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ANALYSIS OF INFLUENCE OF INPUT QUANTITIES AND DISTURBANCES ON GENERATOR OPERATION OF DOUBLY FED MACHINE

ABSTRACT *The control strategy for a DFM-based generator developed by the author as well as examples of time-dependencies measured with the application of laboratory stand are presented in the paper. The differential equations and flux-current dependencies describing current controlled DFM as well as the Laplace transformation of the equations are also given. The operational transmittances of DFM for input quantities and disturbances are defined. The transient responses of DFM are determined on the basis of the defined operational transmittances. A delta function and a step function are taken into consideration as input functions. The derived operational transmittances of DFM allow for penetrating analysis of controlled structure and formulating the detailed conclusions.*

Keywords: *doubly fed machine, control system, operational calculus, transient responses analysis.*

1. INTRODUCTION

Nowadays, slip-ring machines are mainly applied as generators in unconventional electric power systems converting wind or water energy. A slip-ring machine works as a doubly fed machine (DFM) with stator winding connected

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directly 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 DFM in contrast to synchronous machines being basis for majority conventional electric 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 the 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] but the outputs of power controllers 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, 5, 6, 7, 8]. 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 affirmed 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. The 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 this solution the rotor current phase vector was defined in two different coordinate systems: rotating and immovable ones. The sensorless control system for DFM presented in this paper (Fig. 1) [4, 5, 6, 7] allows achieving dynamic properties similar to the systems equipped with position sensor.

In the proposed structure (Fig. 1) a phase locked loop replacing a position sensor controls the 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. In both cases, i.e. in the proposed system and in the encoder-based system, the rotor position angle γ_t is the output quantity. This feature distinguishes the abovementioned systems from the system known from literature sources where PLL is used in order to estimate the phase angle γ_i of rotor current.

