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SYNTHESIS OF A FRACTIONAL-ORDER $PI^{\lambda}D^{\mu}$-CONTROLLER FOR A CLOSED SYSTEM OF SWITCHED RELUCTANCE MOTOR CONTROL

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Обґрунтовано актуальність створення високоякісних систем управління для електроприводів з вентильно-індукторним двигуном (SRM). Використовуючи методи математичного моделювання були отримані перехідні характеристики процесу пуску SRM з різними моментами інерції. На основі аналізу отриманих перехідних характеристик показані особливості процесу пуску SRM, обумовлені динамічною зміною параметрів SRM в процесі його пуску.

Показана низька точність ідентифікації SRM з використанням дрібно-раціональної функції класу rat34, коефіцієнт регресії отриманої моделі склав 85 %. На основі аналізу перехідних характеристик процесу пуску SRM була висунута гіпотеза про можливість ідентифікації SRM дробномірною передавальною функцією. Використовуючи методи математичного моделювання були отримані перехідні характеристики процесу пуску SRM з різними моментами інерції. За допомогою FOMCON MATLAB Toolbox виконана ідентифікація процесу пуску SRM дробномірною передавальною функцією другого порядку. Коефіцієнт регресії отриманої моделі склав 93–96 %.

Для отриманих дробномірних передавальних функцій реалізований метод синтезу дробномірного $PI^{\lambda}D^{\mu}$-регулятора, оптимізованого по мінімуму інтегральної квадратичної помилки (integral square error) перехідної функції замкнутої системи керування дробномірним об'єктом управління. Для синтезу $PI^{\lambda}D^{\mu}$-регулятора був застосований FOMCON MATLAB Toolbox.

Виконано порівняльний аналіз процесів запуску SRM в розімкнутої системі управління, а також запуску в замкнутій системі управління з класичним PID-регулятором цілого порядку і з дробномірним $PI^{\lambda}D^{\mu}$-регулятором. Використання дробномірного $PI^{\lambda}D^{\mu}$-регулятора в порівнянні з класичним регулятором цілого порядку дозволяє знизити перерегулювання з 13.3 % до 2.64 %, підвищити швидкодію в замкнутій САУ, час регулювання знизилвся з 1.48 с до 0.53 с. Отримані результати можуть бути використані для підвищення якості роботи замкнутих систем управління кутовою швидкістю SRM

Ключові слова: вентильно-індукторний двигун, ідентифікація, дробномірна передавальна функція, якість управління, дробномірний регулятор

1. Introduction

Considering simplicity of design, high reliability, power and tuning characteristics of switched reluctance motors (SRM), they are among most promising types of modern electric motors for use in energy-intensive industries [1].

They have a series of advantages in comparison with other controlled AC electric motors. SRM have higher manufacturability, are simpler in maintenance and repair and cheaper. These motors have high energy efficiency and higher resistance to overloads compared with asynchronous and synchronous motors. Comparative analysis of asynchronous motors and synchronous motors with permanent magnets and SRM of NEMA 184T standard size was made in [2] (Table 1).

Table 1

Comparative analysis of performance characteristics of electric motors of various types.

Characteristics	Asynchronous motor	Synchronous motor with permanent magnets	SRM
Rotor weight, Lbs.	18.80	15.20	14.80
Stator weight, Lbs.	51.20	54.20	45.30
Total weight, Lbs.	70.00	69.40	60.10
Performance factor, %	90	94	92
Cost of materials, USD	59.75	384.00	47.10
Torque/USD/ Lbs.	0.57	0.25	0.148

This is important for high-duty equipment (mining, oil and gas production industry, processing industry, oil and gas pumping, heat and water supply, transport and defense industries, etc.) [3].

Therefore, the problem of creation of high-quality and relatively simple control systems for electric drives with SRMs is becoming increasingly important and relevant. However, solution of this problem is hindered by essentially nonlinear characteristics of SRM which makes it difficult to identify SRM as a control object and subsequent synthesis of closed control systems.

The study results can be used to develop methods for identifying the SRM transfer function, simplifying design and improving quality of operation of closed SRM control systems.

2. Literature review and problem statement

Japanese Nidec Corporation is the leader in development and implementation of small- and medium-power SRM electric drives. Total sales in 2014 fiscal year amounted to about USD10 billion [4–6].

NMC commercially produces under U.S. Motors brand a line of industrial small- and medium-power (20–420 hp or 14.7–308.7 kW) SRMs with nominal speed of 1,000, 1,800, 3,600 and 4,500 rpm and overload capacity of 110, 150 and 250 % [6]. Nidec SR Drives Ltd. (NSRD) and Nidec SR Drives Manufacturing Ltd. (NSRM) in the UK have an impressive experience of using SRM technology in mining and power industries.

