Andrzej KANDYBA[1], Marian KALUS[2], Igor Piotr KURYTNIK[3]

Department of Power Electronics, Electrical Drives and Robotics, Faculty of Electrical Engineering, Silesian University of Technology (1), Institute of Innovative Technologies EMAG, Poland (2), Department of Electrical Engineering and Automation University of Bielsko-Biała (3)

Synthesis and simulation of stator rms voltage control circuit of cage induction machine operating as generator in small hydropower plant supplying off-grid customers

Streszczenie. *Przeprowadzono syntezę układu regulacji napięcia wartości skutecznej w obwodzie stojana maszyny indukcyjnej klatkowej, pracującej jako generator na sieć wydzieloną, w oparciu o liniowe kryterium „Symetrycznego optimum" wg C. Kessler'a. Maszyna indukcyjna jest napędzana niskospadową turbiną wodną typu Banki-Michella-Cinka. Proces syntezy układu regulacji został poparty badaniami symulacyjnymi tego układu. (**Synteza układu regulacji napięcia wartości skutecznej w obwodzie stojana maszyny indukcyjnej klatkowej, pracującej jako generator na sieć wydzieloną w małej energetyce wodnej)***

Abstract. *The paper presents synthesis of cage induction motor stator rms voltage control circuit, This machine operates as a generator supplying off-grid customers. It is controlled with the help of linear criterion of "optimum magnitude" suggested by C. Kessler. Induction machine is driven by low-head water turbine of Banki-Michell-Cink type. The synthesis process of the control system has been accompanied by simulation studies of the system.*

Słowa kluczowe: Mała elektrownia wodna, generator asynchroniczny, sieć wydzielona, układ regulacji.
Keywords: Small hydroelectric plant, asynchronous generator, isolated grid, control system

Introduction

Three-phase induction machine is among the simplest and most reliable of all electric machines. It has been comprehensively used in numerous technical applications. It is an electromechanical converter that can operate as either motor or a generator. In case of machine operating with a power grid, change in the machine operational mode is achieved by variation in rotational speed.

Basic condition of using asynchronous machine as a generator in separate grid is its excitation. Capacitor bank may be a source of alternating magnetic field; it is then connected in parallel to the machine stator while machine rotates (Fig. 1). This system is not supplied from the mains, but it may start operating as generator, when self-excitation condition is fulfilled. This condition defines the required size of the capacitors' capacitance, depending on the parameters of an asynchronous machine in the initial state of core saturation [1, 2, 3]:

$$C \geq \frac{1}{2\pi f\left(X_s + X_\mu\right)} \tag{1}$$

where: C – capacitor per phase, f – frequency of generated voltage; X_s – leakage reactance of asynchronous generator; X_μ – magnetizing reactance of asynchronous generator.

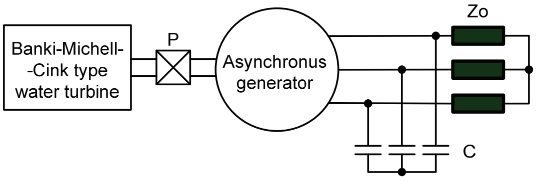

Fig. 1. Connection diagram of asynchronous generator, connected to isolated grid (C – phase condenser capacity, Zo – load impedance, P – mechanical transmission booster - multiplier)

To initiate the process of self-excitation, the initial condition of magnetic remanence in the machine must be met. It is essential that the initial slope of the idle run voltage-current characteristic of the machine $U_1(I_o)$ should be located above the capacitor bank curve $U_C(I_o)$.

2. The concept of rms voltage regulation in a low speed asynchronous machine cage stator circuit, connected to isolated grid, driven by Banki-Michell-Cinks water turbine

Schematic diagram of rms voltage regulation in a low speed asynchronous machine cage stator circuit, connected to isolated grid, driven by Banki-Michell-Cinks water turbine, built on the basis of standard control control theory, is shown in Fig. 2.

