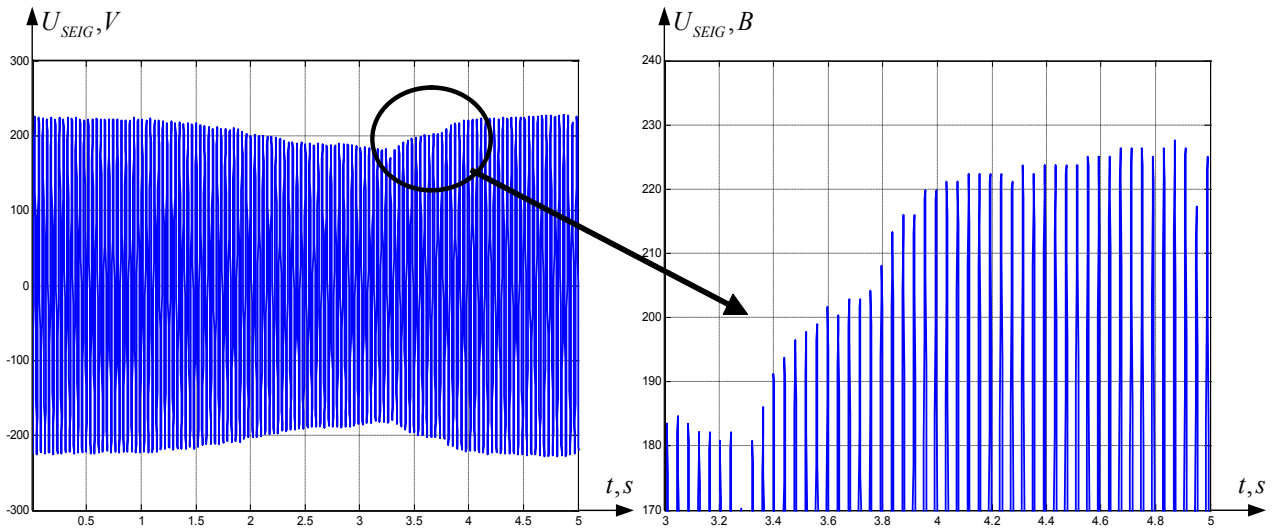


Fig. 6. Transients of linear voltage of SEIG with windings switched in delta for load change from 200Ω to 180Ω

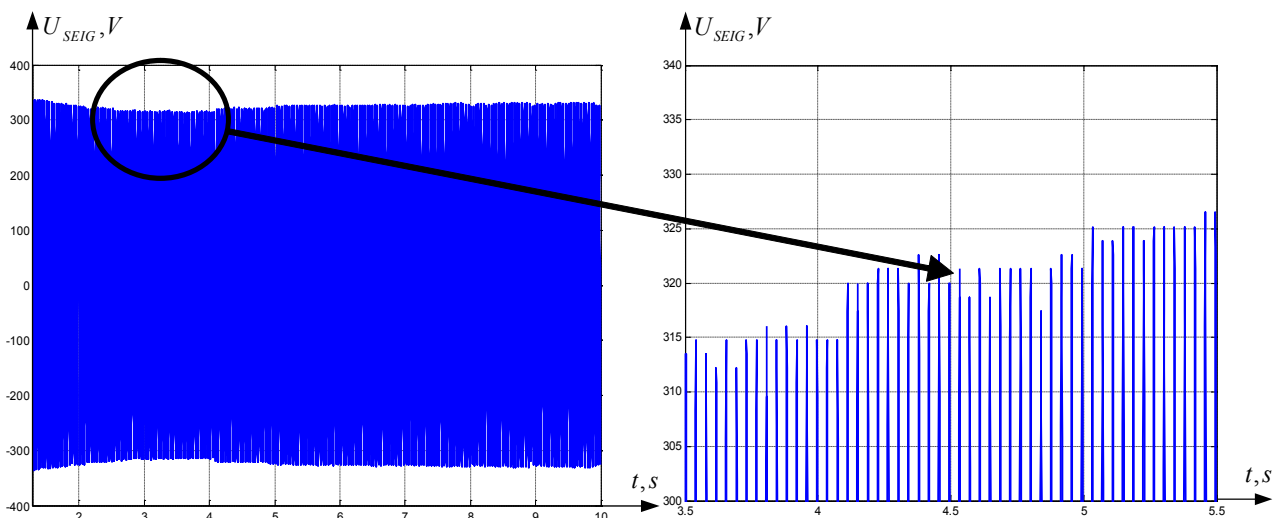


Fig. 7. Transients of linear voltage of SEIG with windings switched in star for load change from 400Ω to 380Ω

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