Comprehensive introduction of 40 to 250 kW SRM into conveyors, mixing plants and grab cranes under license from NSRD was realized by Drax Power Ltd. (Selby, North Yorkshire). The Jeffrey Diamond Co. introduced 35 to 300 kW SRM drives of dust-ignition-proof design with liquid cooling on belt and bottom-hole conveyors and pumps in coal mines [7].

Weir Specialty Pumps Ltd. (Salt Lake City, Utah, USA) has developed high-pressure VSR pumps to supply water and fuel to gas turbine generators in which 74 and 129 kW SRMs were used under NSRD license [8].

Le Tourneau Technologies, Inc. (USA) is engaged in manufacture of loaders with 1,050 to 2,300 hp diesel engines equipped with SRM based electromechanical transmission [9].

In recent years, there has also been a steady trend towards increase in number of solutions for traction electric drives for hybrid and electric cars based on SRM technology. Optimized electric Drivetrain by INtegration (ODIN) project is being implemented in the European Union [10]. This project is aimed at creation of an electric car based on SRM technology.

The pace of development and implementation of SRM electric drives at Russian mining enterprises is considered in [3]. For example, since 2012, VIEM JSC has developed and implemented projects for using SRMs at enterprises of Siberian Coal Energy Co. with total power of 22.5 MW. The project of 1,250 kW, 900 rpm SRM use in KLM-4500 main belt conveyor at Beriozovsky open-pit mine in Krasnoyarsky Kray has been realized. 1,250 kW 630 rpm SRMs have been developed to replace DC motors for main mechanisms of traction, lifting and rotating in ESh 20–90 mining excavator at Tugnuysky open-pit mine. There is also an experience of introducing 500 kW, 850 rpm SRMs for traction electric drive of 136-ton BelAZ-75131 dump truck. The above examples demonstrate expansion of the SRM application scope.

Existing scientific and technical studies propose various approaches to the design of SRM electric drive control systems.

In [11], TSE nonlinear control scheme with prediction based on the control object state equations is proposed for SRM. Based on TSE and predictive control theory, a non-linear intelligent regulator has been developed for the SRM control system. However, predictive control requires additional time for verification of the resulting model which limits scope of control objects with constant or slowly changing parameters.

PSO particle swarm method was used in [12] to determine optimal parameters of the proportional-integral (PI) controller as well as turn-on/turn-off angles to minimize the SRM torque pulsations. The proposed optimization method has a slow convergence which reduces its scope of use in processes with slowly varying parameters.

It is indicated in [13, 14] that SRM has essentially nonlinear characteristics, and two SRM control methods were considered that were successfully used in other intelligent modeling and control applications. Both a system of neuro-fuzzy locally linear models and neural computing methods are used to control SRM. The results indicate applicability of the proposed methods in intelligent control of this essentially nonlinear system. However, this approach requires significant computational resources, both at the stage of neural network training and directly in the control process which increases cost of the control device.

Methods for identifying winding parameters and motor condition are considered in [15, 16] and a method for identifying SRM by an SRM equivalent DC motor with sequential excitation and appropriate control is described in [17]. The proposed method neither reduces complexity of the control object nor enables obtaining of required settings in the control system at significant alteration of electric drive operating modes.

Known SRM control methods are quite complex and require substantial computational power of embedded control devices for their practical implementation.

At present, methods of controlling nonlinear objects based on their representation by fractional-order differential equations [23] have gained significant development.

Ever increasing interest paid to applications of fractional calculus has necessitated development and study of special numerical methods for solving fractional-order differential equations (FDE). Finding analytical solutions for FDE is indeed more difficult than solving ordinary differential equations (ODE) and it is possible to provide numerical approximation of solution in most cases [18, 19]. Numerical methods for solving FDE problems are widely studied.

FOMCON MATLAB Toolbox, a freely distributed library that solves the main problems arising in identification of FDE systems is one of the most complete and functional applications for solving FDE problems with ability to analyze control systems with fractional-order regulators and control objects [20]. This library partially includes elements of other popular libraries dedicated to working with FDE objects: CRONE [21] and NINTEGER [22].

Implementation of high-speed $PI^{\lambda}D^{\mu}$ controllers is a complicated technical problem. Application of discrete Grunwald-Letnikov or Riemann-Liouville forms which are infinite series theoretically involves allocation of infinite volumes of memory and requires a large number of arithmetic operations to be performed during the processor quantization period. Problems of synthesis of systems for controlling objects with a fractional order of astatism were considered and methods for technical implementation of high-speed fractional-order integrating-differentiating regulators were developed in [23]. They enable technical implementation of the proposed method.