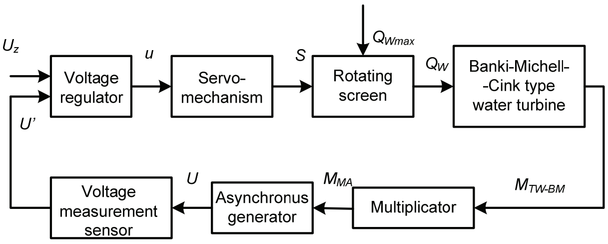

Fig. 2. Schematic diagram of rms voltage regulation in a low speed asynchronous machine cage stator circuit, connected to isolated grid, driven by Banki-Michell-Cinks water turbine. The following designations are adopted here: U_z – set value of rms voltage [V], U' –signal proportional to the actual value of the rms voltage, obtained at the output of the sensor [V]; u – signal obtained at the output of voltage regulator [V]; S – rate of opening of rotating screen servomechanism [dimensionless quantity]; Q_W – flow rate of water that enters the working space of Banki-Michell-Cinks water turbine [m^3/min]; Q_{Wmax} – maximum water flow, corresponding to the maximum opening of rotating screen [m^3/min]; $M_{TW\text{-}BM}$ – rotational torque of Banki-Michell-Cinks water turbine [Nm]; M_{MA} – rotational torque of low speed asynchronous machine cage (at the output multiplier) [Nm].

The controlled variable in the presented control system is the rms voltage in the circuit of low speed asynchronous machine stator cage. The principle of operation of rms voltage control system in low speed asynchronous machine stator cage circuit, is to control the value of water flow in the workspace of Banki-Michell-Cink water turbine. The executive element in the discussed control system is the servomechanism, which directly affects the rotating screen of water turbine (i.e. opening or shutting it down, depending on the value of control signal in voltage controller).

Rms voltage controlsystem in the circuit of low speed asynchronous cage machine stator, connected to isolated grid, driven by Banki-Michell-Cinks water turbine

Block diagram of the rms voltage control system in the circuit of low speed asynchronous cage machine stator, connected to isolated grid, driven by Banki-Michell-Cinks water turbine, is shown in Figure 3 This scheme was designed using the schematic diagram of Figure 2

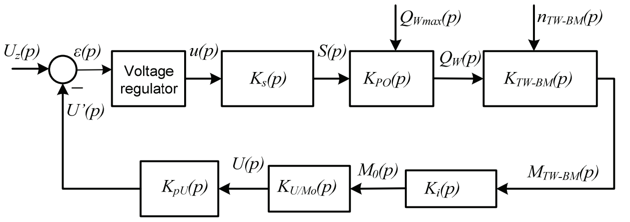

Fig. 3. Block diagram of the rms voltage control system in the circuit of low speed asynchronous machine stator cage, connected to isolated grid, driven by Banki-Michell-Cinks water turbine,

The following designations are used in Figure 3:
$U_z(p)$ – set value of rms voltage [V]; $\varepsilon(p)$ – comparison error [V]; $u(p)$ – output signal (control) from voltage controller[V]; $S(p)$ – opening degree of rotational diaphragm [-], includes between 0 – 1; $Q_{Wmax}(p)$ – maximum water flow, corresponding to the maximum opening of rotating screen [m^3/min]; $Q_W(p)$ – flow rate of water that enters the working space of water turbine [m^3/min]; $n_{TW\text{-}BM}(p)$ – water turbine shaft speed [min^{-1}]; $M_{TW\text{-}BM}(p)$ –rotational torque of water turbine [Nm]; $M_0(p)$ – rotational torque at the output of rotary transmission booster (multiplier), which is equal to the torque at low speed asynchronous cage machine's shaft [Nm]; $U(p)$ – actual value of rms voltage in the low speed cage asynchronous machine's stator circuit [V]; $K_s(p)$ – transfer function of water turbine rotating screen servomechanism, in 1/V, and defined as:

(2)
$$K_s(p)=\frac{S(p)}{u(p)}=\frac{K_s}{pT_s}$$

where: T_s – total opening time of rotating screen servomechanism [s]; $K_s=[S(p)_{max}/u(p)_{max}]$ – static gain factor of rotating screen servomechanism [1/V]. $K_{PO}(p)$ – transfer function of rotating screen, in [m^3/min], defined as:

(3)
$$Q_W=S(p)Q_{W\max}$$

$K_{TW\text{-}BM}(p)$ – cross-flow Banki-Michell-Cinks water turbine transmittance (in [Nm•min/m^3]) is presented in the form of block diagram in Figure 4.

