A Novel Torque Controller with Direct Flux Control for Permanent Magnet Synchronous Motor

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Abstract: Permanent-magnet synchronous motors (PMSMs) are expected to generate a desired torque with high dynamic performance in most traction drive applications. The limitation of current and dc link voltage of a given inverter impact the maximum torque generating capability and the maximum speed with rated torque capability. The paper designs a torque controller directly from a coupling system model for PMSM by using a triple-step nonlinear method, in which the air gap flux control is considered explicitly. From the application point of view, the robustness analysis is discussed for the proposed controller. Finally, the proposed control scheme is carefully verified by simulations. The simulation results show that the proposed nonlinear triple-step controller has a comparative control performance with a widely used controller, and also show that the transition from the constant-torque operation region to the constant-power operation region is straightforward and effective during flux-weakening control.

Keywords: PMSM, torque control, direct flux control, field weakening, triple-step nonlinear method, nonlinear parameter-varying system, two input and two output system.

1. INTRODUCTION

Permanent-magnet synchronous motor (PMSM) is widely used for industrial system, especially for the high-performance motion system, due to its high power density, efficiency, and reliability Gieras (2002). In traction drive applications, such as hybrid electric vehicle (HEV) with a central motor and electric vehicle (EV) with in-wheel motors, the PMSMs are expected to generate a desired torque with high dynamic performance.

For high-performance motor applications, there are two dominating control strategies: field-oriented control (FOC) Blaschke (1972) and direct torque control (DTC) Takahashi and Noguchi (1986). Based on these two control concepts, different control methods have presented in the past decades. FOC-based strategies have a good steady-state performance while DTC-based strategies have a fast dynamic response. With the help of Park’s transformation, the stator current can be decomposed into stator flux current component and stator torque-producing current component. In most industrial applications, the stator flux current component is set to zero to make the torque angle equal to 90°, and then the stator torque-producing current component is controlled independently to generate a corresponding torque Krishnan (2009). This method is suitable for a nonsalient-pole PMSM, but not for salient-pole PMSM. To further explore the potential of PMSM, a maximum torque per ampere (MTPA) strategy is proposed to generate an optimum current trajectory. According to the current trajectory, a decoupling current controller is used to track the current references in Morimoto et al. (1994). Considering that the MTPA strategy is widely used at steady state, excluding the transient response, Consoli et al. (2010) provides a useful modification of the current loop to improve the transient performance. In addition, the increasing computational power of the microprocessors prosppers the advanced model-based control strategies, such as model predictive control Rojas et al. (2013), adaptive output-feedback control Tomei and Verrelli (2013).

The limitation of rotor speed resulting from the voltage constraint contradicts with the requirement to operate in wide speed region (commonly happens to the traction motors in EV and HEV). To overcome this situation, the electromotive force (EMF) is constrained to be less than the maximum available voltage by flux weakening technique. Krishnan (2009) provides a classification of flux-weakening control schemes, namely indirect flux control and direct flux control. Indirect flux control does not explicitly consider the air gap flux control, just bases on current controller with current and voltage constraints. Typically, lookup tables for stator flux current and torque-producing current are precaculated for a desired torque with respect to various operating conditions, such as rotor speed and dc-link voltage Cheng and Tesch (2010); Bae et al. (2003), and then a decoupling current controller is used to track the precaculated current reference. Indirect
flux control is popular in FOC. Direct flux control is common in direct torque control where the transition from the constant-torque operation region to the constant-power operation region is straightforward. Hysteresis controller is needed for direct flux control in classical DTC, which brought many disadvantages, such as high torque and flux ripples. Xu and Rahman (2007) provides a nonlinear variable structure controller to minimize torque and flux ripples and achieve high performance.

The paper will design a torque controller directly from the coupling system model for PMSM by using a triple-step nonlinear method, in which the air gap flux control is considered explicitly. The triple-step nonlinear method was first proposed to design a nonlinear controller for rail pressure system in gasoline direct injection engines Chen et al. (2014), and has been used for motor position control Gao et al. (2014) and motor speed control Chu et al. (2016, 2017). From the perspective of the triple-step nonlinear method, the paper extends the method to the nonlinear parameter-varying system with two control inputs and two control outputs. In addition, from the perspective of PMSM torque control, the paper provides a novel torque controller with direct flux control.

