

SIMULATION OF ELECTRICAL MACHINE SYSTEM WITH PERMANENT MAGNET SINCHRONOUS GENERATOR

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Abstract. The research paper discusses dynamic process simulation of electrical machine system with frequency controlled induction motor and permanent magnet exciting synchronous generator under changeable electrical power as a load varying from no-load mode to rated value. Experimental and analytical investigations show that given machine system is a non-stationary inertial object with changeable electromechanical time constant as a function of the rotation speed. A self tuning up model is developed to simulate the transient process of output voltage and frequency change under fluent electrical load. Matlab – Simulink technology enables to simulate non-stationary dynamic process of electrical machine system with high accuracy. Research testifies that using two loop control system the fluctuations of output voltage and frequency can be decreased under required $\pm 5\%$ limit.

Key words: induction motor, permanent magnet, synchronous generator, characteristics, modelling, simulation.

Introduction

Lately more and more applications obtain synchronous generators with permanent magnet exciting, particularly in wind power engineering [1, 2, 3]. They are available in wide choice, as from several watts up to several mega watts. Main advantages of the permanent magnet synchronous generator in comparison with the direct current exciting conventional synchronous generator are as follows: considerably smaller weight and size in relation to power unit; higher operational reliability because of brushless construction (rotor without slip-rings); higher efficiency because of very small energy losses in magnetic rotor [3].

Essential shortcoming of the permanent magnet synchronous generator is to ensure sufficiently high stability of output voltage and frequency required for direct parallel connection to the electric power network without semi-conductor converter.

Main tasks of this work are to investigate and simulate characteristics of electrical machine system, as well as to estimate the operation possibility of permanent magnet synchronous generator in the micro-cogeneration plant as electrical energy source for self-provision.

Research object and methods

Research object is electrical machine system, which consists of the frequency controlled induction motor AO2-42 with S9G FUJI converter and the permanent magnet synchronous generator 4SH2P100L8. The frequency controlled induction motor is used for simulation of generator operation in the micro-cogeneration plant with gas engine drive. Experimental investigation is made on the test bench (Fig. 1) fitted with the adequate measuring equipment. Parameters of the research object and the test bench equipment is given in the text.

The experimental research is made to determine the deviations of generator output voltage U_2 and frequency f_2 in order to fluent electrical power P as a load, as well as to compile an adequate mathematical model and block-diagram for dynamic process simulation in machine system with the permanent magnet synchronous generator.

The differential equations and the transfer functions of the research object and the load impact are composed using mathematical analyses, operator calculations and Laplace transforms as well as principles of control theory [4, 5]. Transient process simulation in Windows environment is performed using Matlab-Simulink technology [5, 6]. Gains and time constants of the object components are calculated in order to their technical parameters and experimental research results.

Simulation block diagram (Fig. 4) is composed and simulation process is realized using standard block-models from Matlab-Simulink libraries. New method of non-stationary process simulation is developed using discrete tuning of model structure in order to changeable parameters of the real object.