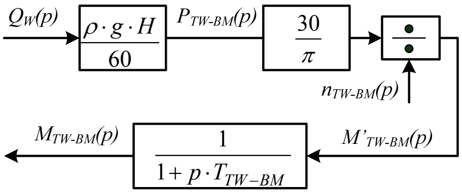

Fig. 4. Block diagram of transfer function of Banki-Michell-Cinks water turbine,

The following designations are used in Figure 4:
ρ – water density [kG/m^3]; g –acceleration of gravity [m/s^2]; H – turbine slope [m]; $P_{TW\text{-}BM}(p)$ – water turbine shaft power [W]; $M'_{TW\text{-}BM}(p)$ – inertialess torque on the shaft of water turbine [Nm]; $T_{TW\text{-}BM}(p)$ – water turbine time constant [s].
$K_i(p)$ – rotary transmission booster (multiplier), defined as follows [dimensionless quantity]:

(4)
$$K_i(p)=\frac{1}{i}$$

where: i – transmission ratio of gear, in [min^{-1}/ min^{-1}], defined as:

(5)
$$i=\frac{n_{MA}(p)}{n_{TW-BM}(p)}$$

where: $n_{MA}(p)$ – rotational speed of a low speed asynchronous cage machine shaft [min^{-1}].

$K_{U/Mo}(p)$ – transfer function relating rms voltage in the circuit of low speed asynchronous cage machine to machine shaft rotational torque [V/Nm]:

(6)
$$K_{U/Mo}(p)=\frac{\Delta U(p)}{\Delta M_o(p)}=\frac{\frac{\Delta U}{\Delta M_o}}{1+p\cdot T_{U/Mo}}$$

where: $T_{U/Mo}$ – time constant, related to the process of rms voltage generation due to torque in the low speed asynchronous cage machine's circuit [s];

$K_{pU}(p)$ – rms voltage current transmission sensor [V/V]:

(7)
$$K_{pU}(p)=\frac{U'(p)}{U(p)}=\frac{U'(p)_{\max}}{U(p)_{\max}}$$

Selection of low speed asynchronous cage machine's stator rms voltage controller and its parameters; machine is connected to isolated grid and driven by water turbine

The synthesis of rms voltage regulator in the low speed asynchronous cage machine's stator circuit, connected to separate grid, was based on the criterion of "optimum magnitude" by C. Kessler [1,]. The starting point for carrying out the synthesis of the regulator, based on this criterion is transmittance of the open-loop control system (without controlled), obtained on the basis of a block diagram shown in Figure 5.

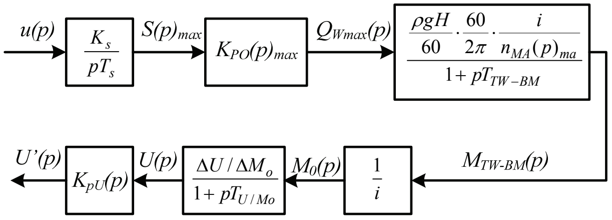

Fig. 5. Block diagram of open-loop rms voltage control system in the stator circuit of low speed asynchronous cage machine

Transmittance of an open-loop control system, obtained on the basis of the block diagram shown above is defined as:

(8)
$$K_o(p)=\frac{U'(p)}{u(p)}=\frac{\dfrac{K_S\cdot Q_{w\max}\cdot\rho\cdot g\cdot H\cdot\dfrac{\Delta U}{\Delta M_o}\cdot K_{pU}}{2\cdot\pi\cdot n_{MA}(p)_{\max}}}{p\cdot T_S\cdot\left(1+p\cdot T_{U/Mo}\right)\cdot\left(1+p\cdot T_{TW-BM}\right)}$$

Basing on the criterion of "optimum magnitude" by Kessler, the voltage controller of Proportional-Integrating-Differentiating (PID) structure type was adopted

Parameters of this structure (integral time of the element “I”, derivative time of the element “D” and gain factor of the element “P”) are determined by following relationships:

$$T_z = 4 \cdot T_{U/Mo} \quad T_W = T_{TW-BM} \quad K_p = \frac{T_s}{2 \cdot K_o \cdot T_{U/Mo}} \tag{9}$$

where:

$$K_o = \frac{K_S \cdot Q_{w\max} \cdot \rho \cdot g \cdot H \cdot \frac{\Delta U}{\Delta M_o} \cdot K_{pU}}{2 \cdot \pi \cdot n_{MA}(p)_{\max}} \tag{10}$$

hence finally:

$$K_P = \frac{\pi \cdot n_{MA}(p)_{\max} \cdot T_S}{K_S \cdot Q_{w\max} \cdot \rho \cdot g \cdot H \cdot \frac{\Delta U}{\Delta M_o} \cdot K_{pU} \cdot T_{U/Mo}} \tag{11}$$

