Michał KUBICKI, Krzysztof PIETRUSEWICZ, Paweł WASZCZUK
WEST POMERANIAN UNIVERSITY OF TECHNOLOGY SZCZECIN
37 Sikorskiego 37, 70-313 Szczecin, Poland

Method of friction modeling and identification in PMSM

Abstract

Friction forces present in the PMSM motor exert a very negative influence on its working parameters. Those effects are extremely nonlinear and their consequences have to be acknowledged at designing both the motor's mechanical construction and its control system. This paper describes a friction coefficients identification method in the PMSM based on the mathematical model. The results of simulation research have been backed up by the real-world object testing. In the first section of this paper a brief summary of the most important aspects of PMSM motors was included while the second one focuses on the theoretical description of friction model that was used during research. Third part of this paper is focused on the detailed description of the PMSM motor model and its simplifying assumptions. The fourth section contains a description and results of concluded research in the Matlab/Simulink environment. Finally, the article concludes with comparison of theoretical results and experimental results obtained from real-world motor.

Keywords: friction modeling, friction identification, PMSM, permanent magnets synchronous motor.

1. Introduction

Permanent magnet synchronous motors (PMSM) have gained a lot of popularity in industrial applications. Many reasons contribute to their positive reception, among them are: high achievable torque, large torque overload and wide speed control range [1, 6]. PMSM motors are commonly used in CNC machines, robotic manipulators and cutting table drives. Their high efficiency and scalability offers much in terms of motor applications, which are so varied that a plethora of different PMSM designs has emerged (e.g. variable magnet position in rotor) – all aiming for optimization in different work environments.

Due to their construction and applicability of vector control, synchronous motors display many positive qualities in their control process as well as in their dynamic behavior. This is achievable through small inertia and large torque overload margin. Drawbacks of PMSM motors include problems in control during relatively small rotational speeds when the speed has to be regulated precisely, e.g. CNC control.

PMSM motor is most often powered by an inverter using a sinusoidal signal. There are many examples in literature presenting the structures of PMSM control [3,7]. Currently the most popular method is FOC (Field Oriented Control), often referred to as 'vector control'. This method uses measurement of feedback current signals, voltage in stator windings as well as rotor's position angle and transforms them into the two-phase system. Based on that information the control system computes new phase voltages, converts them into three-phase system and finally sends respective control signals to the inverter. This control structure, by achieving a very accurate steady state and transient control, leads to high dynamic performance in terms of response times and power conversion.

Friction forces in PMSM exert a negative influence on positioning precision and movement at small velocities. An accurate description of the friction phenomena in motor is difficult due to the nonlinear nature of this effect. Friction is most often modeled as a disturbance in object input which explains steady state error both in control and following tasks.

Designed friction models (i.e. dynamic and static) allow to estimate (within a set tolerance) friction values affecting mechanical parts of motor during its movement. This information is particularly useful in the motor's development process when one of the product's main priorities are its good motion properties and wide speed regulation. It also serves as the basis of control algorithm design with the aim of compensating the negative friction effects on the drive system.

Influence of Coulomb friction on the PMSM motor may be observed during the velocity direction change, start and stop movement phases, movement with low rotational speeds. One of the negative consequences is an appearance of the 'stick-slip' phenomenon. Viscous friction is observable when the motor overcomes the static friction and begins its rotational movement. This friction is proportional to the motor's speed.

2. Friction modeling

During the course of many years a multitude of models describing friction have been designed in order to better understand the phenomenon and counteract it [2]. Generally, one might discern static and dynamic friction models. Usage of before mentioned models depends largely on one's preference and the design goal, but also on the computational difficulty of the problem and model's accuracy.

The general approach to the friction modeling includes four friction elements: static friction, Coulomb friction, viscous friction and Stribeck effect [5].