Therefore, development of methods for identification of nonlinear objects using fractional-order transfer functions in relation to SRM is promising since it will improve quality of SRM control.

3. The aim and objectives of the study

The study objective is to substantiate the possibility of SRM identification by a fractional-order transfer function and synthesis of a fractional-order $PI^{\lambda}D^{\mu}$ controller which will improve quality of SRM control.

To achieve this objective, it is necessary to solve the following tasks:

– determine transient characteristics of the SRM;

– determine a preferred method for SRM identification by comparing indicators of identification quality by fractionally rational transfer functions of integral order and identification by fractional-order transfer functions;

– synthesize a fractional-order $PI^{\lambda}D^{\mu}$ controller of SRM, evaluate regulation parameters in a closed control system with the obtained regulator.

4. Registration of SRM transient characteristics in a mathematical model

To study characteristics of transient characteristics of SRM, a method of mathematical modeling of dynamic processes occurring during SRM turn-on was used with the help of the MATLAB SimPower library. This library contains a sufficient number of predefined variants of technical implementation of SRM with various stator and rotor tooth ratios and nominal powers. The obtained results are shown in Fig. 2.

The graphs presented in Fig. 2 are a transient characteristic of the SRM, a response to a surge in the supply voltage applied.

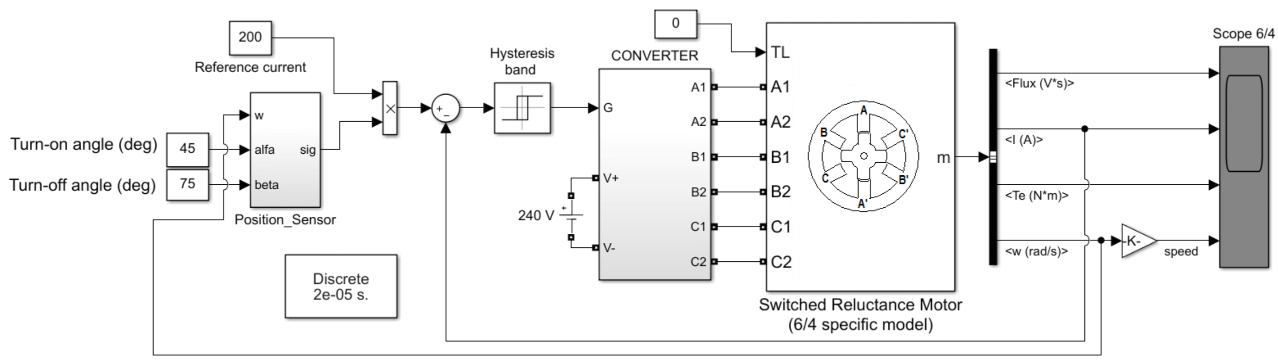

Fig. 1. Implementation of the SRM mathematical model using the SimPower library of the Matlab/Simulink program

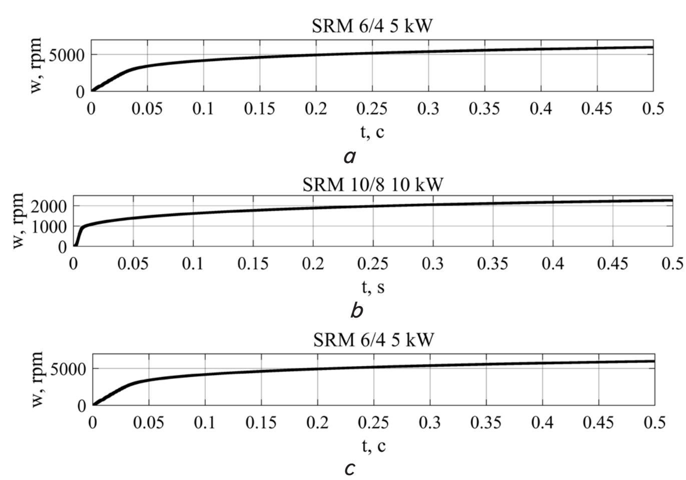

Fig. 2. SRM turn-on transients for various SRM designs and power obtained in a mathematical model. Tooth ratio: *a* — 6/4, power: 5 kW; tooth ratio: *b* — 10/8, power: 10 kW; tooth ratio: *c* — 6/4, power: 75 kW

As the visual analysis of the results of mathematical modeling shows, the nature of angular velocity change during the SRM turn-on is of a qualitatively similar nature, independent of the SRM power and value of tooth ratio. The SRM speed change in time, although being aperiodic in character, differs radically from the exponential form: it is more intensive at the initial stage and more extended at the second stage. Non-linearity of the SRM characteristics is caused by dynamic change of the SRM parameters when angular velocity changes during the turn-on process.

