OVERVIEW OF MODELS AND CONTROL METHODS FOR STEP MOTORS AND PERMANENT MAGNET MOTORS

Igor B. Furtat
Laboratory "Adaptive and intelligent control of networked and distributed systems"
IPME RAS
Saint Petersburg, Russia
cainenash@mail.ru

Nikita S. Slobodzyan
Laboratory "Robotic and mechatronic systems"
Baltic State Technical University
"VOENMEH"
Russia
ja-nikita@mail.ru

Roman A. Pryanichnikov
JSC "Information satellite systems"
named after Academician M.F. Reshetnev
Zheleznogorsk, Krasnoyarsk Territory, Russia
pryanichnikovra@iss-reshetnev.ru

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Abstract

This overview is devoted to the description of step motor models and permanent magnet motor models that can be used to design the control law for these devices. These motors are widely used in various practical applications and scientific equipments due to its high accuracy. A number of works on the design of various control laws for these electrical machines are described. The features of each model and the features of obtained considered control laws are given from the point of view of achieving certain physical properties in the obtained closed-loop systems.

Key words

Step motor, permanent magnet motor, mathematical model, physical properties, control.

1 Introduction

Currently, DC collector motors are being replaced by AC machines, since the latter ones have a long service life and reliability due to the absence of sliding electrical contacts [Viorel and Lorand, 1998; Gieras et al., 2016]. Electric motors are used to study various physical phenomena [Boikov et al., 2016; Tomchina, 2021; Ugalde-Loo et al., 2013]. In aviation and space technology, AC machines are actively used in actuating systems, such as drives for opening large structures, guidance and stabilization systems, etc [Sarhan et al., 2009; Fu et al., 2022]. The most widespread are special synchronous motors, which, compared with other electric motors, have the best indicators of specific power, efficiency, and reliability. These machines include step motors and permanent magnet synchronous motors (PMSM).

In the paper, an overview of mathematical models of step motors and synchronous motors with permanent magnets is given. Based on these models the some effective existing control laws are considered.

Step and synchronous motors can be effectively controlled without feedback in the absence of parametric uncertainty and external disturbances. That is, control is carried out by one-way transmission of command signals from the controller of a higher level to the motor. This makes motor control very easy, eliminating the need for sensors and feedback.

However, under conditions of uncertainty in the motor parameters (for example, changes in resistance, inductance, etc. due to wear and temperature change) and under conditions of external disturbances (for example, changes in the motor load), the open-loop control becomes ineffective. Currently, many methods and approaches have been proposed for design feedback control laws for step and synchronous motors. In our overview, we consider at some of the most cited (according to the Scopus database) control methods. Moreover, searching in Scopus for keywords "stepp motor" and the "survey" or "overview" does not return any important results. Thus, we hope that the proposed survey will be useful to readers.

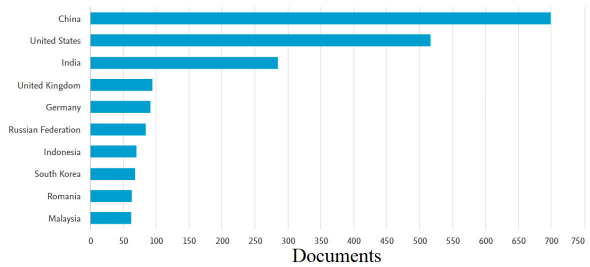

Figure 3. Distribution of the number of publications by country.

2 The step motors

2.1 Analysis of the relevance of control problem

In scientific system Scopus, a search for the keywords "control" and "step motor" in the title of a publication returns 364 publications at the end of April 2022. Given the mention of these words in any part of the publication one has 3164 results. In Russian scientific system Elibrary, a query with the keywords "control" and "step motor" in the title of the publication produces 714 publications at the end of April 2022 (including articles, monographs, patents, dissertations, etc.). Given the mention of these words in any part of the publication one gets 10599 results. Judging by the annual growth of publications over 50 years, the interest in this topic is growing up.

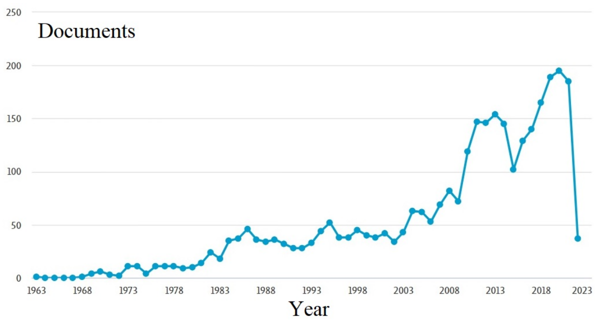

Figure 1. Distribution of the number of publications by years.

Figures 2, 3 show the authors and countries with the number of publications.

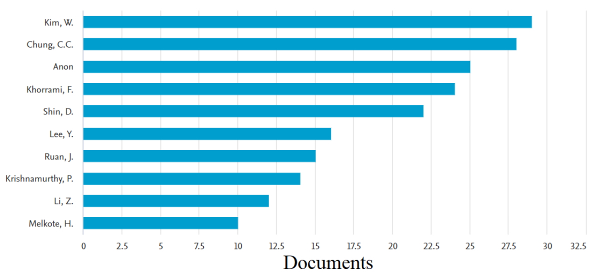

Figure 2. Distribution of the number of publications by authors.