The static friction describes object state when the internal friction forces are larger than the external forces affecting it. The object moves when the static friction is overcome. This phenomenon is described by the following equation:

$$F = \begin{cases} F_e & \text{if } \omega = 0 \text{ and } |F_e| < F_s \\ F_s \operatorname{sgn}(F_e) & \text{if } \omega = 0 \text{ and } |F_e| \geq F_s \end{cases} \quad (1)$$

where:
F_e - external force
F_s - static friction maximum magnitude.

Coulomb friction is a force with opposing direction to the direction of object's movement and has a constant coefficient. The equation describing this effect:

$$F_c = \mu F_N \quad (2)$$

where:
μ - Coulomb friction coefficient
F_N - normal force.

Viscous friction is proportional to the object's velocity. The function that illustrates this dependency is presented below:

$$F = F_v \omega \quad (3)$$

where:
F_v - viscous friction coefficient
ω - velocity.

Stribeck effect is observable for small speeds when the object begins its movement. This effect is nonlinear and the minimum speed value found on the speed curve is named as 'Stribeck velocity'. The graph of the friction model including all these effects is given in the Fig. 1.

Fig. 1. Friction forces model

In this article due to the undertaken simplifications and practical aspect of the presented method (i.e. simulation execution time), a classical approach in friction coefficient identification was used which includes both dynamic and static frictions but omits Stribeck effect. The relation between investigated frictions is given by the following equation:

$$F_f(v) = (F_c + F_v|v|)\operatorname{sgn}(v) \tag{4}$$

The applied model is not continuous for zero speed which leads to numerical problems. Due to this fact, friction coefficients for the PMSM motor were calculated for values above the static friction and the following assumption was made: F_s=F_c.

3. PMSM simulation model

The model used for simulation calculations is based on Space Vector Modulation method. Due to that fact a system of equations can be simplified and transformed to different coordinate systems. Derivation of those vectors is based on substitution of three-phase values of voltages, currents and fluxes by one resulting field vector of those physical properties in complex plane [4, 8].

In order to implement this model in the simulation environment a number of simplifications had to be made:

- symmetrical three-phase winding,
- resistance and inductance of winding is constant,
- hysteresis and saturation phenomena in magnetic windings were omitted,
- losses in rotor and stator were omitted,
- only the first harmonic was considered for the field distribution in the air gap.

Furthermore, cogging and ripple torques were neglected in the model due to construction of exploited in experiment machine, which minimalizes the impact of those phenomena on friction – appropriate arrangement of the permanent magnets.

3.1. PMSM differential equations

$$\begin{aligned}
\frac{di_d}{dt} &= -\frac{R}{L_d}i_d + \frac{L_q p}{L_d}\omega i_q + \frac{1}{L_d}u_d \\
\frac{di_q}{dt} &= -\frac{R}{L_q}i_q - \frac{L_d p}{L_q}\omega i_d - \psi\omega + \frac{1}{L_q}u_q \\
\frac{d\omega}{dt} &= \frac{1}{J}\left[\frac{3p}{2}\psi i_q + (L_d - L_q)i_d i_q - F_c\operatorname{sgn}(\omega) - F_v\omega - \tau_{load}\right] \\
\frac{d\Theta}{dt} &= \omega
\end{aligned} \tag{5}$$

Symbols used in equations are listed in the Tab. 1.

Tab. 1. Description of motor parameters

Parameter	Definition	Unit
R	Stator resistances	Ω
L_d	d-axis stator inductance	H
L_q	q-axis stator inductance	H
J	Moment of inertia	kgm^2
p	Number of rotor pole-pairs	
ψ	Magnetic flux of Permanent magnet	Wb
i_d	d-axis stator current	A
i_q	q-axis stator current	A
u_d	d-axis stator voltage	V
u_q	q-axis stator voltage	V
ω	Angular velocity	rad/s
Θ	Angular displacement	rad
F_c	Coulomb friction factor	Nm
F_v	Viscous friction factor	Nm/rad
τ_{load}	Load torque	Nm

Motor manufacturers' catalogues often contain defined parameters which can be used in simulation model. However, they are not always precise. One must pay attention whether those values are defined for nominal operation or peak operation. One of the problems encountered during the design of simulation model was estimation of flux values from permanent magnets. This particular parameter is commonly omitted in motor producer's parameter list. Instead, estimation of flux can be done using the following pair of equations:

$$\psi = \frac{\sqrt{2}K_t}{3p} \tag{6}$$

$$\psi = \sqrt{\frac{2}{3}}\frac{V_e}{p} \tag{7}$$

where:

K_t - Torque constant, Nm/A
V_e - Voltage constant, V/1000 min^{-1}
p - pole pairs.