Further, a 5 kW SRM with a stator to rotor tooth ratio of 6/4 was taken as the study object. To simulate various technological conditions of operation, variants of the SRM turn-on mode with two different values of the moment of inertia were considered. Variants of transient characteristics of the study object are shown in Fig. 3.

Considering the data obtained as a transient function brought about by the applied supply voltage, we can proceed to identification of SRM as a control object via the Supply Voltage – Rotor Velocity channel.

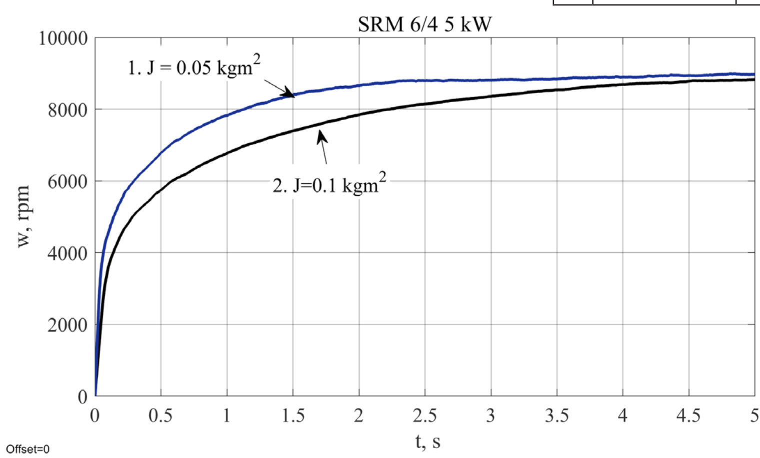

Fig. 3. Transition characteristics of turn-on of the 5 kW SRM, 6/4, with different values of the moment of inertia of the electric drive

5. Identification of SRM by fractionally rational transfer functions of integer order

The System Identification Toolbox (SIT) of the Matlab software was used to identify SRM and determine the transfer function via the Supply Voltage - Rotor Velocity channel.

The SIT is designed to synthesize linear and non-linear models using measured data at the input and output of an identification object. The identified system can be represented as a black box for estimating parameters of a user-defined model. The SIT offers a variety of identification methods: maximum likelihood, minimization of forecast error, system subset identification and others.

When identifying the SRM according to the transient characteristics obtained in Section 4, fractionally rational functions of rat23 and rat34 classes were used as a mathematical model. Regression coefficient R served as an indicator of conformity of the used model and the source data. The lower limit of numerical value of the regression coefficient signaling unsatisfactory conformity of the model used and the source data was assumed to be R_{MIN}=80 %. As a result of processing the source data presented in Fig. 3, numerical coefficients of polynomials of the numerator and the denominator were obtained for various variants of the SRM transfer functions and the corresponding regression coefficients, Table 2.

Table 2

Variants of identification of transient characteristics of turn-on of SRMs with various moments of inertia

No.	SRM moment of inertia	Transfer function	Regression coefficient R, %
1	J=0.05 kg·m^2	$\frac{149.8s^2+3e^5s+1.11e^6}{s^3+616.7s^2+1.98e^4s+3.72e^4}$	91.42
2	J=0.05 kg·m^2	$\frac{252.2.8s^3+8.07e^4s^2+1.09e^6s+2.13e^6}{s^4+153.8s^3+7040s^2+5.56e^4s+7.02e^4}$	98.38
3	J=0.1 kg·m^2	$\frac{51.02s^2+3{,}04e^4s+8.53e^4}{s^3+134.6s^2+2429.5s+2962.2}$	65.8
4	J=0.1 kg·m^2	$\frac{127s^3+1.866e^4s^2+2.137e^5s+3.069e^6}{s^4+71.462s^3+1946s^2+1.197e^4s+1.038e^4}$	85.62

It can be seen from the above data that at moment of inertia J=0.1 kg·m^2, SRM modeling by the transfer function of rat32 class is performed with regression coefficient R=65.8 %<R_{MIN}.

Thus, a sufficient convergence of the results in the entire studied range of the SRM moments of inertia can be obtained by identifying a fractionally rational transfer function of the rat34 class which has three zeros and four poles. The high order of the SRM transfer function and low accuracy of identification may cause poor quality control.