2.2 Mathematical models

The paper [Mihalache et al., 2013] considers open-loop control (without feedback) of a two-phase hybrid step motor (HSM) using a voltage-to-frequency converter. HSMs are motors that convert a sequence of digital pulses into precise step-by-step movements [Mihalache et al., 2013; AL-Sabbagh and Mahdi, 2010; Kelemen and Crivii, 1975; Morar, 2007; Acarnley, 2002]. HSM is compatible with digital control and monitoring (monitoring) systems [Kelemen and Crivii, 1975; Morar, 2007]. The most popular HSMs consist of a stator and two rotors. The motor stator has two control windings, each of which is placed on two diametrically opposite stator poles. The rotors are axially spaced with a permanent magnet at the periphery, which shows that the teeth are evenly distributed, and the first rotor is radially displaced with one tooth [Kelemen and Crivii, 1975]. The HSM develops a mechanical torque higher than the torque generated by step motors with variable resistance [Kelemen and Crivii, 1975; Morar, 2007]. The GSM is controlled in the following modes: wave drive, normal full step and half step [Kelemen and Crivii, 1975; Morar, 2007; Acarnley, 2002]. The wave drive mode includes single-phase power with a series alternating phase alternating voltage. Normal full-step mode involves supplying two phases with alternating voltage. The half-step mode assumes alternating power supply of the phases: two phases - one phase [Kelemen and Crivii, 1975; Morar, 2007].

The paper [Mihalache et al., 2013] presents a new method for simulating in Matlab a controller drive for a hybrid step motor with a full sequence of steps using a voltage-to-frequency converter. The simulation results of the proposed control scheme showed satisfactory results with full-scale experiments. The mathematical model of a hybrid step motor is presented in the form of the following differential equations [Mihalache et al., 2013; AL-Sabbagh and Mahdi, 2010; Kelemen and Crivii, 1975; Morar, 2007; Acarnley, 2002; Zribi and Chiasson, 1991]:

$$
\begin{aligned}
\frac{di_a}{dt} &= \frac{1}{L_a}\left[U_a - R_a i_a + k_m \omega \sin\left(N_R\theta\right)\right],\\
\frac{di_b}{dt} &= \frac{1}{L_b}\left[U_b - R_b i_b - k_m \omega \cos\left(N_R\theta\right)\right],\\
\frac{d\omega}{dt} &= \frac{1}{J}[-k_m i_a \sin\left(N_R\theta\right) + k_m i_b \cos\left(N_R\theta\right)\\
&\quad -B\omega - k_D - Mr],\\
\frac{d\theta}{dt} &= \omega,
\end{aligned}
\tag{1}
$$

where i_a and i_b are phase currents (currents on the corresponding stator windings), U_a and U_b are phase voltages (voltages on the corresponding stator windings), L_a and L_b are phase inductances (inductances on the corresponding stator windings), R_a and R_b are phase resistances (resistances on the respective stator windings),

N_R is a number of rotor teeth (number of teeth per pole pair (or number of stator pole pairs), J is a rotor inertia (total moment of inertia of the rotor and drive elements reduced to the shaft), k_m is a rotor torque constant (or motor torque constant), ω is a rotor speed, θ is a position of the rotor, M_r is a load torque (total torque on the motor shaft).

The value of $k_D \sin(4N_r\theta)$ represents the generated torque due to permanent magnet of the rotor interacting with the magnetic material of the stator poles and k_D is usually between 5% and 10% of the value of $k_m \cdot i_0$, where i_0 is the rated current [Morar, 2007; Zribi and Chiasson, 1991].

The implementation of differential equations (1) in Matlab/Simulink is illustrated in Fig. 4.

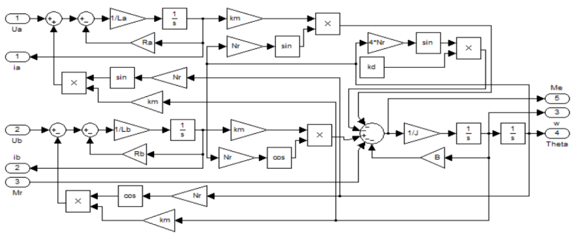

Figure 4. Implementation of differential equations (1) in Matlab/Simulink.

In [Kenjo, 1984], the position control of a step motor with permanent magnets is considered using the exact linearization method. The connection between the exact linearizing transformation and dq-transformation in the theory of electrical machines is shown. It is also shown how constant load torques can be asymptotically eliminated using a non-linear observer.

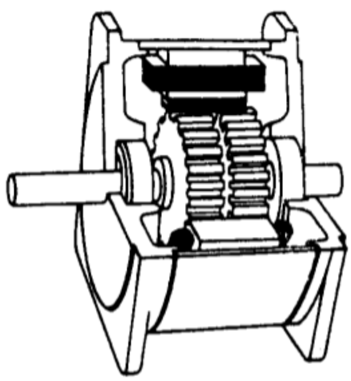

Figure 5. Cross section of a step motor.