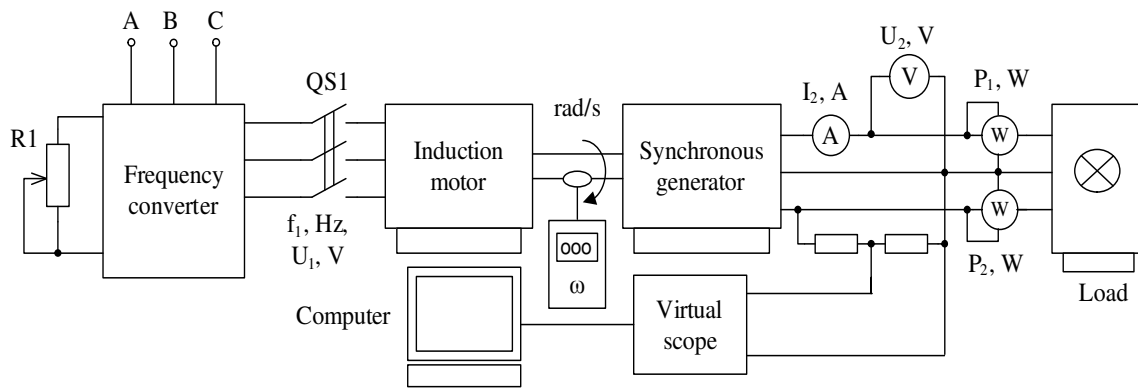


Fig. 1. Test bench for electrical machine system experimental research

Discussion and results

1. Steady state and dynamic characteristics

To get the motor and generator gains, to identify the load P impact on angular speed ω , on output voltage U_2 and frequency f_2 , as well as to make an adequate model for transient process simulation the experimental steady-state characteristics $\omega=f(P)$, $U_2=f(P)$ under fluent load (Fig. 2.a) and $f_2=f(\omega)$, $U_2=f(\omega)$ under no-load mode (Fig. 2.b) as well as run-up characteristic of electrical machine system (Fig. 3) have been made using the test bench (Fig. 1).

The permanent magnet synchronous generator has been charged symmetrically to the lamp rheostat. The output voltage U_2 and electrical power P has been measured by the laboratory voltmeter U_2 and by the wattmeter P_1, P_2 . The angular speed of the shaft has been measured by the infrared electronic tachometer TM – 4010 with accuracy ± 0.1 rad/s.

The output frequency f_2 (with accuracy ± 0.1 Hz) and run-up characteristic of the generator (Fig. 3) has been estimated using the virtual scope Pico-Log ACD 200/50 and personal computer.

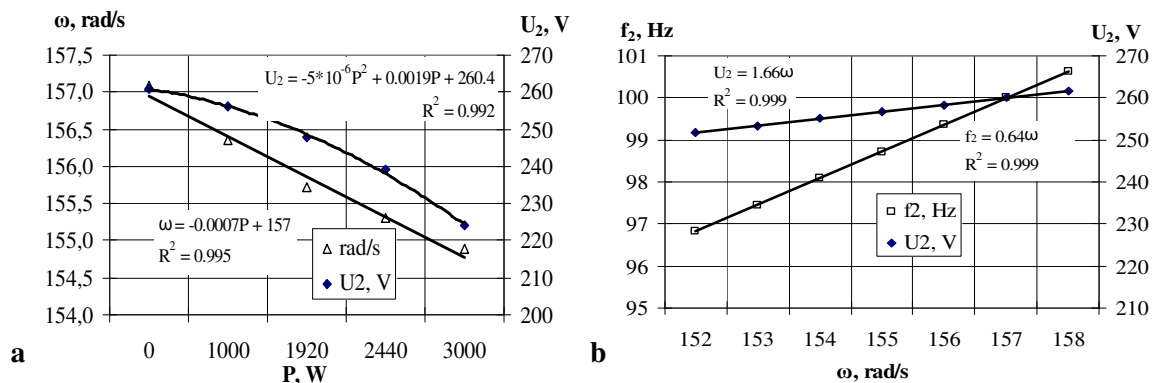


Fig. 2. Steady state characteristics of permanent magnet synchronous generator: a – angular speed ω and output voltage U_2 in order of electrical load P ; b – output frequency f_2 and voltage U_2 in order of angular speed ω under no-load conditions

Experimental run-up characteristic of the electric machine system, obtained by the virtual scope, shows that full acceleration time, caused by mechanical and electrical inertia, from start ($t_0=2900$ ms) of the induction motor to finish ($t_f=3150$ ms) is $t_a=0.25$ s.

During this time the output voltage U_2 and frequency f_2 gradually rises from zero to rated value. S-type deflection of acceleration curve testifies that the motor time constant T_m changes from maximum at low velocity to minimum at rated velocity. Therefore the dynamic model for simulation should be non-stationary with changeable time constant, adapted to the variable angular speed ω .