4. Simulation experiment

Simulation experiments were conducted in Matlab/Simulink environment where the before mentioned PMSM model was implemented. The goal of this research was to evaluate friction coefficients (i.e. viscous and Coulomb) which, as previously mentioned, are often omitted in producer's catalogue notes, while other model's parameters were based upon available data:

Tab. 2. Parameter values used in simulation model

Parameter	Value	Unit
R	19	Ω
L_d	49.16	mH
L_q	49.16	mH
J	0.9	Kgcm^2
p	4	
ψ	0.172*	Wb
F_c	0.0213**	Nm
F_v	0.000168**	Nm/rad
τ_{load}	0	Nm

* Value estimated
** Random values selected for the experiment

For experimental purposes a random values for friction coefficients were introduced. The simulation experiment was based on gradually adjusting rotational speed from –200 rad/s to 200 rad/s with a constant step of 10 rad/s in motor's cascade control loop, while measuring velocity's and torque's values.

The data information was gathered after the motor achieved its set velocity. Torque was calculated using the following equation:

$$T = K_t i_q \tag{8}$$

In order to find friction coefficients registered rotational velocity was placed on x-axis of the graph while the measured torque was put on the y-axis. An equation for the linear interpolation of the measured data points was found. The slope of this function (*ax*) describes the viscous friction coefficient F_v, while the intercept describes the Coulomb friction coefficient F_c.

Fig. 2. Estimation of friction coefficient

The simulation results confirmed the validity of the applied friction coefficient identification method. Friction values introduced into simulation for Coulomb and viscous friction were respectively: F_c= 0.0213 Nm, F_v= 0.000168 Nms/rad. In the concluded experiment those values equated to F_c = 0.02066 Nm for Coulomb friction and F_v= 0.0001625 Nms/rad for viscous friction. In both of these cases RMS error was equal to 1%. Linear approximations were made both for positive and negative rotational movement and the received results were identical.

5. Laboratory test-stand experiment

In order to verify the simulation method a set of experiments has been concluded on a real-world object. The test-stand was built using components supplied by Bernecker and Rainer company. The measurement stand consisted of a Programmable Logic Controller, servodrive and PMSM motor. The motor's parameters (Tab. 2.) were used in simulations found in the preceding section.

In the experiment torque was measured for corresponding velocity values with load free motor shaft. The measurement was repeated thrice in order to verify accuracy of the data; received values were averaged. The data was inserted into prepared Matlab application in order to find friction coefficients and compare them with simulation results. The following graphs show a sample set of data received from conducting the test on a laboratory stand:

As a result of the practical experiment, Coulomb friction value was obtained (F_c= 0.03553 Nm) as well as viscous friction coefficient (F_v= 0.0001991 Nms/rad). These values were entered into the simulation model in order to compare the accuracy of simulation results. They were also compared with real-world object experiment measurements, and the comparison is given in the Fig. 4.

The root-mean-square error between measured values and those simulated by the model was equal to 1.86% which proves the correctness of the undertaken method. Both for the negative and positive rotational movement, the model achieved satisfactory precision. Practical appliance of the presented method is relatively simple and may be used when a need to identify the friction coefficients arises.