Despite the fact that in [Kenjo, 1984] the model is borrowed from [Zribi and Chiasson, 1991], nevertheless, the model in [Kenjo, 1984] has some differences. Thus, the step motor model in [Kenjo, 1984] is described by the following differential equations:

$$
\begin{aligned}
\frac{di_a}{dt} &= \frac{1}{L}\left[U_a - Ri_a + k_m\omega \sin\left(N_R\theta\right)\right], \\
\frac{di_b}{dt} &= \frac{1}{L}\left[U_b - Ri_b - k_m\omega \cos\left(N_R\theta\right)\right], \\
\frac{d\omega}{dt} &= \frac{1}{J}[-k_m i_a \sin\left(N_R\theta\right) + k_m i_b \cos\left(N_R\theta\right) \\
&\quad - B\omega - k_D \sin\left(4N_R\theta\right) - M_R], \\
\frac{d\theta}{dt} &= \omega.
\end{aligned} \tag{2}
$$

The model (2) appears to be more accurate than the model (1) and is detailed with all explanations in [Mihalache et al., 2013].

The model differences between (1) *and* (2). In (2), unlike (1), the same values of L, J are used in all equations, and the term $-k_D \sin\left(4N_R\theta\right)$ instead of $-k_D$.

Now we introduce the state vector x, the control vector u_1 and u_2, as well as other notations in the forms

$$
\begin{aligned}
&x = col\{i_a, i_b, \omega, \theta\}, \\
&K_1 = R/L, \;\; K_2 = k_m/L, \;\; K_3 = k_m/J, \\
&K_4 = B/J, \;\; K_5 = N_R, \;\; K_6 = k_D/J, \\
&u_1 = U_a/L, \;\; u_2 = U_b/L.
\end{aligned}
$$

As a result, the state-space model (2) can be written as

$$
\begin{aligned}
\dot{x}_1 &= -K_1x_1 + K_2x_2\sin(K_5x_4) + u_1, \\
\dot{x}_2 &= -K_1x_2 - K_2x_3\sin(K_5x_4) + u_2, \\
\dot{x}_3 &= -K_3x_1\sin(K_5x_4) + K_3x_2\cos(K_5x_4) \\
&\quad - K_4x_3 - K_6\sin(4K_5x_4) - \frac{M_R}{J}, \\
\dot{x}_4 &= x_3.
\end{aligned} \tag{3}
$$

Equations (3) are actively used in various literature for the synthesis of linear and nonlinear control (more often nonlinear control) of a step motor with permanent magnets. In [Marino and Tomei, 1992], the problem of precise positional control of step motors with permanent magnets with a sinusoidal flux distribution was considered. To ensure accurate positioning, the method of adaptive feedback linearization developed in [Marino and Tomei, 1992] is used. It is assumed that the load torque and the resistance of each phase stator winding are unknown. A non-linear adaptive control scheme is proposed that guarantees global tracking of the trajectory of a given position and global convergence of the estimated parameters. The simulation results are presented.

Feedback linearization methods for (non-adaptive) control of step motors with variable resistance were considered in [Ilic'-Spong et al., 1987] (see [Taylor, 1991] for the adaptive case) and in [Bodson and Chiasson, 1989; Chen and Paden, 1990] for step motors with permanent magnets. In [Bodson and Chiasson, 1989], an indirect adaptive controller is proposed, which combines the linearization method with feedback and the least squares method. However, the approach [Bodson and Chiasson, 1989] requires knowledge of the time derivative of engine state variables, which are usually not available. In [Chen and Paden, 1990], a nonlinear adaptive control was proposed for a reduced-order model (electrodynamics is neglected), i.e., for machines where the flow distribution is not sinusoidal, which often causes torque ripples. To reduce torque pulsations, the periodic distribution of the flow is approximated by a truncated Fourier series, the coefficients of which are considered unknown, and a nonlinear adaptive control is developed.

In [Marino and Tomei, 1992], a nonlinear adaptive control scheme for a two-phase step motor with permanent magnets was proposed. The adaptive control technique is based on the extended parameter consistency property (see [Kanellakopoulos et al., 1991]). It is assumed that only the load moment and the resistance of each phase stator winding are unknown. A more general case, when all engine parameters are unknown, can be solved in a similar way. The proposed control is applicable only to machines with sinusoidal flow distribution.

Now consider the model from [Marino and Tomei, 1992]:

$$\begin{aligned} \frac{di_a}{dt} &= \frac{1}{L}\left[U_a - Ri_a + k_m\omega\sin\left(N_R\theta\right)\right], \\ \frac{di_b}{dt} &= \frac{1}{L}\left[U_b - Ri_b - k_m\omega\cos\left(N_R\theta\right)\right], \\ \frac{d\omega}{dt} &= \frac{1}{J}[-k_m i_a\sin\left(N_R\theta\right) + k_m i_b\cos\left(N_R\theta\right) \\ &\quad -B\omega - M_R], \\ \frac{d\theta}{dt} &= \omega. \end{aligned} \tag{4}$$

The structural differences between models (2) *and* (4). In (4), unlike (2), there is no $-k_D\sin\left(4N_R\theta\right)$ term. Such model is so-called “field weakening model”.