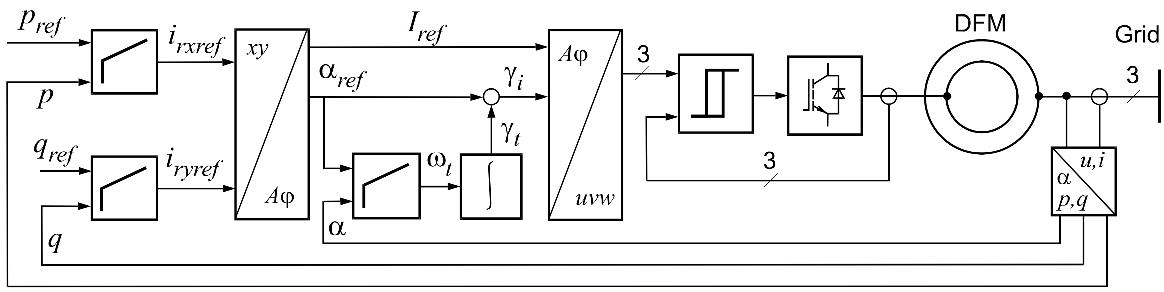

Fig. 1. The PLL-based control system for DFM estimating the rotor position angle

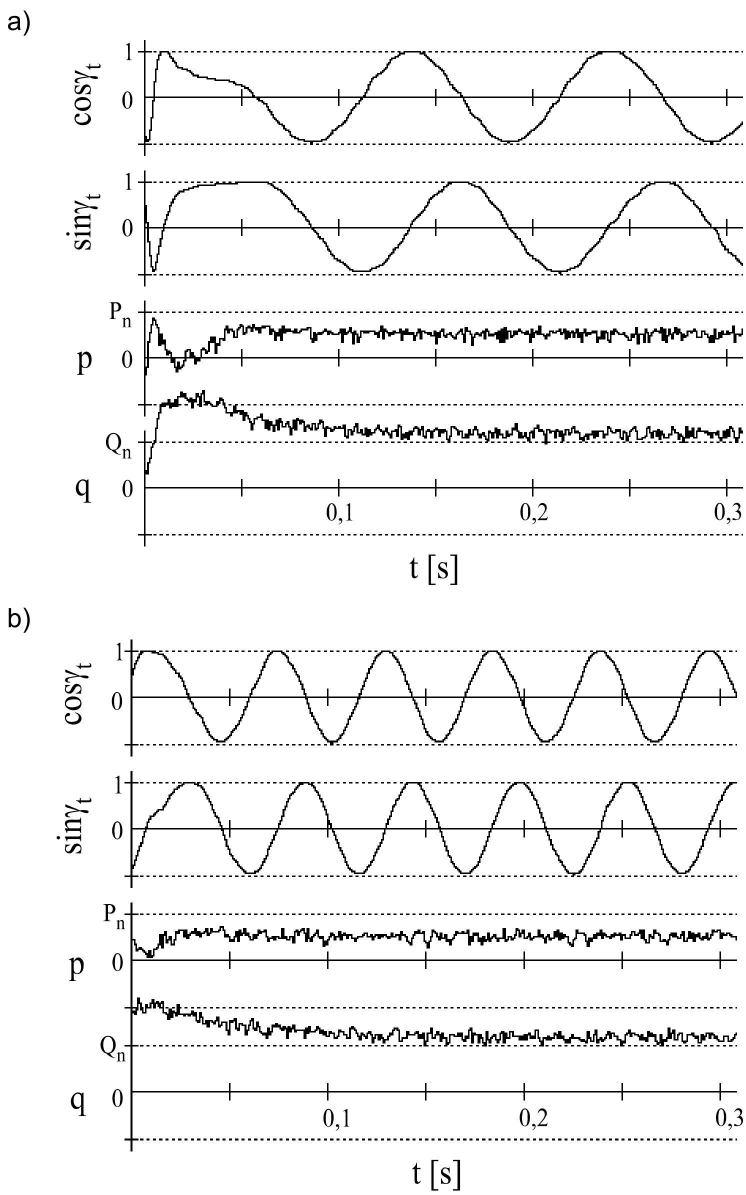

Fig. 2. Time dependencies – examples of synchronization of the DFM control system, where *p*, *q* are active power and reactive power of the DFM, $\cos\gamma_t, \sin\gamma_t$ are functions of rotor position angle estimated in the control system

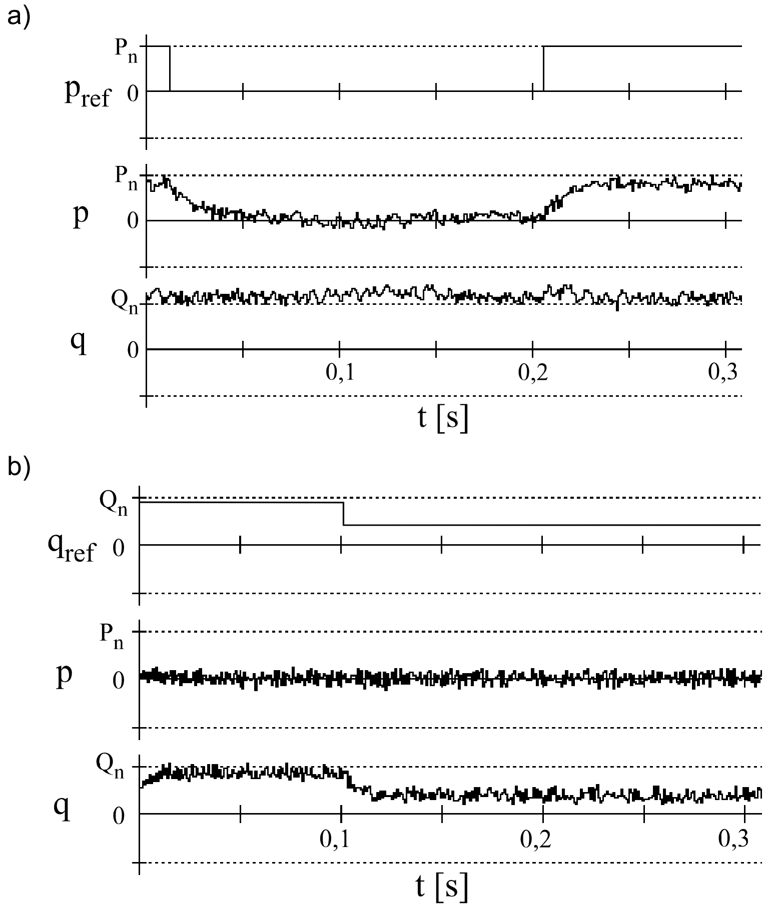

Fig. 3. Transient responses of the system shown in Fig. 1 to a step-change of active and reactive power references

