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Analysis and investigations into sensorless control system based on doubly fed machine working as a generator

***Abstract**. A PLL-based sensorless control system for the double fed machine working as a generator, developed by the author, is analyzed in the paper. The system allows adjusting active power and reactive power of the generator, running to the electric power system. Dynamic properties of the abovementioned control system and control systems equipped with position sensor are similar. Mathematical analysis and experimental results presented in the paper confirm this thesis.*

***Streszczenie**. W pracy poddano analizie bezczujnikowy układ sterowania maszyny dwustronnie zasilanej w zakresie pracy generatorowej z zastosowaniem pętli fazowej. Analizowany układ pozwala na nastawianie mocy czynnej i biernej generatora oddawanej do systemu elektroenergetycznego. Właściwości dynamiczne wspomnianego systemu oraz systemów zawierających czujnik położenia wirnika są zbliżone. Analiza matematyczna i badania eksperymentalne zaprezentowane w pracy potwierdziły tę tezę (**Analiza i badanie bezczujnikowego układu sterowania maszyny dwustronnie zasilanej w zakresie pracy generatorowej**).*

Keywords: double fed machine, sensorless control, phase locked loop, modelling and experiments.
Słowa kluczowe: maszyna dwustronnie zasilana, sterowanie bezczujnikowe, pętla fazowa, modelowanie i eksperymenty.

Introduction

Nowadays, slip-ring machines are mainly applied as generators in unconventional power systems converting wind or water energy. A slip-ring machine works as a doubly fed machine (DFM) with stator winding directly connected to the grid and rotor winding connected to the grid via bidirectional frequency converter and isolating transformer. The frequency of induced voltage is not depended bijectively on the angular velocity of rotor in contrast to synchronous machines being basis for majority conventional power systems. This feature considerably facilitates a choice of a drive for generator. It is especially meaningful in wind and water turbines working with variable rotational speed. An application of DFM with converter-fed rotor winding is economically grounded in these cases. The DFM may also be applied in an electric power system of a ship which uses power reserves of a main drive.

The choice of a structure of a control system for DFM, working as a generator in electric power systems, depends mainly on the installed capacity of the considered system. A proper operation of DFM-based generator connected to the grid is guaranteed by the main controllers of active and reactive power adjusting internal controllers of rotor current components [1, 2, 3, 4, 5, 6, 7] but outputs of linear controllers of active and reactive power or current vector components should by transformed to the rotor-oriented coordinate system where the rotor current is generated. A rotor position angle required as an argument of the abovementioned transformation may be measured by a position sensor or estimated in control system.

The solutions allowing to eliminate a measurement of rotor position angle in DFM control systems are known from the literature sources [1, 2, 3, 4, 6]. An application of a phase locked loop (PLL) in order to eliminate the rotor position sensor (encoder) was proposed in the paper [2] and previous papers of that author. The structure of PLL known from radio engineering was directly copied in those proposals, thus the satisfactory results were not achieved. Numerical calculations and experimental results, inserted in the papers, confirmed poor dynamics of the proposed systems. The interactions of active power and reactive power as well as distortion of current waves and power were observed. Poor dynamics was also observed in the control system proposed in [1] where the rotor position angle was calculated on the basis of measured and estimated rotor current. In that solution the rotor current phase vector (phasor) was defined in two different coordinate systems: rotating and immovable ones. The sensorless control system for DFM presented in this paper (Fig. 1) [4, 6] allows achieving dynamic properties similar to the systems equipped with position sensor. Mathematical analysis and experimental results presented in the paper confirm this thesis.

Structure of the system

A phase locked loop applied in the proposed structure allows removing the position sensor from the DFM-based control system. The PLL controls phase angle α between measured voltage of stator and estimated current of rotor [6]. The PLL consists of proportional-plus-integral (PI) controller and integrator.