Also in [Marino and Tomei, 1992], a nonlinear transformation of coordinates (4) is presented, followed by the synthesis of a nonlinear control law that provides exponential stability in deviations θ, ω and $\dot{\omega}$ from the corresponding equilibrium positions in the case of known model parameters and measurement of these signals. If the stator winding resistance R and the load torque M_R are not exactly known, the resistance varies with temperature and the load torque depends on the load itself, then the adaptive feedback linearization method is used. Model (4) is used in [Chunlei et al., 2022] using a new predictive current control law with a finite set of controls for a two-phase hybrid step motor powered by a three-phase voltage source inverter.

The (4) model is used in [Kim et al., 2021], where a robust nonlinear position control for permanent magnet step motors is proposed. A new one-input-one-output model has also been developed that includes position, velocity, and acceleration, using a switching circuit to account for unknown parameters and external disturbance. In addition, an observer has been developed for estimating position, velocity, acceleration, and perturbation. Since the perturbation refers to an external influence, it is difficult to accurately estimate the perturbation without an observer with a large gain. The use of other observers may lead to a deterioration in the quality of regulation. Then, a non-linear controller based on the backstepping method is developed to suppress the position tracking error. The proposed control algorithm was tested experimentally using a permanent magnet step motor control system.

It is noted in [Kim et al., 2021] that with the increase in power and decrease in the cost of embedded processors in recent years, drives and control systems for step motors with permanent magnets have become increasingly complex. Thus, for positioning applications, a permanent magnet step motor can replace expensive servo motors such as permanent magnet synchronous motors as a cheaper closed-loop replacement.

Various controllers have been proposed to improve the performance of position/speed control in permanent magnet step motors [Shin et al., 2013; Chen and Chin, 2000; Lee et al., 2010; Kim et al., 2013; Shin et al., 2017; Ivanov et al., 2021; Shin et al., 2016; Lee et al., 2017; Le et al., 2017].

Nonlinear controller using field weakening control (with no term $-k_D\sin\left(4N_R\theta\right)$), was introduced to improve position control in [Bodson et al., 1993; Krishnamurthy and Khorrami, 2004].

A simple and effective position and speed controller was proposed in [Chen and Chin, 2000]. In [Lee et al., 2010], a sensorless controller is proposed to control the speed of a step motor.

In [Kim et al., 2013], a microstepping control based on torque modulation was developed to implement field-oriented control and without direct quadrature transformation and reset control of the integrator developed in [Shin et al., 2017] to improve the transient response with position control of a step motor with permanent magnets. Microstep control is also used in [Ivanov et al., 2021].

To reduce the position tracking error, an improved nonlinear damping controller has been proposed [Shin et al., 2016]. In addition, to optimize the characteristics of the control, a nonlinear H_2-control with various linear parameters was developed [Lee et al., 2017].

In [Le et al., 2017], an effective feedback control is proposed, consisting of motor parameter identification, current feedback control, position feedback control, and damping control. To suppress external periodic disturbances, a model predictive controller has been developed [Bodson et al., 1993].

Based on the internal model method, a controller is proposed based on the principle of reducing non-fundamental harmonics for a motor with inverters with a low switching frequency in [Krishnamurthy and Khorrami, 2004; Defoort et al., 2009; Zhou et al., 2018].

3 Permanent magnet motors

3.1 Analysis of the relevance of control problem

In Scopus search engine, a query with the keywords “control” and “three-phase permanent magnet synchronous motor” in the title of the publication yields 55 results as of the end of April 28, 2022. Given the mention of these words in any part of the publication we have 1349 results.

In Elibrary search engine, a query with the keywords "control" and "three-phase synchronous motor with permanent magnets on the rotor" in the title of the publication returns 0 results as of the end of April 28, 2022 (including articles, monographs, patents, dissertations, etc.). Given the mention of these words in any part of the publication one has 5 results (3 patents, 1 computer program and 1 article).

Judging by the annual growth of publications over 50 years, interest in this topic is growing.

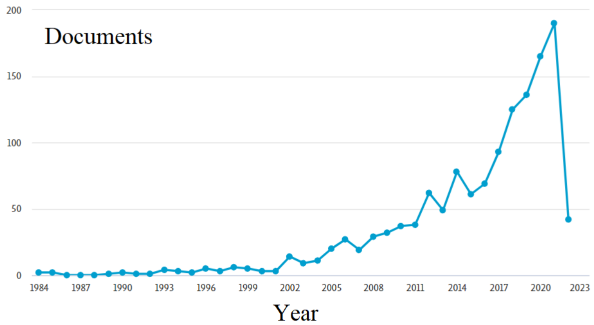

Figure 6. Distribution of the number of publications by years.

Figures 7, 8 show the authors and countries with the number of publications.

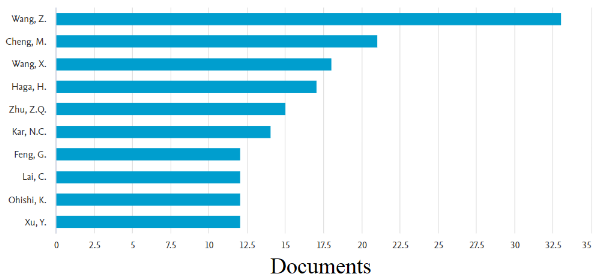

Figure 7. Distribution of the number of publications by authors.