The examples of phase and frequency synchronization of the control system as well as transient responses of the system to a step-change of DFM active and reactive power references are shown in Fig. 2 and 3, respectively. The presented time-dependencies were obtained as a result of experimental investigations [5]. A slip-ring machine 1,1 kW driven by separately excited dc motor 1,5 kW was used in the experimental investigations. The inverter-fed DFM was controlled according to the block diagram (Fig. 1) on the basis of microprocessor system working in real time.

2. EQUATIONS DESCRIBING CURRENT CONTROLLED DFM

Differential equations and flux-current dependencies describing stator winding of induction machine related to the Cartesian coordinate system x-y connected to the stator voltage vector (grid voltage vector) are expressed as follows

$$\frac{d\psi_{sx}}{dt} = -R_s i_{sx} + \omega_s \psi_{sy} + u_s \,, \tag{1}$$

$$\frac{d\psi_{sy}}{dt} = -R_s i_{sy} - \omega_s \psi_{sx} \,, \tag{2}$$

$$\psi_{sx} = L_s i_{sx} + L_m i_{rx} \,, \tag{3}$$

$$\psi_{sy} = L_s i_{sy} + L_m i_{ry} \,. \tag{4}$$

The components ψ_{sx}, ψ_{sy} of phase vector (vector, in short) of stator flux and components i_{sx}, i_{sy} of stator current vector included in the equations are state variables whereas components i_{rx}, i_{ry} of rotor current vector are input quantities if the rotor winding of DFM is fed by a current source. The changes of stator voltage u_s or its angular frequency ω_s are assumed to be the disturbances.

A true current source feeding the rotor winding of DFM is made mostly as a current controlled voltage source inverter with closed loops applied for output phase currents of voltage source inverter (VSI). It should be noted that dynamics of the abovementioned current source depends also on parameters of the winding. Thus, the input quantities i_{rx}, i_{ry} cannot change abruptly i.e. as a step function. However, there is possibility of very fast changes of currents as a consequence of relatively high voltage occurring on terminals of rotor winding. Additionally, the on-off controllers with hysteresis (hysteresis controllers) applied for phase currents of rotor cause quick changes of current components i_{rx}, i_{ry}. The hysteresis controllers of rotor currents adjust the width of the VSI output pulses.

In accordance with Figure 1, the error actuated control system for DFM with active power feedback and reactive power feedback is considered. The power is generated to the grid via DFM stator winding. The frequency of stator (grid) voltage is a constant parameter while the variations of voltage rms can reach some percent. In practice the voltage rms may also be assumed to be a constant parameter. Thus, according to the dependencies (5) and (6), the control of active and reactive power of DFM is reduced to the control of components i_{sx}, i_{sy} of stator current vector in x-y coordinate system connected to the stator voltage vector.

$$p = -u_s i_{sx} \,, \tag{5}$$

$$q = -u_s i_{sy} \,. \tag{6}$$

These components may be interpreted as controlled variables and as the output state variables. In the further considerations, just the increments of these quantities will be taken into account as a response of DFM to changes of the input quantities i_{rx}, i_{ry}. They will be used to define the operational transmittances.

