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Current-independent torque control of permanent-magnet synchronous motors

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Abstract

A current-independent torque equation for the permanent-magnet synchronous motor (PMSM) aiming at direct-drive servo applications is derived from a first principles model. Instead of measuring currents, all required control parameters are derived from optical incremental encoder measurements. The results are verified on a real system in test series showing the effect of static friction and proving the obtained torque model.

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1. Introduction

The permanent-magnet synchronous motor (PMSM) is widely used in industrial applications, e.g. in machine tools, since it provides superior power and torque density, efficiency, reliability and dynamics as compared to other motor types, especially those using slip rings or brushes [1]. Admittedly, controlling a PMSM is a complex task that requires additional electronic components. However, over the last decades the latter became smaller and available at low costs enabling a wider use of the PMSM. Especially in the field of remote controlled airplanes and helicopters it enjoys great popularity, but also manufacturers of domestic appliances discovered its great potential recently.

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Nomenclature

a	a scalar	$\boldsymbol{a}^B$	a space phasor expressed in the frame B
$\boldsymbol{a}$	a vector or space phasor	a_C	a quantity that is given in frame C
$\boldsymbol{A}$	a matrix	$\boldsymbol{\Psi}$	a flux space phasor

In general, weight- and size-limited applications can benefit most from using a PMSM. One particular application is the use as a servo drive in position controlled actuators, which are frequently employed in mobile robotics.

Often, torque, speed and position controllers are cascaded to control a PMSM servo drive, causing the need for feedback signals of these three quantities. For this purpose, much effort has been devoted to the development of sensor-less algorithms for speed and position estimation, that are purely based on measurements of voltages and currents.

However, these algorithms essentially rely on physical effects occurring to a measurable extent during high-speed operation, like the induced back electromotive force (back-EMF). Hence, such algorithms cannot be applied directly to servo applications with a low turning rate due to physical limitations [2]. For this reason, it is common practice to attach additional sensors, e.g. an encoder or a tachometer, to the shaft of the motor to measure its position or speed.

Nevertheless, the underlying torque controller still requires current measurements. Getting these measurements correctly can be a challenging task, because the necessary analog-to-digital conversion has to be synchronised with the pulse-width modulated (PWM) signal controlling the motor. This process can tie a significant amount of hardware resources of a modern microcontroller, which might be needed for other tasks.

In this paper, an approach is presented that does not require any current measurements. Instead, an optical incremental encoder is attached to the motor and all required quantities are derived from it in order to control the torque generated by the motor. Thereby this paper presents an extension to the work presented in [3], where a complete servo control structure is outlined. In contrast, this paper focuses on the validation of the underlying principles.

2. Mathematical Model of the PMSM

A mathematical model of the three-phase PMSM can be found in almost every paper about field-oriented control (FOC), which is also known as vector control. One of the first derivations is presented in [4]. However, for a more comprehensible introduction to motor control see [5]. The fundamentals shown here are also presented in [3].

Assuming saturation, hysteresis losses and eddy currents are negligible, the stator voltage equation can be expressed in the stator reference frame S, usually called the αβ reference frame [5], as

$$\boldsymbol{u}^S = R_S \cdot \boldsymbol{i}^S + \frac{d}{dt}\boldsymbol{\Psi}^S \tag{1}$$

where R_S denotes the resistance of the stator windings and $\boldsymbol{i}_S$ are the three-phase currents. The stator flux is given by

$$\boldsymbol{\Psi}^S = \boldsymbol{L}_S \cdot \boldsymbol{i}^S + \boldsymbol{\Psi}_m^S \tag{2}$$

with $\boldsymbol{L}_S$ describing the self-inductance of the stator and $\boldsymbol{\Psi}_m^S$ being the contribution of the rotor flux. In the rotor reference frame R, which is usually named dq coordinate frame [5], the rotor flux can be treated as a constant, i.e. $\boldsymbol{\Psi}_m^R = \psi_{PM}$. Given the electrical rotor angle ϑ, the dq coordinate frame can be transformed into the αβ reference frame by a simple rotation:

$$\boldsymbol{\Psi}_m^S = \mathrm{e}^{j\vartheta} \cdot \boldsymbol{\Psi}_m^R = \mathrm{e}^{j\vartheta} \cdot \psi_{PM} \tag{3}$$

where j is the unit imaginary number.

The electrical rotor angle is related to the mechanical rotor angle, $\vartheta_{\mathrm{mech}}$, by the number of motor pole pairs p:

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