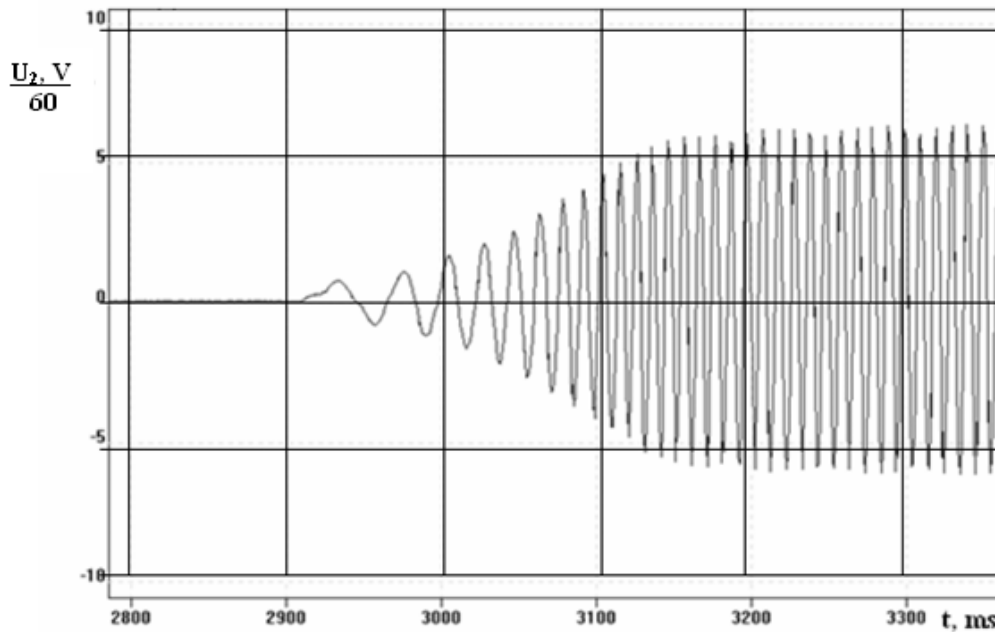


Fig.3. Experimental run-up characteristic $U_{2\max}(t) \cdot \sin 2\pi f_2(t) \cdot t$ of the permanent magnet synchronous generator

2. Mathematical modelling

For inertial dynamic performance simulation of electrical machine system the differential equations of the frequency controlled induction motor and of the synchronous generator should be compiled.

Primary voltage of the induction motor changes by the frequency converter in proportion to the frequency ($U_1/f_1 = \text{const}$). The motor torque M remains unchanged and motor can be loaded at constant torque within the control range. Then the electromechanical performance of the motor under no-load mode can be described by the following differential equation:

$$T_m(f_1, \omega) \cdot \frac{d\omega}{dt} + \omega = K_1 \cdot f_1, \quad (1)$$

where $T_m(f_1, \omega)$ – changeable electromechanical time constant, s;
 ω – motor angular speed, rad/s;
 $K_1 = \omega_0(f_1)/f_1$ – motor gain, rad/s/Hz;
 $\omega_0(f_1)$ – no load angular speed at frequency f_1 , rad/s.

For given motor $K_1 = 157/50 = 3.14$ rad/s/Hz = const.

The differential equation (1) is non-stationary because of changeable time constant of inertia $T_m(f_1, \omega)$, which changes during all transient process of induction motor in accordance with an expression:

$$T_m(f_1, \omega) = \frac{(J_m + J_g) \cdot \left[\left(1 - \frac{\omega}{K_1 \cdot f_1}\right) + s_c^2 \right] \cdot K_1 \cdot f_1}{2 \cdot \mu_c \cdot M_r \cdot s_c}, \quad (2)$$

where $J_m = 0.0162$ kg·m² – motor moment of inertia;
 $J_g = 0.0144$ kg·m² – generator moment of inertia reduced to the motor shaft;
 $s_c = 0.13$ – motor critical slip;
 $\mu_c = M_r/M_c = 2$ – reduced motor critical torque;
 $M_r = P_r/\omega_r = 5000/151.8 = 33$ Nm – motor rated torque;
 $M_c = \mu_c \cdot M_r = 2 \cdot 33 = 66$ Nm – motor critical torque;
 P_r and ω_r – motor rated power and rated angular speed, W and rad/s.

