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Input signals disturbances of controllers in a field-oriented control system with a slip-ring motor and their impact on rotational speed

In the article the authors investigated a field-oriented control system with a slip-ring shaded-pole motor. Additive disturbing signals were introduced into input signals of the control system controllers. The rotational speed waveform was observed as an output of the system. Disturbing signals were sine-wave signals with known frequency. The field-oriented control system was parametrically optimized with the use of an evolutionary algorithm. The testing was carried out with the use of the MATLAB/Simulink software.

Keywords: *slip-ring motor, field-oriented control, distortion, sine wave*

1. INTRODUCTION

The rotational speed of modern control systems is controlled by vector controllers [2, 3, 4, 7, 8, 10, 12]. These controllers offer higher dynamics of the system than scalar controllers. Nowadays, the following vector control methods are used: direct torque control (DTC) [7, 8, 10] and field-oriented control (FOC) [3, 4, 5, 7, 8, 10]. The research described in the article is focused on a FOC system. This system has a number of variations. For further analysis the authors selected a direct field-oriented control (DFOC) system with PI linear controllers (two current controllers, magnetic torque controller, electromagnetic flux controller, and rotational speed controller). In the process of evolutionary parametrical optimization 10 parameters of the controllers were calculated (5 PI controllers boosting parameters and 5 coefficients dependent on integral action times of PI controllers in a control loop) [3, 4, 5].

2. TESTED CONTROL SYSTEM

The DFOC system is presented in Fig. 1.

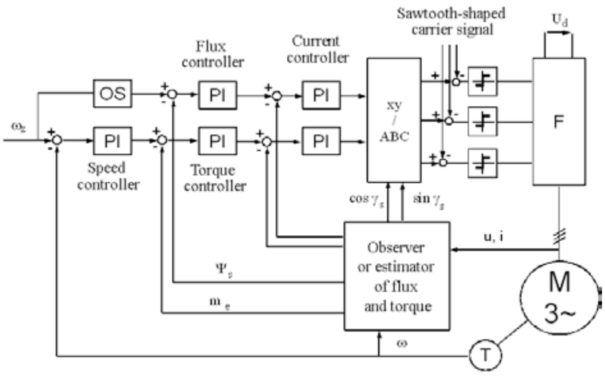

Fig. 1. Direct field-oriented control system (DFOC) [3, 4, 5, 7, 8, 10]

Symbols in the figure stand for the following:

ω_s – set rotational speed of the controlled induction motor,
OS – electromagnetic flux weakening module, F – inverter,
PI – linear PI controllers
U_d – reference voltage of the F inverter,
u, i – voltages and phase currents of the induction motor,
ω – current value of the slip-ring motor rotational speed,
cos γ_s, sin γ_s – cosinus and sinus of the angle needed for the transformation from the xy to the ABC system,

Ψ_s – estimated value of the magnetic flux of the motor,
m_e – estimated value of the electromagnetic torque of the motor,
M – low power induction motor,
T – tachogenerator.

What is characteristic of this system is the fact that the sinus and cosinus of the γ_s angle are calculated based on the measurements of phase currents and voltages and based on the mathematical model of a slip-ring shaded-pole motor (the mathematical model parameters of the this motor were calculated earlier by a different evolutionary algorithm [7, 8, 10]). The process of parametric optimization [11] was conducted with the use of an evolutionary algorithm. The calculations of parameters required for the controllers were made [3, 4, 5]. The results of these calculations can be seen in Table 1.

Table 1.
Calculated settings of PI controllers of the DFOC system, with the use of an evolutionary algorithm

$K_{p,1}$	$K_{p,2}$	$K_{p,3}$	$K_{p,4}$	$K_{p,5}$	$T_{p,1}$	$T_{p,2}$	$T_{p,3}$	$T_{p,4}$	$T_{p,5}$	F_t [rotations /min]
2.00	5.00	5.00	9.00	15.0	0.40	0.30	2.00	0.10	0.10	$2.27*10^5$

Symbols used in the table:
$K_{p,1}$ – boosting of the current controller in the control loop of the magnetic flux,
$K_{p,2}$ – boosting of the current controller in the control loop of the speed controller,
$K_{p,3}$ – boosting of the magnetic flux controller,
$K_{p,4}$ – boosting of the electromagnetic torque controller,
$K_{p,5}$ – boosting of the rotational speed controller,
$T_{p,1}$; $T_{p,2}$; $T_{p,3}$; $T_{p,4}$; $T_{p,5}$ – coefficients dependent on integral action times of the controllers in the control loop, as above.
F – quality criterion which is a total of modules of differences in the value of rotational speed generated on the basis of current settings of controllers and the value of rotational speed set to the control system in discrete moments of time (simulation time step – 0.001 s, simulation time – 5 s).