3. OPERATIONAL EQUATIONS DESCRIBING DFM AND CURRENT TRANSFORMS

The equations (1), (2) and dependencies (3), (4) transformed to the operational form are expressed as follows

$$s\psi_{sx} = -R_s I_{sx} + \omega_s \psi_{sy} + U_s \, , \tag{7}$$

$$s\psi_{sy} = -R_s I_{sy} - \omega_s \psi_{sx} \, , \tag{8}$$

$$\psi_{sx} = L_s I_{sx} + L_m I_{rx} \, , \tag{9}$$

$$\psi_{sy} = L_s I_{sy} + L_m I_{ry} \, , \tag{10}$$

where $\psi_{sx} = \psi_{sx}(s)$, $\psi_{sy} = \psi_{sy}(s)$, $I_{sx} = I_{sx}(s)$, $I_{sy} = I_{sy}(s)$, $I_{rx} = I_{rx}(s)$, $I_{ry} = I_{ry}(s)$, $U_s = U_s(s)$. The abovegiven equations and dependencies should be transformed in the way allowing to derive transforms I_{sx}, I_{sy} of controlled quantities and then to define the operational transmittances of DFM. Consideration of dependencies (9), (10) in equations (7), (8) results in system of equations with unknowns I_{sx}, I_{sy}. The transforms of stator current vector components are the solution of this system.

$$\begin{aligned} I_{sx} = & -\frac{L_m}{L_s} \cdot \frac{L_s^2 s^2 + L_s R_s s + L_s^2 \omega_s^2}{L_s^2 s^2 + 2L_s R_s s + L_s^2 \omega_s^2 + R_s^2} I_{rx} + \frac{L_m R_s \omega_s}{L_s^2 s^2 + 2L_s R_s s + L_s^2 \omega_s^2 + R_s^2} I_{ry} + \\ & + \frac{L_s s + R_s}{L_s^2 s^2 + 2L_s R_s s + L_s^2 \omega_s^2 + R_s^2} U_s , \end{aligned} \tag{11}$$

$$\begin{aligned} I_{sy} = & -\frac{L_m}{L_s} \cdot \frac{L_s^2 s^2 + L_s R_s s + L_s^2 \omega_s^2}{L_s^2 s^2 + 2L_s R_s s + L_s^2 \omega_s^2 + R_s^2} I_{ry} - \frac{L_m R_s \omega_s}{L_s^2 s^2 + 2L_s R_s s + L_s^2 \omega_s^2 + R_s^2} I_{rx} - \\ & - \frac{L_s \omega_s}{L_s^2 s^2 + 2L_s R_s s + L_s^2 \omega_s^2 + R_s^2} U_s . \end{aligned} \tag{12}$$

The number of parameters occurring in the abovegiven dependencies can be reduced if time-constant $T_s = L_s/R_s$ for stator winding is defined.

4. OPERATIONAL TRANSMITTANCES

According to Figure 1, the active power controller exerts influence on DFM by controlling variable i_{rxref}. The reactive power controller likewise exerts influence on DFM by controlling variable i_{ryref}. Therefore, the operational transmittance defined as

$$K(s) = \frac{I_{sx}}{I_{rx}} = \frac{I_{sy}}{I_{ry}} = -\frac{L_m}{L_s}\left(1 - \frac{T_s s + 1}{T_s^2 s^2 + 2T_s s + T_s^2 \omega_s^2 + 1}\right), \tag{13}$$

may be called as a leading transmittance whereas the transmittances determining the influence of other quantities – as disturbance transmittances

$$K'(s) = \frac{I_{sx}}{I_{ry}} = -\frac{I_{sy}}{I_{rx}} = \frac{L_m}{L_s} \cdot \frac{T_s \omega_s}{T_s^2 s^2 + 2T_s s + T_s^2 \omega_s^2 + 1}, \tag{14}$$

$$K_x''(s) = \frac{I_{sx}}{U_s} = \frac{1}{R_s} \cdot \frac{T_s s + 1}{T_s^2 s^2 + 2T_s s + T_s^2 \omega_s^2 + 1}, \tag{15}$$

$$K_y''(s) = \frac{I_{sy}}{U_s} = -\frac{1}{R_s} \cdot \frac{T_s \omega_s}{T_s^2 s^2 + 2T_s s + T_s^2 \omega_s^2 + 1}. \tag{16}$$

The significant influence of the grid voltage u_s on the controlled variables i_{sx}, i_{sy} as a result of relatively small value of resistance R_s may be concluded on the basis of the abovegiven dependencies (15), (16) whereas interactions of the controlled variables i_{sx}, i_{sy} and input quantities i_{ry}, i_{rx} in different axes of coordinate system x-y connected to the stator voltage vector are not large, according to the dependency (14).