Using Laplace transforms to differential equation (1), we obtain an operator equation (3) and a transfer function (4) for transient process simulation in frequency controlled induction motor:

$$T_m(f_1, \omega) \cdot \omega(s) \cdot s + \omega(s) = K_1 \cdot f_1(s), \quad (3)$$

$$W_m(s) = \frac{\omega(s)}{f_1(s)} = \frac{K_1}{T_m(f_1, \omega) \cdot s + 1}, \quad (4)$$

where $f_1(s)$ and $\omega(s)$ – Laplace transforms of input voltage frequency and angular speed;
 s – Laplace variable.

Transfer functions for simulation of generator output voltage $U_2(t)$ and its frequency $f_2(t)$ dependent on angular speed under no-load mode are as follows:

$$W_{g_u}(s) = \frac{U_2(s)}{\omega(s)} = \frac{K_U}{T_e \cdot s + 1} \quad \text{and} \quad W_{g_f}(s) = \frac{f_2(s)}{\omega(s)} = \frac{K_f}{T_e \cdot s + 1}, \quad (5)$$

where $U_2(s)$ and $f_2(s)$ – Laplace transforms of output voltage and frequency ;

$K_U = 1.66$ V/rad/s and $K_f = 0.64$ Hz/rad/s – generator gains, obtained from experimental characteristics (Fig. 2.b.);

$T_e \approx X_{gf} / (2\pi f \cdot R_g) = 4 / (2 \cdot 3.14 \cdot 50 \cdot 0.9) = 0.014$ s – electromagnetic time constant;

X_{gf} and R_g – inductive and active resistance of generator measured at frequency f .

For load impact simulation on to motor shaft angular speed ω and on to generator output voltage U_2 , the transfer functions have been compiled using experimental data of angular speed and output voltage change under variable electrical power as a load (Fig. 2.a.):

$$W_{\Delta\omega}(s) = \frac{\Delta\omega(s)}{P(s)} = \frac{K_{\Delta\omega}}{T_m \cdot s + 1} \quad \text{and} \quad W_{\Delta U_2}(s) = \frac{\Delta U_{2\max}}{T_e \cdot s + 1} = \frac{U_2 \cdot e^{-0.039R}}{T_e \cdot s + 1}, \quad (6)$$

where $P(s)$ and $\Delta\omega(s)$ – Laplace transforms of electrical load and of angular speed change ;

$K_{\Delta\omega} = 0.0007$ rad/s/W and $\Delta U_{2\max} = U_2 \cdot e^{-0.039R}$ V – gains, obtained from experimental characteristics (Fig. 2.a.);

$T_m \approx 0.005$ s – electromechanical time constant at high angular speed and small changes;

R – one phase active resistance of electrical load, Ω .

3. Transient process simulation

The simulation block-diagram of the electrical machine system is compiled using standard blocks from “Simulink” libraries. The block-diagram (Fig. 4.) consists of several subsystems as the modules for calculation and simulation: “Time constant” – the module for automatic calculation of the time constant T_m dependent on fixed parameters and changeable angular speed (Formula 2); “Induction motor” – the module for dynamic electromechanical process simulation in frequency controlled induction motor under no-load mode (Formula 4); “Generator” – the module for electromagnetic process simulation in permanent magnet synchronous generator under no-load mode (Formulas 5, Fig.5); “ $\Delta\omega(P)$ ” and “ $\Delta U_2(R)$ ” – the modules for impact of electrical power P and load resistance R on to angular speed of the motor shaft and generator output voltage simulation (Formulas 6); “ $U_{2\max} \sin \omega t$ ” – the module for output voltage amplitude and frequency simulation (Fig. 6).

Transfer function of the induction motor (4) should be adapted to changeable time constant T_m dependent on angular speed ω . As continuous change of T_m in transfer function (4) is not feasible the method of discrete commutation is proposed. For this purpose the module “Induction motor” is composed of six circuits commuting by multiport switch in accordance to discrete values of time constant T_m automatically calculated by module “Time constant”: $T_{m1}=0.25$ s; $T_{m2}=0.2$ s; $T_{m3}=0.15$ s; $T_{m4}=0.1$ s; $T_{m5}=0.05$ s; $T_{m6}=0.025$ s.