Simulation studies of small hydropower plant connected to isolated grid

The tool used for the construction of hydroelectric power plant model was SIMULINK package, part of the MATLAB program. "Power System Blockset" tool was used to build a model of asynchronous machine, it is part of the SIMULINK tools package called "Blocksets & Toolboxes". The individual components of small hydro power plant were designed with the help of static and dynamic elements from the SIMULINK integrated libraries. Opportunity to define original blocks, by combining and grouping the already existing elements was also utilised.

Model simulation studies were carried out for the following ratings [4, 5, 6, 7] of Banki-Michella-Cinka water turbine: rotational speed range: 300 – 600 [min^{-1}]; height of fall H = 5 [m]; maximum water flow of turbine's working space Q_{Wmax} = 90 [m^3/min]; turbine power P_{TW-BM} = 75 [kW]; time constant of water turbine T_{TW-BM} = 3 [s]; water density ρ = 1000 [kg/m^3]; acceleration of gravity g = 9,81 [m/s^2];

Rotating screen servomechanism: servomechanism total opening time T_s = 10 [s]; servomechanism static gain factor K_s = 0,1 [1/V];

Water turbine screen: maximum water flow, corresponding to the maximum opening of rotating screen Q_{Wmax} = 90 [m^3/min];

Rotary gear (multiplicator): transmission ratio i = 2 [-];

Low speed cage asynchronous machine ratings: voltage U_N = 3 x 400 [V]; power P_N = 75 [kW]; speed n_N = 985 [min^{-1}]; efficiency η_N = 93,5 [%];current I_{SN} = 130 [A]; electromagnetic torque (at machine shaft) M_{En} = 727 [Nm]; moment of inertia of the machine J = 2,16 [kgm^2];

Three-phase switching capacitor capacity C_K = 3x470 [µF];

Rms voltage sensor data: proportional gain factor K_{pU} =0,01 [V/V];

PID type controller: controller integral time T_z = 5,32 [s]; controller derivative time T_W = 3 [s]; proportional gain coefficient K_p = 12,8;

Simulation input data: simulation time: 100 [s]; simulation step constant; simulation algorithm used: ode 4 (Runge-Kutt).

Simulation results are presented in Figure 6 and Figure 7.

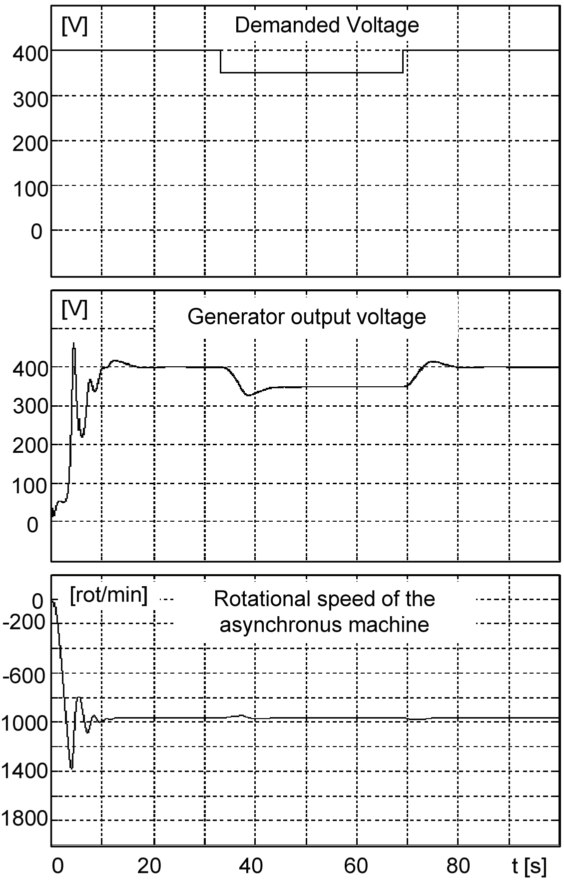

Fig. 6. Time courses of characteristic physical quantities, in closed-loop rms voltage control system, as response to the change of the required (set) voltage value