Fig. 3. Obtained actual velocity and torque signals fromtest-stand

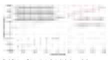

Fig. 4. Friction coefficients estimation for simulated and measured values

6. Conclusions

Friction relations and their identification is an issue of an upmost importance for all machines. The knowledge of their negative influence on machine's operation is a popular research topic. In many motion solutions friction is a major issue, especially for precise positioning and elimination of set errors in control and following tasks. In this paper a method was described that can be used to identify viscous and Coulomb friction in permanent magnet synchronous motor. Undertaken simulation research and real-world tests proved correctness of the proposed solution and therefore it can be successfully used in other motor applications. Presented results may be applied in design stages of motor's control algorithms and its mechanical construction.

7. References

[1] Foo G., Rahman M.F.: Sensorless Sliding-Mode MTPA Control of an IPM Synchronous Motor Drive Using a Sliding-Mode Observer and HF Signal Injection. IEEE Transactions on Industrial Electronics, vol. 57, no.2, pp. 1270-1278, 2010.

[2] Lee D.H., Ahn J.W.: Dual speed control scheme of servo drive system for a nonlinear friction compensation, IEEE Transactions on Power Electronics, vol. 23, no. 2, pp. 959-965, 2008.
[3] Liu H.S., Zhu Z.Q., Mohamed E., Fu Y.L., Qi X.Y.: Flux-Weakening Control of Nonsalient Pole PMSM Having Large Winding Inductance, Accounting for Resistive Voltage Drop and Inverter Nonlinearities, IEEE Transactions on Power Electronics, vol. 27, no. 2, pp. 942-952, 2012.
[4] Liu H.X., Li S.H.: Speed Control for PMSM Servo System Using Predictive Functional Control and Extended State Observer, IEEE Transactions on Industrial Electronics, vol. 59, no. 2, pp. 1171-1183, 2012.
[5] Lornic M., Bela L.: Modeling, Identification, and Compensation of Stick-Slip Friction, IEEE Transactions on Industrial Electronics, vol. 54, no. 1, pp. 511-521 ,2007.
[6] Morel F., Lin-Shi X., Retif J.M., Allard B., Buttay C.: A Comparative Study of Predictive Current Control Schemes for a Permanent-Magnet Synchronous Machine Drive, IEEE Transactions on Industrial Electronics, vol. 56, no. 7, pp. 2715-2728, 2009.
[7] Preindl M., Bolognani S.: Model Predictive Direct Speed Control with Finite Control Set of PMSM Drive Systems, IEEE Transactions on Power Electronics, vol. 28, no. 2, pp. 1007-1015, 2013.
[8] Zawirski K.: Sterowanie silnikiem synchronicznym o magnesach trwałych. Wydawnictwo Politechniki Poznańskiej, ISBN 83-7143-337-9, 2005.

Received: 03.06.2016 Paper reviewed Accepted: 01.08.2016

Michał KUBICKI, MSc

Born in 1986, Szczecin, Poland. Received MSc degree in 2010 from West Pomeranian University of Technology in automatics and robotics. Started his work towards PhD degree in 2014. Currently employed as a research assistant at West Pomeranian University of Technology. Research interests include artificial intelligence, optimization, game theory and modeling.

e-mail: michal.kubicki@zut.edu.pl

Krzysztof PIETRUSEWICZ, DSc

Born in 1977, Szczecin, Poland. He graduated (MSc eng.) from Faculty of Electrical Engineering of West Pomeranian University of Technology in Szczecin, Poland in 2002, where he has been working as an assistant professor since 2006. At the same university he gained PhD (2005) and DSc (2012).He also cooperated with Cargotec Sweden AB (Applied Research Department, HIAB) as a researcher. From October'2016 Associate Professor at WPUT, Faculty of Electrical Engineering.

e-mail: krzysztof.pietrusewicz@zut.edu.pl

Paweł WASZCZUK, MSc

Born in 1986, Szczecin, Poland. Received MSc degree in 2010 from West Pomeranian University of Technology in automatics and robotics. PhD student and research assistant at West Pomeranian University of Technology in Szczecin. His main scientific interests are control theory, mechatronics and modeling.

e-mail: pawel.waszczuk@zut.edu.pl