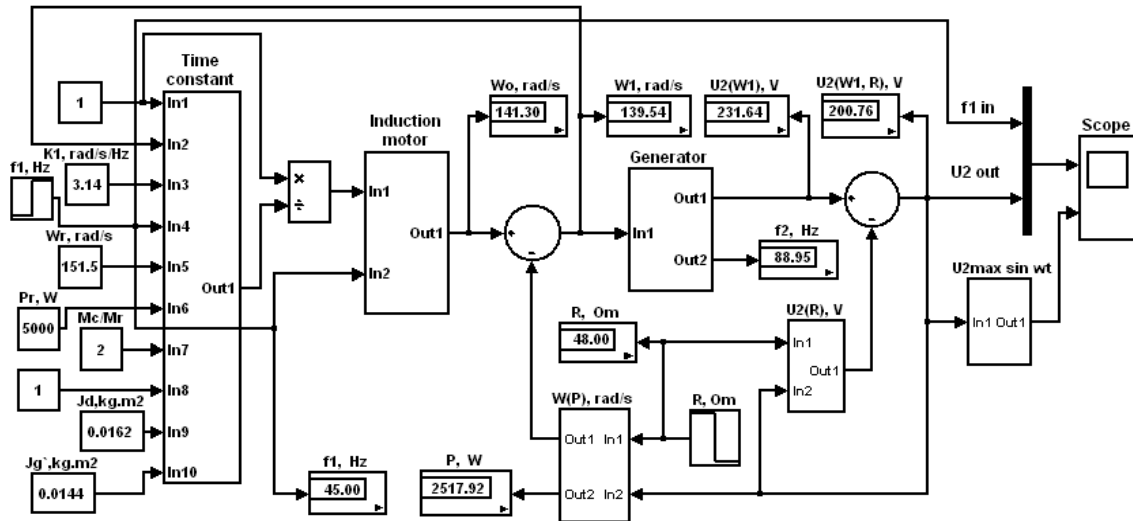


Fig.4. Simulation block-diagram of the electrical machine system

Simulations show that such method makes possible to get S-type transient characteristics of generator output effective voltage $U_2 = f(t)$ (Fig. 5), and of output sine wave voltage $U_2 = U_{2max} \sin 2\pi f_2 t$ (Fig. 6) as a step response of input voltage frequency ($f_1 = \text{const.}$) with high adequacy to experimental results (Fig. 3).

Simulated response of output voltage under no-load mode ($0 < t \leq 0.5$ s) and on rated load ($t > 0.5$ s) for step input impact ($f_1 = 45$ Hz) demonstrates that U_2 decreases for 31 V (Fig. 5).

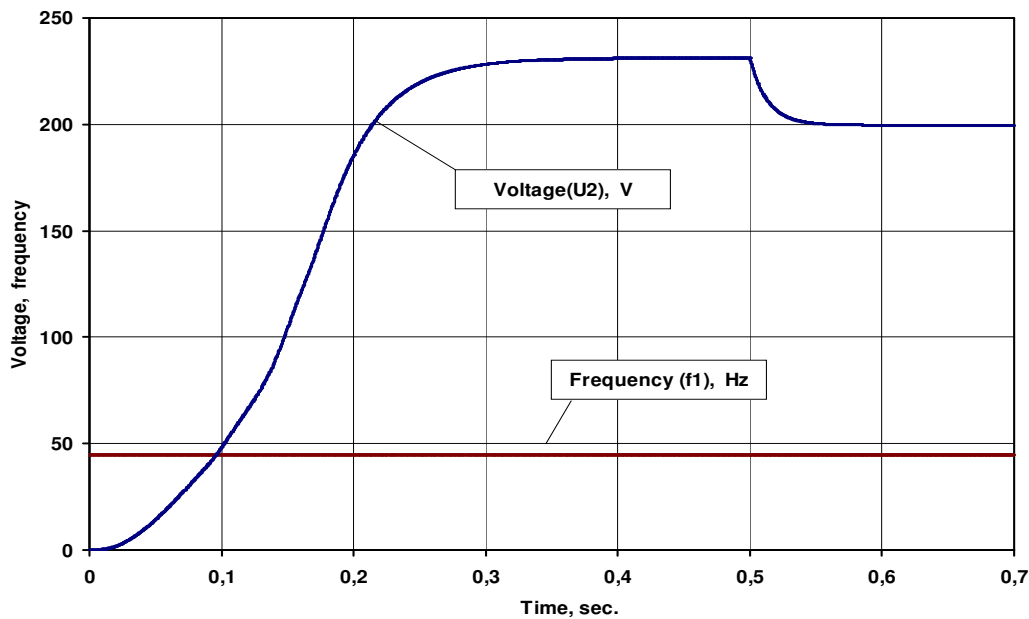


Fig.5. Simulated characteristics of input frequency $f_1 = f(t)$ and output voltage $U_2 = f(t)$