The processes set for the described control system were the following:
- step change of rotational speed which was to be executed by the DFOC system,
- step change of load torque after the rotational speed sets in.

Ideal waveforms of rotational speed (Fig. 2): the set process (b) and the process executed by the control system (a).

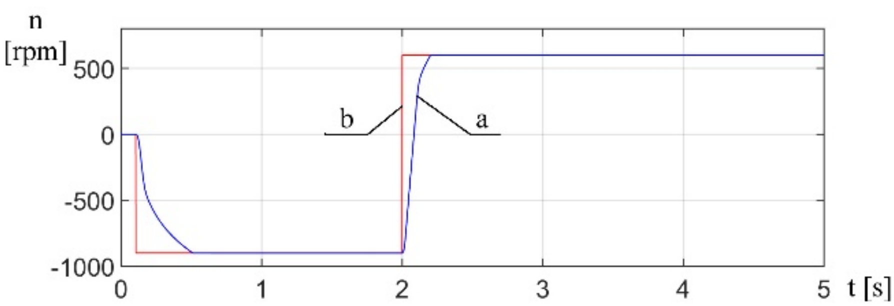

Fig. 2. Waveforms of rotational speed: the set process (b) and the process executed by the control system based on the calculated parameters of PI controllers (a)

So far the calculations have been focused on proper and sub-optimal calculation of settings of PI controllers for different versions of the FOC system and for different motors (squirrel-cage, slip-ring shaded-pole motors) [1, 2, 3, 4, 5, 9, 10]. The impact of different evolutionary algorithm parameters on the obtained evolutionary results was investigated. Further in the work the authors tested the impact of sine-wave disturbances introduced to input signals of a control system on output waveforms (rotational speed waveform and electromagnetic torque waveform). These tests were based on simulations carried out with the use of MATLAB/Simulink.

3. TESTING DFOC RESISTANCE TO SINE-WAVE DISTURBANCES

A block diagram of each linear controller of the tested control system can be seen in Fig. 3. Here an extra input was assumed through which a sine-wave disturbing signal entered. This signal was then added to the input signal of a linear controller. The impact of such disturbances on the system dynamics [6] (Fig. 3) was tested with the use of a known-amplitude sine and frequency as an additive component of the controller input signal.

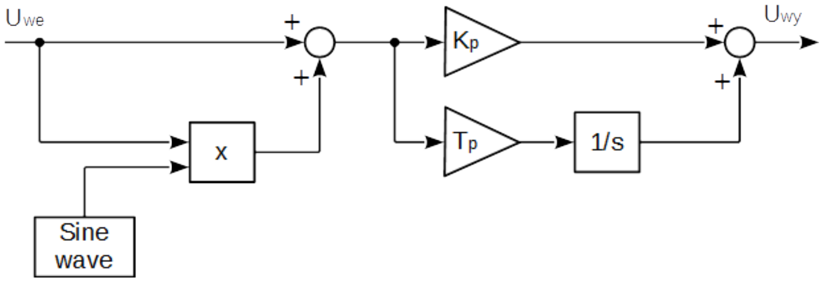

Fig. 3. Diagram of the controller with sine-wave disturbances in the input signal:
U_{we} – input signal of the controller; U_{wy} – output signal of the controller: K_p – controller boosting;
T_p – coefficient dependent on integral action times

The system was tested in the following manner: an additive sine-wave disturbing signal was introduced to all controllers simultaneously, then rotational speed waveform and electromagnetic torque waveform were observed,

The output measure was the mean absolute percentage error (MAPE) expressed by a commonly known formula [3, 5]:

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{x_{zi} = x_i}{x_{zi}}\right|100\% \qquad (1)$$

where:

MAPE – value of mean absolute percentage error,

n – number of moments of time in which the values of errors were calculated (n = 5000, Δt = 0.001 s),

x_{zi} – set value of rotational speed measured in the successive i-th moment of time,

x_i – output value of the FOC control system in the successive moment of time *i*.

The calculation results are presented in Table 2.

Selected waveforms of rotational speed to be conducted by the DFOC control system with a slip-ring shaded-pole motor can be seen in Fig. 5-7.

