Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 50-1 (2017) 758–763

Model Predictive Torque Control of Permanent Magnet Synchronous Machines

Tobias Englert * **Stefan Grüner** ** **Knut Graichen** *

* *Institute of Measurement, Control and Microtechnology Ulm University, 89081 Ulm, Germany*
e-mail: [tobias.englert,knut.graichen]@uni-ulm.de.
** *Robert Bosch Automotive Steering GmbH, 73527 Schwäbsich Gmünd, Germany*
e-mail: Stefan.Gruener@bosch.com.

Abstract: This contribution presents a nonlinear model predictive torque control (MPTC) scheme for permanent magnet synchronous machines (PMSMs) to provide a desired torque in an energy efficient way over a wide operational range. The MPTC relies on the nonlinear dq-model and uses a numerically efficient gradient method in combination with the augmented Lagrangian method to account for voltage and currents constraints. Simulation results show the performance and robustness of the control scheme as well as the computational efficiency and real-time feasibility.

Keywords: MPC, torque control, PMSM, nonlinear constraints, augmented Lagrangian technique, gradient method, real-time.

1. INTRODUCTION

Permanent magnet synchronous machines (PMSMs) are widely used in industrial and automotive applications due to the high energy efficiency and torque density. Typical control tasks are either to control the rotor speed or to deliver a desired torque over a certain speed range of the motor.

Various control strategies for PMSMs can be found in the literature. Most of them are based on the classical dq-model and are known as field-oriented control (FOC). Beside proportional-integral controllers (Schröder, 2009), approaches using state-space controllers (Quang and Dittrich, 2008), fuzzy controller (Jun et al., 2004) and backstepping methods (Morawiec, 2013) are mentioned in the literature. A flatness-based control based on a reluctance network model instead of the dq-model was recently presented in Faustner et al. (2015a,b). However, these approaches struggle with more challenging tasks such as flux weakening operation mode or the adherence of constraints, e.g. given by the maximum DC-link voltage or the maximum phase current. Often these properties are not taken into account explicitly or only in a heuristic manner (Bolognani et al., 2011).

On the other hand, model predictive control (MPC) is a suitable control approach to account for constraints and several MPC algorithms were presented recently for PMSMs, see e.g. Preindl et al. (2013); Preindl and Bolognani (2013); Cimini et al. (2015); Chai et al. (2013). These control schemes account for the above mentioned constraints by using different approaches and trade-offs to achieve real-time feasibility. For instance, Preindl and Bolognani (2013) uses a (low-dimensional) finite control set that might induce torque ripples, while Cimini et al. (2015) as well as Chai et al. (2013) do not consider flux weakening or anisotropic machines.

With regard to automotive applications, the PMSM control task is even more difficult, since further constraints such as battery current limits that are communicated by the battery management system (BMS) must be taken into account. In particular, the focus in this research is on an automotive application such as electric power steering systems, which requires a high performance control with high torque accuracy and very fast dynamics in the whole operation range of the motor from zero to the maximum rotor speed.

Motivated by the above mentioned challenges, this paper presents a new nonlinear model predictive torque controller (MPTC) for PMSMs. The MPTC uses a real-time gradient method based on the dq-model, that can be applied to both isotropic and anisotropic machines. The aforementioned, nonlinear constraints are considered using an augmented Lagrangian formulation. Simulation results show the performance, robustness and computational efficiency of the MPTC. In particular, the high computational speed is demonstrated by run-time results on a standard PC and dSPACE hardware, indicating the portability to an electronic control unit (ECU) in future automotive applications.

2. PROBLEM STATEMENT

The MPTC scheme presented in this work is based on the well-known dq-model for PMSMs. Along with a short introduction of the motor model, this section derives the constraints and reference values as well as the general optimal control underlying the MPTC.

2.1 Dynamic model

Figure 1 shows a schematic drawing of the considered drive that can be divided into a mechanical and an electrical subsystem. A convenient approach is to model the electrical

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2017.08.249

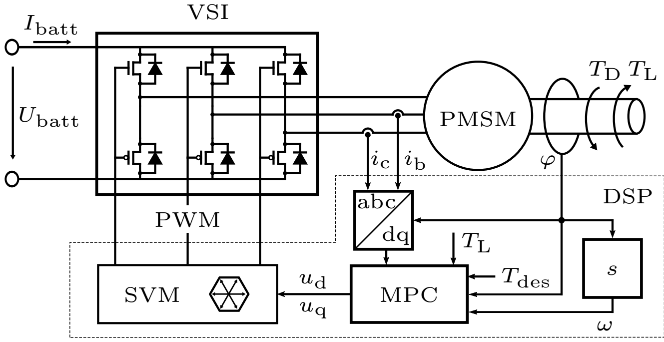

Fig. 1. Mechanical and electrical PMSM subsystems.