6. SRM identification by means of fractional-order transfer functions

An alternative way to identification of nonlinear dynamic objects by means of a transition function of a complex shape (Fig. 3) consists in the use of the apparatus of the fractional-order differential equation (FDE) and representation of control objects by means of corresponding transfer functions.

Fractional differential calculus is a generalization of operations of integration and differentiation by non-integer order operator ${}_aD_t^\alpha$ where a and t define limits of the operation, and α sets fractional order of the operation as follows:

$$ {}_aD_t^\alpha=\begin{cases}\dfrac{d^\alpha}{dt^\alpha}, & \Re(\alpha)>0,\\ 1, & \Re(\alpha)=0,\\ \int\limits_a^t (dt)^{-\alpha}, & \Re(\alpha)>0,\end{cases} \qquad (1)$$

where it is assumed that α∈ℝ but may take a complex value [24]. There are several generally accepted definitions of a fractional-order differential, for example,

– Riemann-Liouville definition [25]:

$$ {}_aD_t^{\alpha} = \frac{1}{\Gamma(m-\alpha)} \left(\frac{d}{dt}\right)^m \int_a^t \frac{f(\tau)}{(t-\tau)^{\alpha-m+1}} dt, \tag{2} $$

for $m-1<\alpha<m$, $m\in\mathbb{N}$ where $\Gamma(\cdot)$ is the Euler gamma function;

– alternative Grunwald-Letnikov definition [25]:

$$ {}_aD_t^{\alpha} = \lim_{h\to 0} \frac{1}{h^a} \sum_{j=0}^{\left[\frac{t-a}{h}\right]} (-1)^j \binom{\alpha}{j} f(t-jh), \tag{3} $$

where $[\cdot]$ symbol denotes operation of taking the integer part.

Laplace transform of the α-th derivative of the signal $x(t)$ where $\alpha\in\mathbb{R}_+$ (at zero initial conditions) is given by the formula:

$$ L\left(D^{\alpha}x(t)\right) = s^{\alpha}X(s). \tag{4} $$

Fig. 4 shows transition functions for aperiodic (*a*), and oscillatory (*b*) fractional-order links calculated using the FOMCON MATLAB Toolbox.

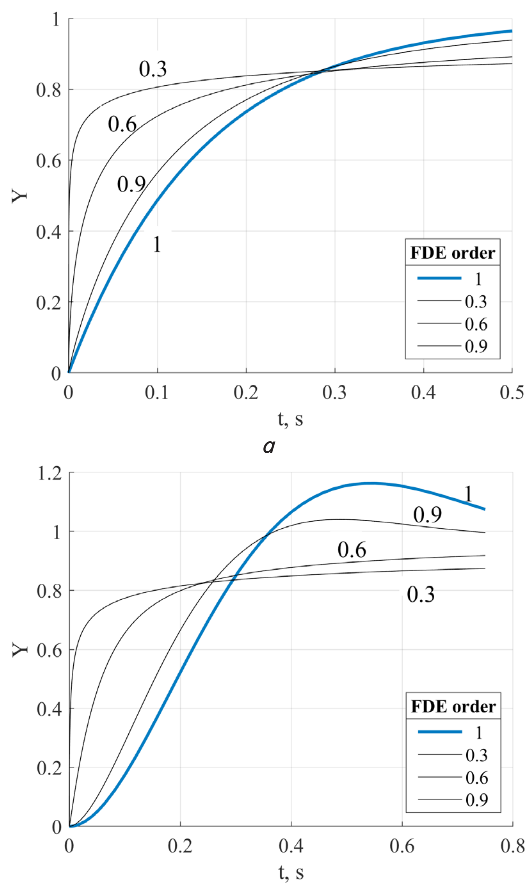

Fig. 4. Transition functions for fractional-order links of various orders: *a* – aperiodic; *b* – oscillatory

The obtained transient characteristics of elementary fractional links are qualitatively very close to real transient characteristic of the SRM (Fig. 3).