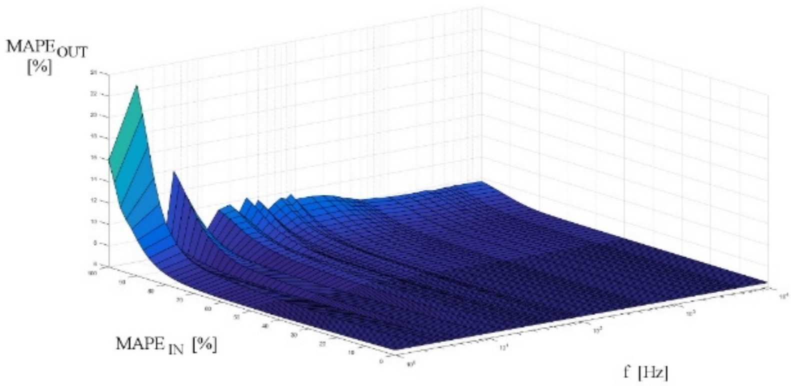

Fig. 4. Dependency of the parameters of an additive sine-wave disturbing signal (frequency f and the contents of this disturbing signal in the basic signal $MAPE_{IN}$) on the level of disturbances in the output signal $MAPE_{OUT}$

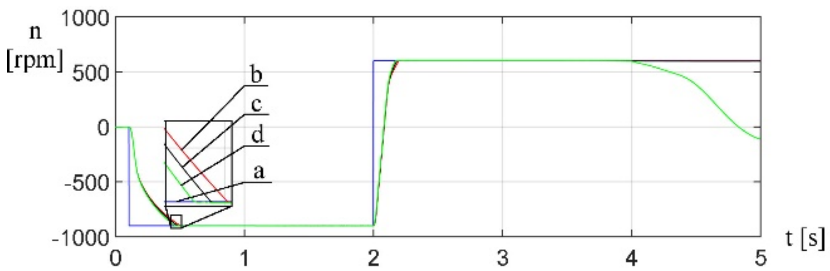

Fig. 5. Response of a control system with introduced additive disturbing signals for 1Hz on the level b – 10%; c – 50%; d – 100% for the set step of rotational speed and load step in the 4th second of simulation – a

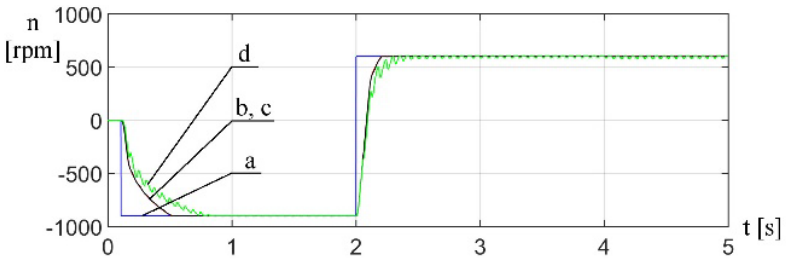

Fig. 6. Response of a control system with introduced additive disturbing signals for 1Hz on the level b – 10%; c – 50%; d – 100% for the set step of rotational speed and load step in the 4th second of simulation – a

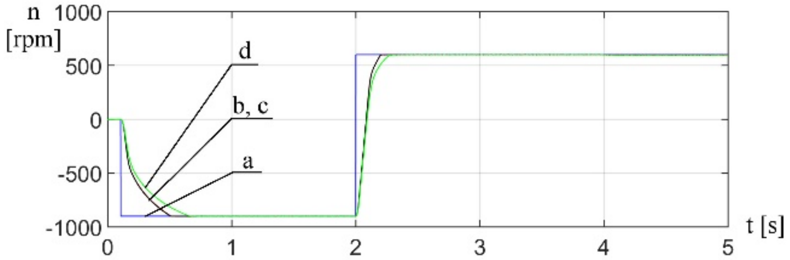

Fig. 7. Response of a control system with introduced additive disturbing signals for 1kHz on the level b – 10%; c – 50%; d – 100% for the set step of rotational speed and load step in the 4th second of simulation – a

4. CONCLUSIONS

A non-zero average value of the absolute percentage error of the output quantity of the system with no introduced disturbances results from the fact (Fig. 2) that the set value of the rotational speed is not equal to the value of the rotational speed conducted by the control system. In the case of a control system with no disturbing signals introduced, there is a minimal overshoot and the control time does not exceed 0.5 s. In the 4th second the system was loaded with an external torque and the system responded with immediate stabilization of rotations. After the disturbances were introduced to internal signals of the control system, the system behaved similarly up to the disturbance level of 50%. Above this level of the $MAPE_{IN}$ value, the system was unstable and there were visible vibrations of the rotational speed. This effect was characteristic of low frequency values, up to 1 kHz. The lower was the frequency of additive disturbing signals, the more unstable was the system (Fig. 4, 5). Therefore it is possible to deduct the following: the DFOC system tolerates sine-wave additive disturbing signals up to the value of their 50% content and is stable. Once this boundary is crossed, the machines will wear out more quickly and their operations will be unexpected.

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