subsystem in the dq-reference frame using the amplitude-invariant dq-transformation (Schröder, 2009). This leads to the ordinary differential equations (ODEs)

$$L_{\mathrm{d}} \tfrac{\mathrm{d}}{\mathrm{d}t} i_{\mathrm{d}} = -(R_{\mathrm{s}} + R_{\mathrm{vsi}}) i_{\mathrm{d}} + L_{\mathrm{q}} \omega i_{\mathrm{q}} + u_{\mathrm{d}} \tag{1a}$$

$$L_{\mathrm{q}} \tfrac{\mathrm{d}}{\mathrm{d}t} i_{\mathrm{q}} = -(R_{\mathrm{s}} + R_{\mathrm{vsi}}) i_{\mathrm{q}} - L_{\mathrm{d}} \omega i_{\mathrm{d}} - \omega \psi_{\mathrm{p}} + u_{\mathrm{q}} \tag{1b}$$

with the mechanical and electrical rotor speed n and $\omega = \frac{2\pi z_{\mathrm{p}}}{60} n$, respectively. Further system parameters are the number of pol-pairs z_{p}, the stator resistance R_{s}, the dq-inductances L_{d}, L_{q}, and the permanent flux linkage ψ_{p}. [1] Finally, R_{vsi} represents the resistance of the voltage source inverter (VSI) in Figure 1, which in all other respects is an ideal component by assumption.

The mechanical subsystem of the PMSM can be derived by the law of conservation of angular momentum, i.e.

$$J\dot{\omega} = \left(T_{\mathrm{D}}(i_{\mathrm{d}}, i_{\mathrm{q}}) - \tfrac{\mu_{\mathrm{f}}}{z_{\mathrm{p}}} \omega - T_{\mathrm{L}} \right) z_{\mathrm{p}} \tag{2}$$

with the driving torque expression

$$T_{\mathrm{D}}(i_{\mathrm{d}}, i_{\mathrm{q}}) = \tfrac{3}{2} z_{\mathrm{p}} \left(\psi_{\mathrm{p}} i_{\mathrm{q}} + i_{\mathrm{d}} i_{\mathrm{q}} (L_{\mathrm{d}} - L_{\mathrm{q}}) \right) , \tag{3}$$

the load torque T_{L}, the moment of inertia J, and the friction coefficient μ_{f}.

In many motor applications, it is reasonable to use a time scale separation to consider the two subsystems (1) and (2) in a decoupled manner, cf. e.g. Preindl and Bolognani (2013). This paper, however, focuses on high dynamic performance drives, e.g. in automotive steering systems, which essentially necessitates to account for both subsystems simultaneously in the MPTC design as the time scales of both subsystems are in the same order of magnitude.

2.2 System constraints

Depending on the DC-link voltage, which is assumed to match the (possible time-varying) battery voltage U_{batt}, the VSI provides eight voltage vectors in the stator-fixed $\alpha\beta$-reference frame, see Figure 2. Using space vector modulation (SVM), a continuous set for $\alpha\beta$-input voltages can be generated by actuating the VSI with PWM signals. As a result of the modulation, the $\alpha\beta$-voltages lie inside the hexagon spanned by the aforementioned eight voltage

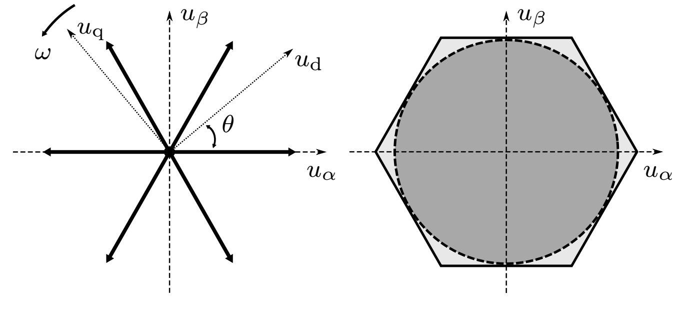

Fig. 2. Voltage constraints in the $\alpha\beta$-reference frame.

vectors. However, in order to reduce torque ripples, the voltages are typically restricted to the dashed inner circle in Figure 2, i.e.