5. TRANSIENT RESPONSES OF DFM

As it was mentioned in the Introduction, the components of rotor current vector cannot changing abruptly i.e. as a step function. It also concerns pulse-changes having character the delta function. Therefore, the following derivation of delta function $k(t)$ and step function $h(t)$ has mainly theoretical meaning.

However, changes of input quantities i_{rx}, i_{ry} caused by relatively high voltage occurring on terminals of rotor winding are much faster than changes of transient component of stator current and therefore, the obtained time dependencies are similar to the true ones being the response of DFM to a step-change of the reference components i_{rxref}, i_{ryref}.

Delta function responses

The derived operational transmittances were transformed to the form allowing finding the time-equivalents:

$$K(s) = -\frac{L_m}{L_s}\left(1 - \frac{T_s s + 1}{T_s^2 s^2 + 2T_s s + T_s^2 \omega_s^2 + 1}\right) = -\frac{L_m}{L_s}\left[1 - \frac{1}{T_s}\cdot\frac{s + 1/T_s}{(s + 1/T_s)^2 + \omega_s^2}\right], \quad (17)$$

$$K'(s) = \frac{L_m}{L_s}\cdot\frac{T_s\omega_s}{T_s^2 s^2 + 2T_s s + T_s^2\omega_s^2 + 1} = \frac{L_m}{L_s}\cdot\frac{1}{T_s}\cdot\frac{\omega_s}{(s + 1/T_s)^2 + \omega_s^2}, \quad (18)$$

$$K_x''(s) = \frac{1}{R_s}\cdot\frac{T_s s + 1}{T_s^2 s^2 + 2T_s s + T_s^2\omega_s^2 + 1} = \frac{1}{L_s}\cdot\frac{s + 1/T_s}{(s + 1/T_s)^2 + \omega_s^2}, \quad (19)$$

$$K_y''(s) = -\frac{1}{R_s}\cdot\frac{T_s\omega_s}{T_s^2 s^2 + 2T_s s + T_s^2\omega_s^2 + 1} = -\frac{1}{L_s}\cdot\frac{\omega_s}{(s + 1/T_s)^2 + \omega_s^2}, \quad (20)$$

Considering the unit area of delta function $\delta(t)$ the time-equivalents for the abovegiven operational transmittances are as follows:

$$k(t) = -\frac{L_m}{L_s}\left[\delta(t) - \frac{1}{T_s}\exp\left(-\frac{t}{T_s}\right)\cos\omega_s t\right], \quad (21)$$

$$k'(t) = \frac{L_m}{L_s}\cdot\frac{1}{T_s}\exp\left(-\frac{t}{T_s}\right)\sin\omega_s t, \quad (22)$$

$$k_x''(t) = \frac{1}{L_s}\exp\left(-\frac{t}{T_s}\right)\cos\omega_s t, \quad (23)$$

$$k_y''(t) = -\frac{1}{L_s}\exp\left(-\frac{t}{T_s}\right)\sin\omega_s t. \quad (24)$$

Each obtained time dependency for $t \geq 0$ is the DFM response to input quantity changing as a delta function. It should be noted that the DFM responses (23), (24) to the grid voltage u_s changing as a delta function formulate equations of harmonic oscillator. The initial magnitude of weak damped oscillations can be large for typical values of stator self-inductance L_s (2…3) expressed as a dimensionless quantity. A short-lived disappearance of the grid voltage occurring as a result of damage of the power system may be considered as a pulse-change of the voltage u_s. The oscillatory transient component included in the equation (21) as well as the equation (22) also formulate harmonic oscillator but with much smaller magnitude of oscillation (typical values of resistance R_s expressed as a dimensionless quantity are about 0,02…0,05). Thus, the influence of input quantities i_{rx}, i_{ry} on magnitude of disappearing oscillations of controlled variables i_{sx}, i_{sy} is much smaller than influence of voltage u_s. The problems of oscillations and their dampening were discussed in papers [4] and [5], respectively.