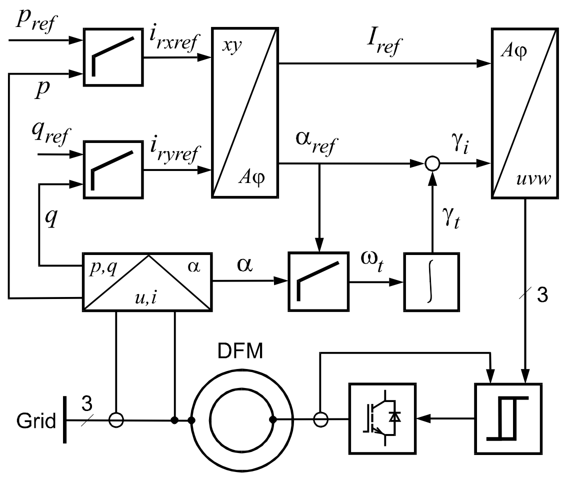

Fig. 1. The DFM-based control system with the use of PLL in order to estimate a rotor position angle

In both cases, i.e. in the proposed system and in the encoder-based systems, a rotor position angle is an output quantity (of PLL or encoder). This feature distinguishes the abovementioned systems from the system known from literature source [2] where PLL was used in order to estimate the phase angle γ_i of rotor current.

Mathematical analysis of the system

An influence of phase locked loop on operation of the system is analysed mathematically whereas an influence of main controllers of active power and reactive power is omitted because they are not necessary for stable operation of the system.

The following simplifying assumptions have been taken into account in theoretical analysis:
- magnitude and frequency of the grid voltage are constant
- DFM has two poles whereas rotational speed of rotor is an input quantity
- a true inverter fed rotor winding is replaced by the ideal current source; it means that instantaneous phase vector of rotor current (current vector) generated by this source is equal to the reference vector of rotor current with components I_{ref} and γ_i
- all variables of DFM are accessible for measurement in control system.

In accordance with the abovegiven assumptions the phase angle γ_i of rotor current is obtained in the structure shown in Fig. 1 as a result of the following addition:

$$\gamma_i = \gamma_t + \alpha_{ref} \tag{1}$$

where γ_t is rotor position angle related to the stator-voltage-oriented coordinate system, the rotor position angle is estimated by the PLL, α_{ref} is reference angle of phase shift between rotor current transformed to the stator-oriented coordinate system and stator voltage. Differentiating both sides of equation (1), the angular frequency of rotor current may be obtained as follows:

$$\omega_i = \omega_t + \frac{d\alpha_{ref}}{dt} \tag{2}$$

The following dependency between the frequencies is true:

$$\frac{d\alpha}{dt} = \omega_i + \omega_r - \omega_s \tag{3}$$

where α is actual angle of phase shift between rotor current transformed to the immovable coordinate system and stator voltage, ω_s is angular frequency of stator voltage, ω_i is angular frequency of rotor current, ω_r is angular velocity of rotor. It should be explained that $\omega_i + \omega_r$ is angular frequency of rotor current transformed to the immovable coordinate system.

Replacing ω_i in (3) by dependency (2), the following equation may be obtained:

$$\frac{d\alpha}{dt} = \frac{d\alpha_{ref}}{dt} + \omega_t + \omega_r - \omega_s \tag{4}$$

The equation expressed for increments of variables has the following form:

$$\frac{d\Delta\alpha}{dt} = \frac{d\Delta\alpha_z}{dt} + \Delta\omega_t + \Delta\omega_r - \Delta\omega_s \tag{5}$$

Variations in rotor angular velocity $\Delta\omega_r$ and angular frequency $\Delta\omega_s$ of stator voltage in the abovegiven equation may be assumed to be disturbances.

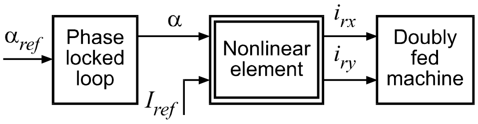

Fig. 2. Block-components of the control system for DFM

The system shown in Fig. 1 may be substituted in a simplification by a chain connection of the phase locked loop, nonlinear element and doubly fed machine (Fig. 2). In the simplified structure the block of main controllers for active and reactive power is omitted accordingly with the previous assumption. The respective block-components of the system shown in Fig. 2 may by described – depending on requirements – by differential equations, operational transmittances or nonlinear transfer function.

Operational transmittance may be obtained by transformation of a time-equation to the operational form at zero initial conditions. The equation (5) transformed to the operational form is given as follows:

$$s\Delta\alpha(s) = s\Delta\alpha_{ref}(s) + \Delta\omega_t(s) + \Delta\omega_r(s) - \Delta\omega_s(s) \tag{6}$$

where s is Laplace's operator. A proportional-plus-integral (PI) controller, described by the following operational transmittance, is applied for controlling the angle of phase shift α.

$$G_{PI}(s) = \frac{\omega_t(s)}{\alpha_{ref}(s) - \alpha(s)} = k_p\left[1 + \frac{1}{T_i s}\right] \tag{7}$$

That results in the following dependency:

$$\omega_t(s) = k_p\left[1 + \frac{1}{T_i s}\right]\left[\alpha_{ref}(s) - \alpha(s)\right] \tag{8}$$

where k_p is amplification factor and T_i is time constant of PI controller.