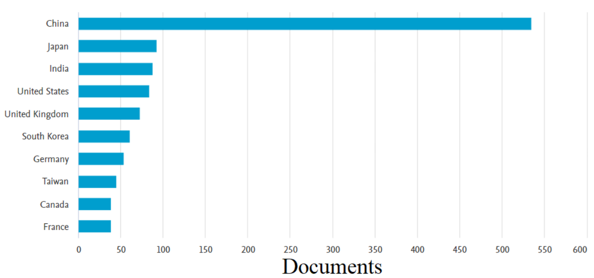

Figure 8. Distribution of the number of publications by country.

The picture of three-phase synchronous motor with permanent magnets on the rotor is shown in Fig. 9

Figure 9. Three-phase synchronous motor with permanent magnets.

3.2 Mathematical models

The paper [Guo et al., 2022] considers positional sensorless control of a three-phase synchronous motor with permanent magnets on the rotor based on an adaptive observer in sliding modes.

The mathematical model of the engine in the reference frame α-β is represented as follows, e_α and e_β are EMF of the motor, respectively:

$$\begin{aligned} \frac{di_\alpha}{dt} &= \frac{1}{L_s}\left[-R_s i_\alpha + u_\alpha - e_\alpha\right], \\ \frac{di_\beta}{dt} &= \frac{1}{L_s}\left[-R_s i_\beta + u_\beta - e_\beta\right], \\ e_\alpha &= -\frac{\pi}{\tau} v \psi_f P \sin(\theta), \\ e_\beta &= \frac{\pi}{\tau} v \psi_f P \cos(\theta), \end{aligned} \tag{5}$$

where u_α, u_β, i_α, i_β, e_α, e_β are voltage, current and EMF of the motor, respectively, in the reference frame α-β.

In the stationary reference frame α-β, the dynamic model of the engine is represented as follows [Kommuri et al., 2016; Qiao et al., 2013]:

$$\frac{di_j}{dt} = \frac{1}{L}\left[-Ri_j + u_j - e_j\right]. \tag{6}$$

Here $j \in \{\alpha, \beta\}$. The stator currents are $i_j \in \mathbb{R}$, u_j is a voltages, e_j is a back EMF defined as

$$\begin{aligned} e_\alpha &= -K_E \omega_e \sin(\theta_e), \\ e_\beta &= K_E \omega_e \cos(\theta_e), \end{aligned} \tag{7}$$

velocity dynamics ω_e is given by

$$\begin{aligned} \frac{d\omega_e}{dt} &= \frac{P}{J}\phi_m\left[-sin(\theta_e)i_\alpha + cos(\theta_e)i_\beta\right] \\ &\quad -\frac{f_v}{J}\omega_e - \frac{T_L}{J}, \\ T_e &= \frac{3}{2}\phi_m P\left[-sin(\theta_e)i_\alpha + cos(\theta_e)i_\beta\right]. \end{aligned} \tag{8}$$

Here R is a stator resistance, L is a synchronous inductance, P is a number of pole pairs, J is a moment of inertia, K_E is a back-emf constant, ϕ_m is a rotor flux, f_v is a viscous friction, T_L is a load torque, and θ_e and ω_e are the position and speed of the motor, respectively. In the model above, i_j and u_j are the measured quantities, and e_j is considered as an unknown quantity. It is known that the back emfs in (6) are functions of the rotor speed and position shown in (7).

In [Kommuri et al., 2016; Qiao et al., 2013; Kommuri et al., 2018; Liu and Li, 2012; Alecsa et al., 2012; Jang et al., 2008], the problem of automatic control of the speed of an electric vehicle (EV) driven by a permanent magnet synchronous motor (PMSM) is studied. A reconfiguration scheme based on a higher order sliding mode observer is proposed in the event of sensor failures/failures to maintain good control performance. Appropriate controlled engine output torque allows the desired vehicle reference speed to be monitored to ensure continued safe operation of the vehicle. The effectiveness of sensor-based overall fail-safe speed control is shown when an electric vehicle is subjected to influences such as wind force and road roughness using the highly accurate CarSim software package. Experiments are presented with a three-phase 26 W PMSM to demonstrate the correctness of the proposed fault detection scheme.

In [Gaeta et al., 2013], the PMSM model is described by the following equations:

$$\begin{array}{l} v_{abc} = r_s i_{abc} + \frac{d\lambda_{abc}}{dt}, \\ \lambda_{abc} = L_{abc} i_{abc} \\ \quad +[\cos(2\vartheta_r),\ \cos(2(\vartheta_r - \frac{2\pi}{3}), \\ \quad \cos(2(\vartheta_r + \frac{2\pi}{3})]^{\mathrm{T}} \lambda_{pm}, \end{array} \tag{9}$$

where $r_s = \mathrm{diag}(r_s)$ and the matrix elements L_{abc} are

$$\begin{array}{l} L_{hh} = L_{ls} + \frac{L_d + L_q - 2L_{ls}}{3} \\ \quad - \frac{L_d - L_q}{3} \cos[2(\vartheta_r + \alpha)], \\ L_{kh} = L_{hk} = -\frac{L_d + L_q - 2L_{ls}}{6} \\ \quad - \frac{L_d - L_q}{3} \cos[2(\vartheta_r + \gamma)], \\ \alpha = \begin{cases} 0,\ h = a, \\ -\frac{2}{3}\pi,\ h = b, \\ \frac{2}{3}\pi,\ h = c, \end{cases} \\ \gamma = \begin{cases} -\frac{\pi}{3},\ (h,k) = (a,b), \\ \pi,\ (h,k) = (b,c), \\ \frac{1}{3}\pi,\ (h,k) = (a,c). \end{cases} \end{array} \tag{10}$$