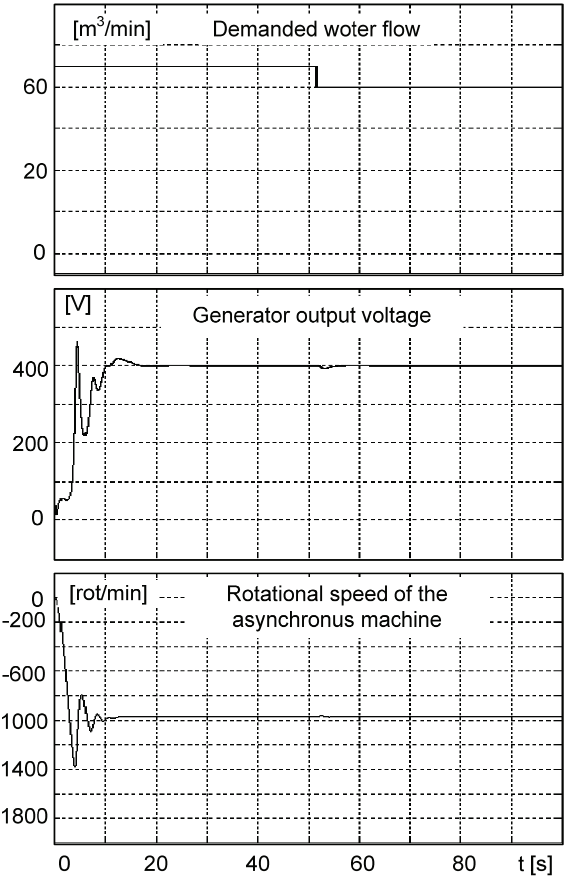

Fig.7. Time courses of characteristic physical quantities, in closed-loop rms voltage control system, as response to the change of the required (set) water flow

Summary

Aims of the simulation tests were:

Determination of the time courses of characteristic physical quantities in individual circuits such as: the control and regulation system, water turbine, rotating screen servomechanism, cage asynchronous machine connected to isolated grid. The voltage control system adopted is of closed-loop type and responses are calculated for inputs of uniit-step change of rms voltage and artificial disturbance of the maximum water flow at the entrance of rotating screen of water turbine.

The following conclusions can be drawn on the basis of simulation studies:

Choice of structure and selection of settings for the rms voltage in the circuits of low speed asynchronous cage machine, based on the linear criterion of "optimum magnitude" by C. Kessler, has made it possible to obtain good dynamics of rms voltage time course in the control structures, with minimum over-regulation in response to unit-step voltage input. Moreover, the advantage of this type of controller is a strong resistance to external disturbances (changes in the maximum water flow at the entrance of rotating screen of water turbine);

Frequency of currents and voltages and the rotational speed of low speed asynchronous cage machine, connected to isolated grid, are nearly independent of changes in quantities such as torque at water turbine shaft, electromagnetic torque, amplitude of voltage and current in the circuit of the machine and the power expended to dedicated network circuit. At the same time, they are strongly influenced by the capacity of the three-phase commutation capacitor, connected to the stator circuit and to the equivalent circuit parameters of asynchronous cage machine;

Asynchronous cage machine applied as generator operating with small water turbine, connected to isolated grid, should possess better insulation then standard machine (by c. 30%). This is enforced by strong overexcitation of asynchronous cage machine, which is accompanied by significant increase in stator voltage.

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***Authors**: dr inż. Andrzej Kandyba of Power Electronics, Electrical Drives and Robotics, Faculty of Electrical Engineering, Silesian University of Technology, ul. B. Krzywoustego 2 44-100 Gliwice, E-mail" Andrzej.Kandyba@polsl.pl dr inż. Marian Kalus Institute of Innovative Technologies EMAG, Poland, 40-189 Katowice, Leopolda 31., mkalus@emag.pl prof. dr hab. Inż. Igor Piotr Kurytnik Department of Electrical Engineering and Automation University of Bielsko-Biała ikurytnik@ath.bielsko.pl*