To identify the SRM with fractional-order transfer functions, the FOMCON MATLAB Toolbox (FMT) [20] was used which is closest in functionality to the System Identification Toolbox. FMT provides the ability to identify fractional control objects by their characteristics, both in time and frequency domains. FMT allows one to identify a control object of a fractional-order model in continuous time as follows:

$$ G(s) = \frac{\sum_{i=0}^{m} b_i \cdot s^{\beta_i}}{\sum_{j=0}^{n} a_j \cdot s^{\alpha_j}}. \tag{5} $$

Identification is performed by tuning the initial model using the least squares method which minimizes the error norm.

$$ \left\| y(t) - y_{id}(t) \right\|^2, \tag{6} $$

by searching for the required set of parameters

$$ \Theta = \begin{bmatrix} a_n & a_{n-1} & \cdots & a_0 \\ \alpha_n & \alpha_{n-1} & \cdots & \alpha_0 \\ b_m & b_{m-1} & \cdots & b_0 \\ \beta_m & \beta_{m-1} & \cdots & \beta_0 \end{bmatrix}. \tag{7} $$

Using the FOMCON MATLAB Toolbox, the procedure for identifying transient characteristics of turn-on of the SRM with various values of the moment of inertia of the electric drive was performed. The identification results are shown in Table 3.

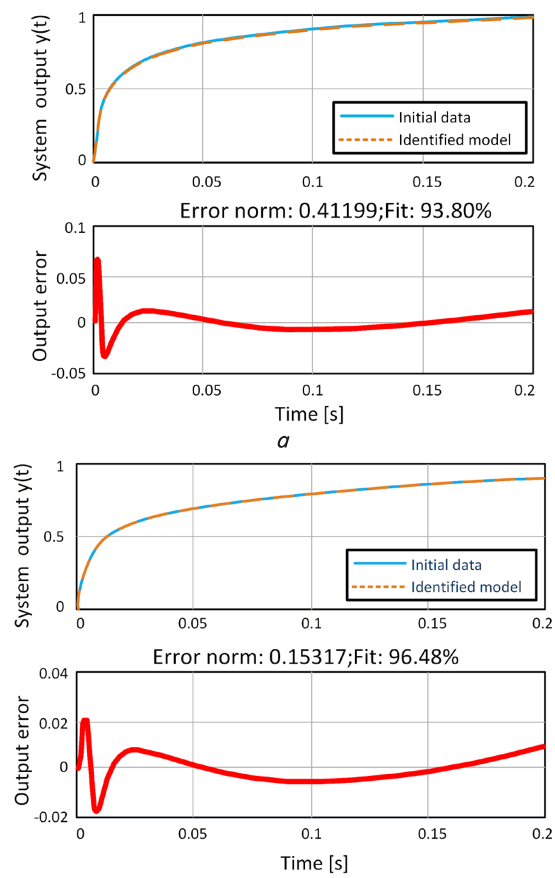

Fig. 5. Results of verification of transient characteristics of turn-on of the SRM electric drive by means of fractional-order transfer functions at various values of the drive moment of inertia and coefficient of regression: *a* – J=0.05 kg·m^2, R=93.8 %; *b* – J=0.1 kg·m^2, R=96.48 %

Fig. 5 shows results of verification of the obtained models performed directly in the FOMCON MATLAB Toolbox.

Table 3

Results of identification of transient characteristics of turn-on of the SRM electric drive by means of fractional-order transfer functions.

No.	SRM moment of inertia	Transfer function	Coefficient of regression *R*, %
1	J=0.05 kg·m^2	$W(s)=\dfrac{1}{0.0212s^{0.78}+0.88s^{0.092}+1}$	93.8
2	J=0.1 kg·m^2	$W(s)=\dfrac{1}{0.039s^{1.156}+0.87s^{0.1802}+1}$	96.48

It was established that structure of transfer functions of the SRM turn-on process does not depend on magnitude of the moment of inertia and is described by a link of the second order. For the SRM turn-on options considered, coefficient of regression R was 93–96 % which confirms high accuracy of the models obtained. It should also be noted that value of the coefficient of regression R weakly depends on magnitude of the moment of inertia and significantly exceeds the coefficient of regression obtained by identifying the SRM by means of fractionally rational transfer function of rat34 class, Table 2.

7. Synthesis of fractional-order PI$^\lambda$D$^\mu$ controller

The fractional-order PID controller was first introduced by Podlubny in [26]. This generalized regulator called the PI$^\lambda$D$^\mu$ controller has an integrator of λ order and a differentiator of μ order. Recent studies show that the PI$^\lambda$D$^\mu$ fractional-order controller is superior to the classical PID in a number of applications [27–30].

Transfer function of the fractional-order PID controller is as follows:

$$G(s)=K_P+\frac{K_I}{s^\lambda}+K_D\cdot s^\mu. \tag{8}$$

Obviously, if we take λ=μ=1, the result is a classical integer-order PID controller. The PI$^\lambda$D$^\mu$ controller has significantly greater capabilities in the controller tuning.

Classical integer-order PID controller was synthesized for the variant of SRM identification by a fractionally rational transfer function, according to Tables 2–4. The PID controller was tuned in MATLAB using the built-in tool for automatic tuning PID controllers.