Step function responses

The transform of DFM response to the input quantity changing as a unit step function 1(*t*) may be obtained as follows

$$H(s) = K(s) \cdot \frac{1}{s} = -\frac{L_m}{L_s}\left(\frac{1}{s} - \frac{T_s s + 1}{T_s^2 s^2 + 2T_s s + T_s^2 \omega_s^2 + 1} \cdot \frac{1}{s}\right) =$$
$$= -\frac{L_m}{L_s}\left\{\frac{1}{s} - \frac{1}{T_s^2 \omega_s^2 + 1}\left[\frac{1}{s} - \frac{s + 1/T_s}{(s + 1/T_s)^2 + \omega_s^2} + T_s \omega_s \frac{\omega_s}{(s + 1/T_s)^2 + \omega_s^2}\right]\right\}, \tag{25}$$

Assuming: $c^2 = \left(T_s^2 \omega_s^2 + 1\right)^{-1}$ in the abovegiven dependency:

$$h(t) = -\frac{L_m}{L_s}\left\{1 - c^2\left[1 + \exp\left(-\frac{t}{T_s}\right)\left(-\cos \omega_s t + T_s \omega_s \sin \omega_s t\right)\right]\right\} =$$
$$= -\frac{L_m}{L_s}\left\{1 - c^2 + c \exp\left(-\frac{t}{T_s}\right)\cos\left(\omega_s t + arctg\,\omega_s T_s\right)\right\}. \tag{26}$$

The following simplifications were assumed in the abovegiven dependencies for typical relative values of time-constant T_s:

a) $T_s\omega_s = X_s/R_s >> 1$, where the stator reactance X_s is given as follows: $X_s = L_s\omega_s$
b) $arctg\omega_s T_s \approx \pi/2$
c) $c^2 \approx 0$.

Considering the abovementioned simplifications:

$$h(t) \approx -\frac{L_m}{L_s}\left[1 - \frac{R_s}{X_s}\exp\left(-\frac{t}{T_s}\right)\sin\omega_s t\right], \qquad \text{for} \quad t \geq 0 \tag{27}$$

The step function response (27) corresponding to the leading transmittance includes the unit step function and the oscillatory transient component with a small initial magnitude. The step function responses are likewise derived for disturbances:

$$h'(t) = \frac{L_m}{L_s}\left[c' - c\exp\left(-\frac{t}{T_s}\right)\sin(\omega_s t + arctg\omega_s T_s)\right] \approx$$
$$\approx \frac{L_m}{L_s}\cdot\frac{R_s}{X_s}\left[1 - \exp\left(-\frac{t}{T_s}\right)\cos\omega_s t\right], \qquad \text{where} \quad c' = \frac{T_s\omega_s}{1 + T_s^2\omega_s^2} \tag{28}$$

$$h_x''(t) = \frac{1}{R_s}\left[c^2 - c\exp\left(-\frac{t}{T_s}\right)\cos(\omega_s t + arctg\omega_s T_s)\right] \approx \frac{1}{X_s}\exp\left(-\frac{t}{T_s}\right)\sin\omega_s t \tag{29}$$

$$h_y''(t) = \frac{1}{R_s}\left[c' - c\exp\left(-\frac{t}{T_s}\right)\sin(\omega_s t + arctg\omega_s T_s)\right] \approx -\frac{1}{X_s}\left[1 - \exp\left(-\frac{t}{T_s}\right)\cos\omega_s t\right] \tag{30}$$

Considering any step-change of rotor current or stator voltage, the abovegiven dependencies should include the magnitude of this step-change. For example if $u_s = U_{sn}\cdot 1(t)$ the rough step function responses are as follows:

$$h_x''(t) \approx -\frac{U_{sn}}{X_s}\exp\left(-\frac{t}{T_s}\right)\sin\omega_s t \tag{31}$$

$$h_y''(t) \approx -\frac{U_{sn}}{X_s}\left[1 - \exp\left(-\frac{t}{T_s}\right)\cos\omega_s t\right] \tag{32}$$

The DFM transient response (32) to the step-change of grid voltage u_s from zero to the rated value includes oscillatory transient component and steady component – magnetizing current. This dependency deals with stator current component i_{sy}. In accordance with dependencies (31) and (32), the initial magnitude of stator current oscillations determined by step-change of voltage u_s from zero to the rated value equals to the magnetizing current.