Introducing increments of variables into dependency (8) and then considering this dependency in (6), the operational transmittances describing phase locked loop for increments of set variable or disturbances may be derived. Omitting the influence of disturbances on the controlled variable (α), the operational transmittance for set value (α_{ref}) may be defined as follows:

$$G(s) = \frac{\Delta\alpha(s)}{\Delta\alpha_{ref}(s)} = 1 \tag{9}$$

Accordingly to the abovegiven dependency and considering integral action of the controller, which eliminates steady-state error, the controlled variable (α) is equal to the set value (α_{ref}) in both steady states and dynamic states, i.e.:

$$\alpha = \alpha_{ref} \tag{10}$$

The nonlinear element belonging to the structure shown in Fig. 2 transforms the components of rotor current vector from the polar coordinates system to the Cartesian coordinate system:

$$i_{rx} = I_{ref}\cos\alpha \tag{11}$$

$$i_{ry} = I_{ref}\sin\alpha \tag{12}$$

Analogical dependency may be written for controlling variables i_{rxref}, i_{ryref}, occurring in the structure shown in Fig. 1, what together with equation (10) means that controllers of active and reactive power in this structure exert an influence on the controllers of rotor current vector components in the same way like in the system with encoder.

The DFM is the last link of the structure shown in Fig. 2. Equations describing DFM in terms of the Cartesian coordinate system connected to the stator voltage vector have the following form:

$$\frac{d}{dt}\psi_{sx} = -\frac{R_s}{L_s}\psi_{sx} + \omega_s\psi_{sy} + \frac{R_s L_m}{L_s} i_{rx} + U_s \tag{13}$$

$$\frac{d}{dt}\psi_{sy} = -\frac{R_s}{L_s}\psi_{sy} - \omega_s\psi_{sx} + \frac{R_s L_m}{L_s} i_{ry} \tag{14}$$

where ψ_{sx}, ψ_{sy} are components of stator flux vector, U_s is stator voltage, R_s, L_s, L_m are parameters of DFM. In a case of current controlled rotor winding of DFM and omitting disturbances, the abovegiven system includes linear equations with constant coefficients describing an oscillating element.

The characteristic equation for the system (13), (14) expressed as a matrix is given as follows:

$$\det(\mathbf{A} - s\mathbf{I}) = 0 \qquad (15)$$

where $\mathbf{A}$ is matrix of coefficients, $\mathbf{I}$ is unitary matrix:

$$\mathbf{A} = \begin{bmatrix} -R_s/L_s & \omega_s \\ -\omega_s & -R_s/L_s \end{bmatrix} \qquad \mathbf{I} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

There are two complex roots of characteristic equation (15) in the left half-plane of complex variable s:

$$s_{1,2} = -\frac{R_s}{L_s} \pm j\omega_s \qquad (16)$$

The roots are placed in the vicinity of imaginary axis because of their small real part R_s/L_s. It means that DFM with current controlled rotor winding has small margin of stability. Oscillations of flux with frequency ω_s are also transmitted to the stator current and power. The oscillations are weakly damped with time-constant L_s/R_s.