In (9) and (10) r_s is a stator resistance, L_{ls} is a leakage inductance, and L_d and L_q are synchronous inductances along the *d* and *q* axes. The angular positions α and γ take into account the spatial phase shift of the three stator windings with inductance variations.

Article [Gaeta et al., 2013] is devoted to modeling and control of three-phase permanent magnet synchronous motors (PMSM) under phase failure conditions. Appropriate frame transformations are introduced to obtain a *q-d* axis model similar to that normally used for machines operating under normal conditions. The adoption of such a model also makes it possible to implement vector control strategies for PMSM drives under phase failure conditions over a wide operating range. Modelling and experimental tests confirm the validity of the theoretical analysis.

Suitable models for speed and position control arise from the voltage distribution in a three-phase AC system and from the torque equilibrium equation [Vas, 1998; Belda and Vosmik, 2016]. Taking into account the Clark and Park transformation, the original set of equations, given in the rotating field *d-q* coordinate system or rotating frame of reference, looks like this:

$$\begin{array}{l} u_{Sd} = R_S i_{Sd} + L_d \frac{d}{dt} i_{Sd} - L_q \omega_e i_{Sq}, \\ u_{Sq} = R_S i_{Sq} + L_q \frac{d}{dt} i_{Sq} - L_d \omega_e i_{Sq} + \psi_M \omega_e, \end{array} \tag{11}$$

where R_S, L_d, L_q and ψ_M are motor parameters, u_{Sd}, u_{Sq} are *d-q* voltages (system inputs), i_{Sd}, i_{Sq} are *d-q* currents, ω_e is a electrical rotor speed (mechanical speed $\omega_m = \omega_e/p$, p is the number of pairs of poles.

$$\begin{array}{l} J \frac{d^2}{dt^2} \vartheta_e = \frac{3}{2} p^2 [\psi_{M\,S} i_{Sq} + (L_d - L_q) i_{Sd} i_{Sq}] \\ \quad -B\omega_e - p\tau_L, \end{array} \tag{12}$$

where ϑ_e is a rotor position, and τ_L is a load moment.

The models (11)-(12) can be converted to state-space models as follows (surface PMSM is considered $L_d = L_q = L_S$):

– speed control with system output $y = [i_{Sd}, i_{Sq}, \omega_e]^{\mathrm{T}}$:

$$\frac{d}{dt}\begin{bmatrix} i_{Sd} \\ i_{Sq} \\ \omega_e \\ \tau_L \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{L_S} & \omega_e & 0 & 0 \\ -\omega_E & -\frac{R_S}{L_S} & -\frac{\psi_M}{L_S} & 0 \\ 0 & \frac{3}{2}\frac{p^2}{J}\psi_M & -\frac{B}{J} & -\frac{p}{J} \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{Sd} \\ i_{Sq} \\ \omega_e \\ \tau_L \end{bmatrix} + \begin{bmatrix} \frac{1}{L_S} & 0 \\ 0 & \frac{1}{L_S} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_{Sd} \\ u_{Sq} \end{bmatrix};$$

– position control with system output $y = [i_{Sd}, i_{Sq}, \vartheta_e]^{\mathrm{T}}$:

$$\frac{d}{dt}\begin{bmatrix} i_{Sd} \\ i_{Sq} \\ \omega_e \\ \vartheta_e \\ \tau_L \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{L_S} & \omega_e & 0 & 0 \\ -\omega_E & -\frac{R_S}{L_S} & -\frac{\psi_M}{L_S} & 0 \\ 0 & \frac{3}{2}\frac{p^2}{J}\psi_M & -\frac{B}{J} & -\frac{p}{J} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} i_{Sd} \\ i_{Sq} \\ \omega_e \\ \vartheta_e \\ \tau_L \end{bmatrix} + \begin{bmatrix} \frac{1}{L_S} & 0 \\ 0 & \frac{1}{L_S} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_{Sd} \\ u_{Sq} \end{bmatrix}.$$

The last both forms can be represented by a single state-space model:

$$\dot{x} = A(\omega_e)x + Bu, \quad y = Lx.$$

For such model can be effectively use the control methods [Furtat, 2011; Furtat, 2014; Margun and Furtat, 2015; Furtat et al., 2015].

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4 Conclusions

The results of the present paper have shown the importance of using step motors and permanent magnet motors in various practice and scientific tasks. We also have shown that the use of various control schemes allows one to save the physical properties of motors depending on the influence of the environment and changes in the parameters of the motors themselves. For example, the adaptive control laws allow one to effectively save the physical properties of the motors when the parameters of these motors are partially or completely unknown. Thus, the application of adaptive schemes significantly expands the application area of these motors, including in space technologies.