6. CONCLUSIONS

The derived operational transmittances of current controlled DFM allow for the penetrating analysis of controlled structure and as a consequence it allows formulating the following conclusions:

1. The components of DFM stator current vector expressed in the coordinate system connected to the stator voltage vector may be considered as controlled variables instead of active and reactive power because of high stability of grid voltage and frequency.
2. The input quantities i.e. components of rotor current vector cannot change as a step function. However, the rapid changes of rotor current are possible as a result of the relatively high voltage occurring on terminals of rotor winding and application of on-off controllers for phase currents of rotor. Then, the properties of current controlled DFM may be evaluated on the basis of transient responses i.e. delta function response and step function response.
3. There is a strong impact of grid voltage on the controlled variables as a result of small value of stator resistance in the considered DFM control system whereas the interactions of controlled variables and input quantities in different axes of coordinate system x-y connected to the stator voltage vector are not large. It means that the step-change or delta-change of grid voltage (disappearance of voltage in damaged power system) cause the large-magnitude oscillations of both components of stator current.

LITERATURE

1. Arsudis D., Vollstedt W.: *Sensorless power control of the DFM AC machine with nearly sinusoidal line current*, EPE – European Conference on Power Electronics and Applications, Aachen – Germany, 1989, pp. 899-904.
2. Bogalecka E.: *Zagadnienia sterowania maszyną dwustronnie zasilaną pracującą jako prądnica w systemie elektroenergetycznym*, Prace Naukowe WSM w Gdyni, Gdynia 1997.

3. Krzemiński Z., Popenda A., Ladach P., Melcer M.: *Sensorless control system of double fed induction machine with predictive current controller*, EPE – European Conference on Power Electronics and Applications, Graz – Austria, 2001, pp. P1-P9.
4. Popenda A.: *Decoupling control of doubly fed induction machine without rotor position measurement*, PCIM – Conference on Power Electronics / Intelligent Motion, Nuremberg – Germany, 1995, pp. 561-571.
5. Popenda A.: *Practical realization of damping feedback in DFM control system*, PCIM – Conference on Power Electronics / Intelligent Motion, Nuremberg – Germany, 2001.
6. Popenda A.: *Analiza i badanie bezczujnikowego układu sterowania pracą prądnicową maszyny dwustronnie zasilanej*, Gospodarka Paliwami i Energią, 2004, nr 9-10, pp. 24-27.
7. Popenda A.: *The DFM control system based on PLL*, Communications, Scientific Letters of the University of Žilina, 2009, Vol. 11, 1/2009, pp. 55-59.
8. Tnani S., et alia: *Novel control strategy of double-fed induction machines*, EPE – European Conference on Power Electronics and Applications, Seville, 1996, pp.1.553-558

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ANALIZA WPŁYWU WYMUSZEŃ I ZAKŁÓCEŃ NA PRACĘ GENERATOROWĄ MASZYNY DWUSTRONNIE ZASILANEJ

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STRESZCZENIE *W pracy zaprezentowano opracowaną przez autora strategię sterowania pracą generatorową maszyny dwustronnie zasilanej (MDZ). Zaprezentowano przy tym przebiegi czasowe zmierzone na stanowisku laboratoryjnym. Podano równania różniczkowe oraz zależności strumieniowo-prądowe opisujące MDZ sterowaną prądowo, jak również przekształcenie Laplace'a przedstawionych równań. Zdefiniowano transmitancje operatorowe dla wielkości wymuszających i zakłóceń. Określono odpowiedzi czasowe MDZ na wymuszenia w postaci delty Diraca i skoku jednostkowego na podstawie zdefiniowanych transmitancji operatorowych. Wyprowadzone transmitancje operatorowe pozwoliły na wnikliwą analizę struktury sterowania oraz sformułowanie szczegółowych wniosków.*