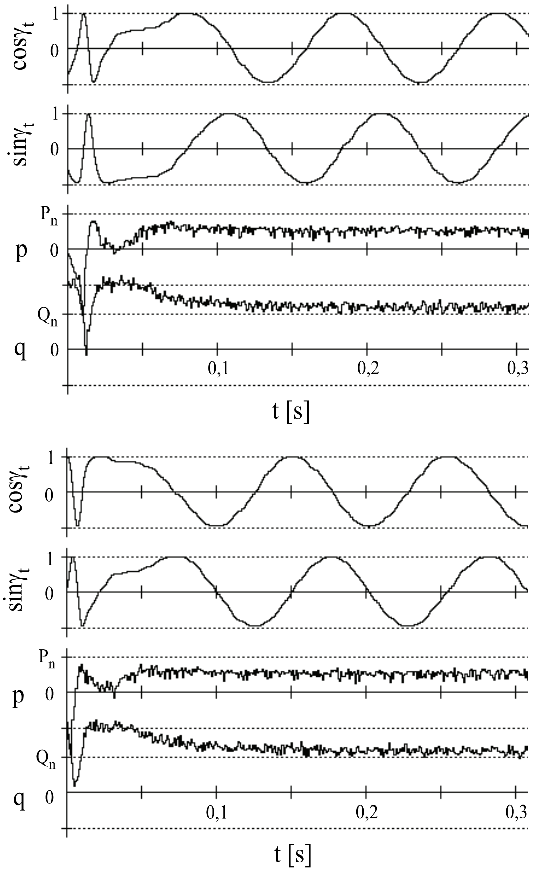

Fig. 3. Time-dependencies measured in experimental system – examples of system synchronization, where p, q are active power and reactive power of DFM, $\cos\gamma_t$, $\sin\gamma_t$ are functions of rotor position angle estimated by the control system

Experimental results

A slip-ring machine driven by separately excited DC motor was used in experimental investigations [6]. The DFM was controlled by inverter according to the block diagram (Fig. 1) on the basis of microprocessor system working in real time. In the experimental system both rotational speed and armature current of DC motor were not controlled. Thus, the rotational speed of driving DC motor was changing in accordance with its speed versus torque curve, depending on active power of the DFM driven by the DC motor.

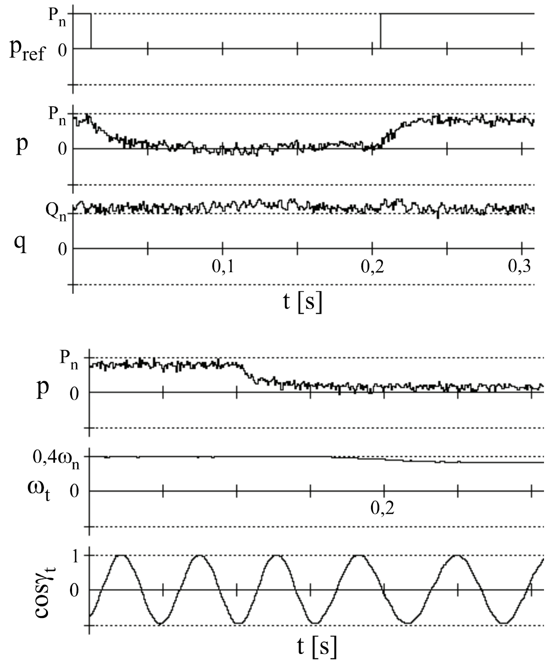

Fig. 4. Time-dependencies measured in experimental system – examples of transient responses of the system to a step change of active power reference, where ω_t is rotor angular velocity, estimated by the PLL in terms of stator-voltage-oriented coordinate system

Examples of time-dependencies illustrating synchronization process of investigated system since the inverter is started-up are given in Fig. 3. The system is being in synchronism before one period of grid voltage is over i.e. synchronization time is less than twenty milliseconds. Differences in time-dependencies result from various initial values of the estimated rotor position angle γ_t.

Examples of transient responses of the investigated system to a step change of active power reference are given in Fig. 4. Small interactions between active power and reactive power during controlling process are observed. The rotor angular velocity ω_t, estimated in terms of stator-voltage-oriented coordinate system, decreases as a result of the generator active power reduction, whereas the rotor angular velocity in terms of stator-oriented coordinate system increases ($\omega_r = \omega_s - \omega_t$). Variations in rotor angular velocity do not disturb the control system operation.

Time-dependencies of active power (p) and reactive power (q) and time-dependencies of the respective stator current vector components in terms of the coordinate system connected to the stator voltage vector are the same if the stator voltage (U_s) is constant.

Conclusions

Control systems for the DFM working as a generator, based on the rotor position angle sensor (encoder), allow for the decoupled control of the active power and reactive power. Previous attempts to eliminate encoder away from the DFM-based control systems caused deterioration of dynamical properties of those systems. The PLL-based sensorless control system for the DFM working as a generator, developed by the author, allows for decoupled adjustment of active power and reactive power just like the system equipped with position sensor. Results of analysis and experimental investigations, presented in the paper, confirm good properties of the system. Minor interactions between active power and reactive power in the experimental system result from simplified calculation of phase angle [4, 6]. The structure developed by the author is uncomplicated. As a consequence, high computational capacity of microprocessor system is not required.

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