$$U_{\mathrm{abs}} = \sqrt{u_{\mathrm{d}}^2 + u_{\mathrm{q}}^2} \leq U_{\max} = \tfrac{1}{\sqrt{3}} U_{\mathrm{batt}}. \tag{4}$$

A further constraint concerns the maximum phase current $I_{\max}$ of the system, which is either limited by the VSI or by the motor. This constraint may also be varied over time to take advantage of the thermal capacity of the motor (Qi et al., 2015). Mathematically, this constraint can be expressed in the dq-reference frame by the spherical inequality

$$I_{\mathrm{abs}} = \sqrt{i_{\mathrm{d}}^2 + i_{\mathrm{q}}^2} \leq I_{\max}. \tag{5}$$

A final constraint is imposed on the battery current, i.e. $I_{\mathrm{batt,min}} \leq I_{\mathrm{batt}} \leq I_{\mathrm{batt,max}}$. The limits are assumed to be provided by a BMS and may vary over time. Using a simple energy balance consideration, the battery current can be expressed as $I_{\mathrm{batt}} = \frac{3}{2} \frac{(i_{\mathrm{d}} u_{\mathrm{d}} + i_{\mathrm{q}} u_{\mathrm{q}})}{U_{\mathrm{batt}}}$, eventually leading to the box constraint

$$I_{\mathrm{batt,min}} \leq \tfrac{3}{2} \tfrac{(i_{\mathrm{d}} u_{\mathrm{d}} + i_{\mathrm{q}} u_{\mathrm{q}})}{U_{\mathrm{batt}}} \leq I_{\mathrm{batt,max}}. \tag{6}$$

The MPTC has to account for these constraints (4)–(6), which are essentially nonlinear in their arguments.

2.3 Computation of reference values

The generation of a desired torque T_{des} depends nonlinearly on the dq-currents according to (3) as well as on the constraints (4) - (6). The robustness and performance of the MPC can be significantly improved by generating corresponding reference values

$$\hat{\boldsymbol{i}} = \begin{bmatrix} \hat{i}_{\mathrm{d}} \\ \hat{i}_{\mathrm{q}} \end{bmatrix}, \ \hat{\boldsymbol{u}} = \begin{bmatrix} \hat{u}_{\mathrm{d}} \\ \hat{u}_{\mathrm{q}} \end{bmatrix} = \begin{bmatrix} (R_{\mathrm{s}} + R_{\mathrm{vsi}}) \hat{i}_{\mathrm{d}} - L_{\mathrm{q}} \omega \hat{i}_{\mathrm{q}} \\ (R_{\mathrm{s}} + R_{\mathrm{vsi}}) \hat{i}_{\mathrm{q}} + L_{\mathrm{d}} \omega \hat{i}_{\mathrm{d}} + \omega \psi_{\mathrm{p}} \end{bmatrix} \tag{7}$$

for the dq-currents and dq-voltages. Similar to the steady-state condition in Preindl and Bolognani (2015), $\hat{\boldsymbol{u}}$ follows from the stationary solution of the differential equations (1) and ω. Moreover, the battery current constraint (6) is neglected in the following to keep the complexity for computing $(\hat{\boldsymbol{i}}, \hat{\boldsymbol{u}})$ within reasonable limits.

The primary goal for computing the reference values $(\hat{\boldsymbol{i}}, \hat{\boldsymbol{u}})$ is to provide the desired torque T_{des}, i.e.

$$\tfrac{3}{2} z_{\mathrm{p}} \left(\psi_{\mathrm{p}} \hat{i}_{\mathrm{q}} + \hat{i}_{\mathrm{d}} \hat{i}_{\mathrm{q}} (L_{\mathrm{d}} - L_{\mathrm{q}}) \right) = T_{\mathrm{des}} , \tag{8}$$

as energy efficient as possible. This is basically the same as minimizing the Joule losses (Schröder, 2009) [2] , leading to the maximum torque per ampere (MTPA) trajectory

[1] These parameters are not necessarily constant, e.g. R_{s} typically depends on the temperature and L_{d}, L_{q} as well as ψ_{p} may depend nonlinearly on the dq-currents and the rotor angle. Such dependencies can be taken into account by the presented MPTC approach in a straightforward manner. For simplicity, however, they are assumed to be constant in this paper.

[2] Minimizing Joule losses is particularly relevant in automotive applications due to the typically low DC-voltages and high currents.