If an angular speed of the motor shaft is kept invariable, frequency of output voltage stay constant ($f_2 = \text{const.}$, if $\omega = \text{const.}$). Output voltage U_2 changes more than ± 7 % of rated value, if electrical load of generator varies from no-load to rated value (Fig. 2, Fig. 5). Such deviation is inadequate to existing norms and requirements. We can make a conclusion that for diminish of output voltage and frequency deviations under permissible level ± 5 %, the two loop control system of generator should be designed with the feedback of angular speed ω and the feedback of output voltage U_2 .

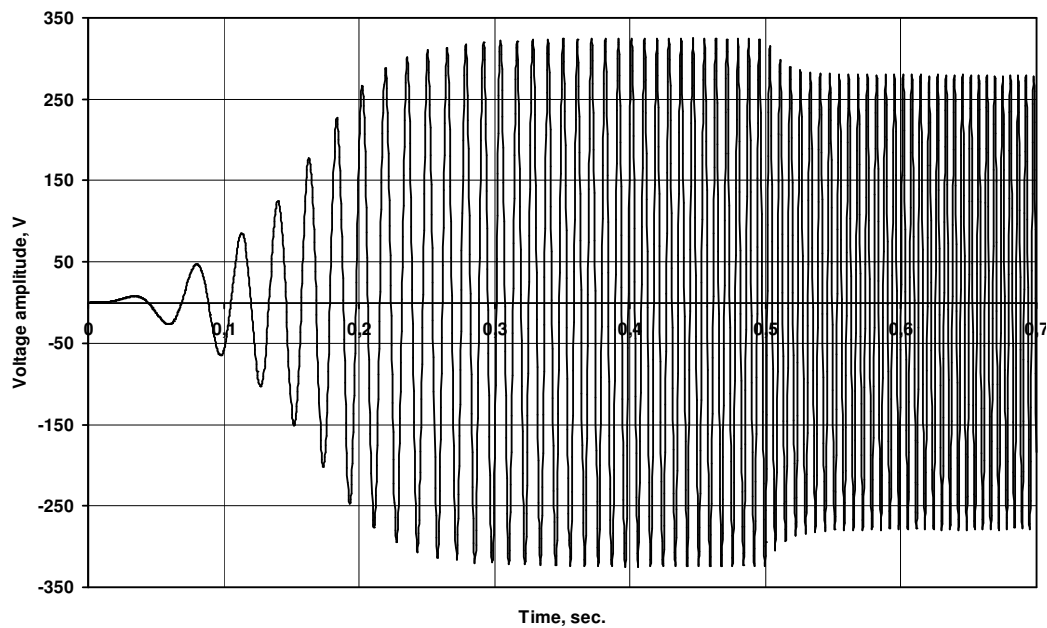


Fig.6. Simulated run-up characteristic $U_{2\max}(t) \cdot \sin 2\pi f_2(t) \cdot t$ of the permanent magnet synchronous generator

Conclusions

1. For transient process simulation with appropriate accuracy in frequency controlled induction motor, the mathematical model should be adapted to the changeable time constant T_m using the method of discrete self-tuning by commutation of separate transfer functions $W_m(s)$ throughout the area of angular speed ω change.
2. If an angular speed of the generator shaft is kept invariable, output voltage U_2 deviates more than $\pm 7\%$ of rated value under electrical load, which varies from no-load to rated value. Such deviation is inadequate to existing norms.
3. To introduce the micro-cogeneration plant with permanent magnet synchronous generator for electric energy self-provision, the two loop control system of micro-cogeneration plant should be designed to keep deviations of output voltage and frequency below $\pm 5\%$ limit.

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