References

Acarnley, P. (2002). *Stepping Motors - A guide to theory and practice, 4th Edition*. The Institution of Electrical Engineers, London.

AL-Sabbagh, Q. S. and Mahdi, A. S. (2010). Pulse width modulation high performance hybrid stepper motor. *Journal of Engineering*, **16** (4).

Alecsa, B., Cirstea, M. N., and Onea, A. (2012). Simulink modeling and design of an efficient hardware-constrained fpga-based pmsm speed controller. *IEEE Transactions on Industrial Informatics*, **8** (3), pp. 554–562.

Belda, K. and Vosmik, D. (2016). Explicit generalized predictive control of speed and position of pmsm drives. *IEEE Transactions on Industrial Electronics*, **63** (6), pp. 3889–3896.

Bodson, M. and Chiasson, J. (1989). Application of nonlinear control methods to the positioning of a permanent magnet stepper motor. *Proc. of the IEEE 28th Conf. on Decision and Control, Tampa*.

Bodson, M., Chiasson, J., Novotnak, R., and Rekowski, R. (1993). Highperformance nonlinear feedback control of a permanent magnet stepper motor. *IEEE Transactions on Control Systems Technology*, **1** (1), pp. 5–14.

Boikov, V., Andrievsky, B., and Shiegin, V. (2016). Experimental study of unbalanced rotors synchronization of the mechatronic vibration setup. *Cybernetics and Physics*, **5** (1), pp. 5–11.

Chen, D. and Paden, B. (1990). Nonlinear adaptive torque-ripple cancellation for step motors. *Proc. of the IEEE 29th Conf. on Decision and Control, Honolulu*.

Chen, J.-J. and Chin, K.-P. (2000). Automatic flux-weakening control of permanent magnet synchronous motors using a reduced-order controller. *IEEE Transactions on Power Electronics*, **15** (5), pp. 881–890.

Chunlei, W., Cao, B., Qu, X., and Fan, C. (2022). An improved finite control set model predictive current control for a two-phase hybrid stepper motor fed by a three-phase vsi. *Energies*, **1222** (3).

Defoort, M., Nollet, F., Floquet, T., and Perruquetti, W. (2009). A third-order sliding-mode controller for a stepper motor. *IEEE Transactions on Industrial Electronics*, **56** (9), pp. 3337–3336.

Fu, Z., Liu, Z., and Liu, X. (2022). A dual-redundancy two-phase hybrid stepping motor for satellite antenna drive system. *Energies*, **15**, pp. 1–14.

Furtat, I. (2011). Robust control of electric generator with compensation of perturbations. *Journal of Computer and Systems Sciences International*, **50** (5), pp. 785–792.

Furtat, I. (2014). Adaptive predictor-free control of a plant with delayed input signal. *Journal of Computer and Systems Sciences International*, **75** (1), pp. 139–151.

Furtat, I., Furtat, E., and Tupichin, E. (2015). Modified backstepping algorithm with disturbances compensation. *IFAC-PapersOnLine*, **48** (11), pp. 1056–1061.

Gaeta, A., Scelba, G., and Consoli, A. (2013). Modeling and control of three-phase pmsms under open-phase fault. *IEEE Transactions on Industry Applications*, **49** (1), pp. 74–83.

Gieras, J., Piech, Z., and Tomczuk, B. (2016). *Linear Synchronous Motors: Transportation and Automation Systems, Second Edition*. CRC Press, Taylor and Francis Group.

Guo, X., Yin, Z., Zhanga, Y., and Baia, C. (2022). Position sensorless control of pmlsm based on adaptive complex coefficient sliding mode observer. *Energy Reports*, **8**, pp. 687–695.

Ilic'-Spong, M., Marino, R., Peresada, S., and Taylor, D. (1987). Feedback linearizing control of switched reluctance motors. *IEEE Transaction on Automatic Control*, **32**.

Ivanov, D., Maradzhiev, I., and Grigorova, T. (2021). Fpga implementation of microstepping control of stepper motor with advanced mixed current decay. *Proc. of the. 12th National Conference with International Participation, ELECTRONICA, 27-28 May 2021, Sofia*.

Jang, J.-S., Park, B.-G., Kim, T.-S., Lee, D., and Hyun, D.-S. (2008). Parallel reduced-order extended kalman filter for pmsm sensorless drives. *Proc. of the IEEE Ind. Electron. Soc. Annual Conf.*, pp. 1326–1331.

Kanellakopoulos, I., Kokotovic, P., and Marino, R. . (1991). An extended direct scheme for robust adaptive nonlinear control. *Automatica*, **27**, pp. 247–255.

Kelemen, A. and Crivii, M. (1975). *Motoare electrice pas cu pas*. Editura Tehnica, Bucuresti.

Kenjo, T. (1984). *Stepping Motors and Their Microprocessor Controls*. Oxford, U.K.: Clarendon.

Kim, W., Lee, Y., Shin, D., and Chung, C. (2021). Nonlinear gain position control using only position feedback for permanent magnet stepper motors. *IEEE Transactions on Power Electronics*.

Kim, W., Shin, D., and Chung, C. (2013). Microstepping with nonlinear torque modulation for permanent magnet stepper motors. *IEEE Transactions on Control Systems Technology*, **21** (5), pp. 1971–1979.