Parameters of the PI$^\lambda$D$^\mu$ controller were synthesized using the FOMCON MATLAB Toolbox. The regulator was optimized according to the criterion of minimum integral square error of the transition function of the closed control system.

Let us use the control object model obtained by identifying the SRM turn-on process given in (8):

$$W_{2J}=\frac{1}{0.039s^{1.156}+0.87s^{0.1802}+1}. \tag{9}$$

Initially, parameters of the PID controller were set to K_P=K_I=K_D=100; λ=μ=1=1. At the first stage, exponents were fixed so that the integer-order PID controller was practically evaluated. The search limits were set in the range K=[0; 1000] for transfer coefficients. For default simulation, refined Oustaloup filter approximation was used with the following parameters: (ω=[0: 0001; 10000]; N=10). Optimization using these tuning operations led to the following set of parameters for the integer-order PID controller: K_P=0.33295; K_I=12.45; K_D=2.4011.

Then gain coefficients were fixed and initial orders of the integrator and the differentiator set equal to λ=μ=1=0.5.

As a result of optimization, the following orders of the integrator and the differentiator were found: λ=0.31875 and μ=0.95597. Parameters of tuning of the PI$^\lambda$D$^\mu$ controller obtained in the FOMCON MATLAB Toolbox are shown in Fig. 6.

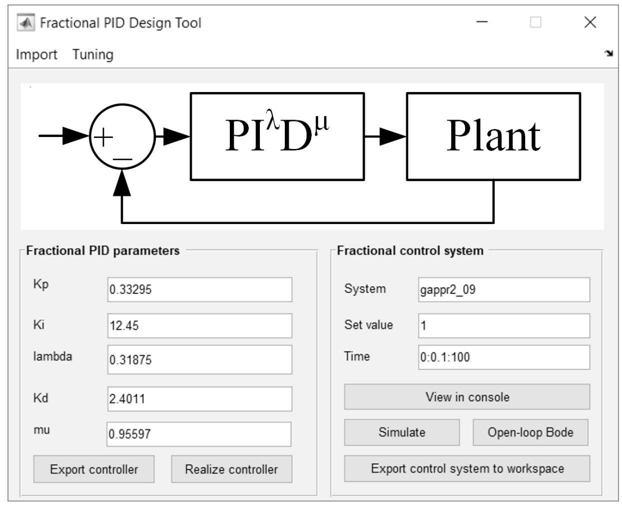

Fig. 6. The results of automatic tuning the PI$^\lambda$D$^\mu$ controller obtained in the FOMCON MATLAB Toolbox

Comparative analysis of the SRM turn-on processes in an open control system as well as in a closed control system with a classical integer-order PID controller and with a fractional-order PI$^\lambda$D$^\mu$ controller was performed. The results are presented in Fig. 7.

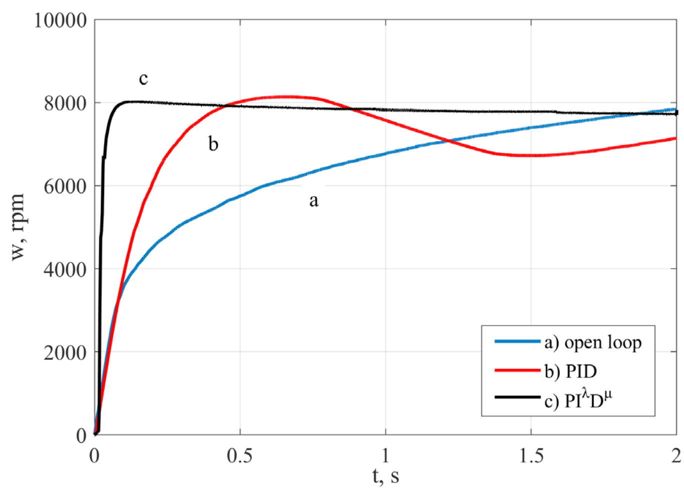

Fig. 7. Turn-on of SRM with various variants of developed PID controllers for open and closed control systems

Use of a fractional-order PI$^\lambda$D$^\mu$ controller as compared to the classical integer-order regulator enables reduction of overshoot from 13.3 % to 2.64 %, increase in response speed of the closed ACS, cut of regulation time from 1.48 s to 0.53 s while reducing response variability of transient characteristics.

The obtained results confirm superiority of the $PI^{\lambda}D^{\mu}$ controller over the classical integer-order regulator. Closed control systems with $PI^{\lambda}D^{\mu}$ controllers have greater speed and less overshoot compared to integer-order regulators with no restrictions on the control forcing.