The rest of the paper is organized as follows. Section 2 presents a decoupling dynamic model and constraint of PMSMs. In Section 3, a nonlinear torque controller is derived from a controller-design-oriented model by using the triple-step nonlinear method, and robustness analysis is given. After that, the proposed control scheme is verified by simulations and main results are shown in Section 4. Finally, conclusions are outlined in Section 5.

2. MODEL AND CONSTRAINT OF PMSMS

In PMSMs, the permanent magnets are embedded in the rotor to produce a constant magnetic field, while the windings are mounted on the stator to create a rotating magnetic field. According to rotor construction, PMSMs are broadly divided into two categories, salient-pole PMSMs and nonsalient-pole PMSMs.

Although there are some difference between these two categories of PMSM, the dynamics can be described by an equivalent two-phase circuit model, as shown in Fig. 1. Using the Kirchhoff voltage laws, the dynamic model in d-q reference frame are expressed as

\[
i_d = \frac{R_s}{L_d}i_d + \frac{L_q}{L_d}\omega_e i_q + \frac{1}{L_d}u_d \tag{1a}
\]

\[
i_q = -\frac{L_d}{L_q}\omega_e i_d - \frac{R_s}{L_q}i_q + \frac{1}{L_q}u_q - \frac{\phi_f}{L_q} \omega_e \tag{1b}
\]

where \(i_d\) and \(i_q\) are the \(d-\) and \(q-\)axis stator current components, respectively, \(u_d\) and \(u_q\) are the \(d-\) and \(q-\)axis stator terminal-voltage components, respectively, \(L_d\) and \(L_q\) are the \(d-\) and \(q-\)axis inductances, and \(R_s\) is the stator resistance, \(\phi_f\) is the flux linkage generated by the PMs, and \(\omega_e\) is the electrical angular velocity. The \(d-\) and \(q-\)axis stator flux-linkage components \(\phi_d\) and \(\phi_q\) are given as

\[
\phi_d = \phi_f + Lqid \tag{2a}
\]

\[
\phi_q = Lqiq \tag{2b}
\]

The torque generated at the rotor shaft \(T_e\) is calculated by

\[
T_e = p\phi_f i_q + p(L_d - L_q)i_d \tag{3}
\]

where \(p\) is the number of pole pairs.

![Fig. 1. Equivalent circuit in d-q reference frame](Image)

Considering the power limitations of the PMSM drives, the stator current and terminal-voltage limitation are given as follows

\[
i_d^2 + i_q^2 \leq i_{max}^2 \tag{4a}
\]

\[u_d^2 + u_q^2 \leq u_{max}^2. \tag{4b}\]

where \(i_{max}\) and \(u_{max}\) are the maximum stator phase current and the maximum stator phase voltage, respectively. Assuming that the PMSM is at steady state and the voltage drop caused by the stator resistance can be neglected, the stator terminal-voltage limitation (4b) can be represented as

\[
\phi_d^2 + \phi_q^2 \leq \left(\frac{u_{max}}{\omega_e}\right)^2. \tag{5}
\]

As depicted in Eq. (5), in the case that the dc link voltage decrease or the electrical angular velocity increases (always happens to electric vehicle application), the field weakening technique is introduced to further increase PMSM speed, i.e., the field weakening technique is expected to make the PMSM produce the rated torque with the highest attainable speed. The boundary conditions given in (4a) and (5) are shown in Fig. 2 by a current-limit circle and three voltage-limit ellipses.

The limitation of current and dc link voltage of a given inverter impact the maximum torque generating capability and the maximum speed with rated torque capability. Considering the necessity of field weakening for PMSMs and the air gap flux is wanted to be controlled directly, the outputs to be controlled are selected as

\[
y_1 = T_e \tag{6a}
\]

\[
y_2 = \phi_d^2 + \phi_q^2 \tag{6b}
\]

To understand the structure of these two outputs to system inputs, taking the derivative of \(y_1\) and \(y_2\) with respect to time yields

\[
\begin{bmatrix}
y_1 \\
y_2
\end{bmatrix} = \begin{bmatrix}
p(L_d - L_q)i_q \\
2L_d(\phi_f + L_d i_d)
\end{bmatrix} \begin{bmatrix}
i_d \\
i_q
\end{bmatrix} + \begin{bmatrix}
2(\phi_f + L_d i_d)
\end{bmatrix} \dot{\phi}_f. \tag{7}
\]

After substituting (1) into (7), the PMSM dynamics can be presented as the following vector form

\[
\dot{y} = \text{b}(y, p)u + a_0(y, p)\omega_e + a_1(y, p) + B\dot{\phi}_f \tag{8}
\]
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