Kommuri, S., Defoort, M., Karimi, H., and Veluvolu, K. (2016). A robust observer-based sensor fault-tolerant control for pmsm in electric vehicles. *IEEE Transactions on Industrial Electronics*, **63** (12), pp. 7671–7681.

Kommuri, S., Lee, S., and Veluvolu, K. (2018). Robust sensors-fault-tolerance with sliding mode estimation and control for pmsm drives. *IEEE/ASME Transactions on Mechatronics*, **23** (1), pp. 17–28.

Krishnamurthy, P. and Khorrami, F. (2004). Voltage-fed permanent-magnet stepper motor control via position-only feedback. *IEE Proceedings - Control Theory and Applications*, **151** (4), pp. 499–510.

Le, K., Hoang, H., and Jeon, J. (2017). An advanced closed-loop control to improve the performance of hybrid stepper motors. *IEEE Transactions on Power Electronics*, **32** (9), pp. 7244–7255.

Lee, J., Hong, J., Nam, K., Ortega, R., Praly, L., and Astolfi, A. (2010). Sensorless control of surface-mount permanent-magnet synchronous motors based on a nonlinear observer. *IEEE Transactions on Power Electronics*, **25** (2), pp. 290–297.

Lee, Y., Shin, D., Kim, W., and Chung, C. (2017). Nonlinear h2 control for a nonlinear system with bounded varying parameters: Application to pm stepper motors. *IEEE/ASME Transactions on Mechatronics*, **22** (3), pp. 1349–1359.

Liu, H. and Li, S. (2012). Speed control for pmsm servo system using predictive functional control and extended state observer. *IEEE Transactions on Industrial Electronics*, **59** (2), pp. 1171–1183.

Margun, A. and Furtat, I. (2015). Robust control of linear mimo systems in conditions of parametric uncertainties, external disturbances and signal quantization. *Proc. of the 20th International Conference on Methods and Models in Automation and Robotics, MMAR 2015, Poland*.

Marino, R. and Tomei, P. (1992). Adaptive control of stepper motors via nonlinear extended matching. *IFAC Proceedings Volumes*, **25** (29), pp. 135–139.

Mihalache, G., (Adam), A. Z., and Livint, G. (2013). Open-loop control of hybrid stepper motor with two phases using voltage to frequency converter. *Proc. of the 8th International Symposium on Advanced Topics in Electrical Engineering, May 23-25, 2013, Bucharest, Romania*.

Morar, A. (2007). *Comanda inteligentă a acţionărilor electrice cu motoare pascu pas*. Editura Mediamira, Cluj Napoca.

Qiao, Z., Shi, T., Wang, Y., Yan, Y., Xia, C., and He, X. (2013). New sliding mode observer for position sensorless control of permanent magnet synchronous motor. *IEEE Transactions on Industrial Electronics*, **68** (2), pp. 710–719.

Sarhan, A., El-Wakeel, A., and Kotb, A. (2009). Analysis and control of hybrid stepper motor for automatic sun-tracking system. *Proc. of the International Conference on Aerospace Sciences and Aviation Technology 13 (AEROSPACE SCIENCES)*, pp. 1–12.

Shin, D., Kim, W., Lee, Y., and Chung, C. (2016). Enhanced nonlinear damping for a class of singularly perturbed interconnected nonlinear systems. *Automatica*, **65** (1), pp. 36–42.

Shin, D., Kim, W., Lee, Y., and Chung, C. (2017). Nonlinear control with state-dependent reset integrator for a class of singularly perturbed interconnected nonlinear systems. *IEEE Transactions on Control Systems Technology*, **25** (4), pp. 1193–1203.

Shin, D., Kim, W., Lee, Y., and Chung, C. C. (2013). Phase compensated microstepping for permanent magnet stepper motors. *IEEE Transactions on Power Electronics*, **60** (12), pp. 5773–5780.

Taylor, D. (1991). Adaptive control design for a class of doubly-salient motors. *Proc. of the IEEE 90th Conf. on Decision and Control, Brighton*.

Tomchina, O. (2021). Control of vibrational field in an elastic vibration unit with dc motors and time-varying observer. *Cybernetics and Physics*, **4** (10), pp. 277–286.

Ugalde-Loo, C., Amezquita-Brooks, L. A., Liceaga-Castro, E., and Liceaga-Castro, J. (2013). Structural robustness assessment of electric machine applications using individual channel analysis and design. *Cybernetics and Physics*, **2** (2), pp. 108–118.

Vas, P. (1998). *Sensorless vector and direct torque control*. Oxford Univ.

Viorel, I.-A. and Lorand, S. (1998). *Hybrid Linear Stepper Motors*. Mediamira, Romania.

Zhou, Z., Xia, C., Yan, Y., Wang, Z., and Shi, T. (2018). Disturbances attenuation of permanent magnet synchronous motor drives using cascaded predictiveintegral-resonant controllers. *IEEE Transactions on Power Electronics*, **33** (2), pp. 1514–1527.

Zribi, M. and Chiasson, J. (1991). Position control of a pm stepper motor by exact linearization. *IEEE Transaction on Automatic Control*, **36** (5).