8. Discussion of results obtained in the study of closed SRM control systems with fractional-order $PI^{\lambda}D^{\mu}$ controllers

With the help of the SimPower library in Matlab/Simulink, mathematical simulation of processes of turn-on of SRMs in a power range from 5 to 75 kW with various tooth ratios and moment of inertia of the working machine was performed. It was established that shape of the transit characteristics of the SRM angular velocity (Fig. 2, 3) does not depend on power and design of the SRM and is aperiodic, significantly different from the exponential character. Non-linearity of the SRM characteristics is explained by dynamic change of the SRM parameters when angular velocity changes during the turn-on process. It was hypothesized that the SRM can be identified by means of a fractional-order transfer function.

Using the Matlab/System Identification Toolbox, the SRM identification was performed by means of fractionally rational transfer functions of integer order. When the SRM was identified by a fractionally rational transfer function of rat34 class, coefficient of regression of the resulting model was 85 % (Table 2). The SRM identification with the help of the fractional-order transfer function was performed using the FOMCON MATLAB Toolbox. When the SRM was identified by means of a fractional-order transfer function of the second degree, regression coefficient was 93–96 % (Fig. 5, Table 3) which confirms advantage of using the proposed SRM model. Using the FOMCON MATLAB Toolbox, a $PI^{\lambda}D^{\mu}$ controller was synthesized and optimized in terms of minimum integral quadratic error of the transition function of the closed system of control of a fractional-order control object (Fig. 6). Comparative analysis of the SRM turn-on processes with various types of regulators has shown that the use of a fractional-order $PI^{\lambda}D^{\mu}$ controller compared to the classical integer-order regulator reduces overshoot from 13.3 % to 2.64 %, increases speed of the closed ACS and cuts regulation time from 1.48 s to 0.53 s (Fig. 7).

The obtained results confirm the possibility of SRM identification with a fractional-order transfer function and improving quality of the SRM control when using the fractional-order $PI^{\lambda}D^{\mu}$ controller.

Effect of random measurement errors on operation of a closed fractional-order control system which may worsen conclusions is a serious issue of this study. The issues of propagating computation errors for fractional-order differential equations in modern computational mathematics have not been investigated.

Further studies of the considered problem may consist in establishing existence of a unique relationship between the SRM electromechanical parameters (active resistance and winding inductance, inertia, etc.) and parameters of the SRM fractional-order transfer function (Table 2) and the fractional-order $PI^{\lambda}D^{\mu}$ controller.

9. Conclusions,

1. Mathematical simulation of turn-on of 5 to 75 kW SRMs with various tooth ratios was performed with the help of the SimPower library in Matlab/Simulink. It was established that shape of the transient characteristics of the SRM in terms of angular velocity does not depend on power and design of the SRM and is aperiodic essentially differing from the exponential character. Non-linearity of the SRM characteristics is explained by dynamic change of the SRM parameters when angular velocity changes during the turn-on process. It was hypothesized that the SRM can be identified by a fractional-order transfer function.

2. Using the System Identification Toolbox, the SRM was identified by fractionally rational transfer functions of integer order. Sufficient convergence of the results was obtained in identifying the SRM with the help of a fractionally rational transfer function of the rat34 class which has three zeros and four poles, regression coefficient of the resulting model was 85 %. Using the FOMCON MATLAB Toolbox, identification of the SRM turn-on process with the help of a fractional-order transfer quadratic function of second order was performed. Regression coefficient of the fractional model was 93–96 % which confirms advantage of using the proposed fractional-order identification.

3. A fractional-order $PI^{\lambda}D^{\mu}$ controller optimized in terms of minimum integral square error of the transition function of the closed system of control of the fractional-order object was synthesized for the obtained transfer functions of the SRM turn-on process. FOMCON MATLAB Toolbox was used for synthesis of the $PI^{\lambda}D^{\mu}$ controller. Comparative analysis of processes of the SRM turn-on in an open control system as well as in a closed control system with a classical integer-order PID controller and with a fractional-order $PI^{\lambda}D^{\mu}$ controller was performed. In the case under study, the use of a fractional-order $PI^{\lambda}D^{\mu}$ controller compared to the classical integer-order regulator enables reduction of overshoot from 13.3 % to 2.64 %, rise of speed of the closed ACS and cut of regulation time from 1.48 s to 0.53 s.

The obtained results confirm superiority of the fractional-order $PI^{\lambda}D^{\mu}$ controller over the classical integer-order regulator.

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