Control Engineering Practice 31 (2014) 1–8

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

An experimental assessment of finite-state Predictive Torque Control for electrical drives by considering different online-optimization methods

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ARTICLE INFO

Article history:
Received 3 September 2013
Accepted 10 June 2014
Available online 15 July 2014

Keywords:
Predictive Torque Control
Prediction horizon
Reduced switching frequency
Induction machine

ABSTRACT

Finite-State Predictive Torque Control (FS-PTC) is experimentally investigated based on different online-optimization methods by using a two-level voltage source inverter for an induction machine. The calculation time and the switching frequencies are important research points for FS-PTC industrial applications. Long-step FS-PTC methods are expected to improve the performance of the system. However, the calculation time will increase exponentially with the increase of the prediction horizon. A reduced switching frequency PTC (RSF-PTC) method by considering the reductions of the switching frequency and the calculation time is tested. Based on this algorithm, an extended prediction horizon is proposed and verified on a common test bench. A torque-band based PTC (TB-PTC) method is proposed and discussed in this paper. The TB-PTC method pre-calculates the torque error between the predicted torque and the torque reference. The optimization method focuses on the flux error and the switching frequency for switching states which constrain the torque error within the torque-band. The conventional FS-PTC method, the RSF-PTC method with one-step and two-step horizons and the TB-PTC method are developed and experimentally compared in this work. The results confirm that conventional FS-PTC, RSF-PTC and TB-PTC methods can work well in the full speed range. When the switching frequencies and the calculation effort are taken into consideration, the RSF-PTC algorithm shows the better performance. However, the conventional FS-PTC method and the TB-PTC method have better current performance.

1. Introduction

A model predictive control (MPC) method has been widely used in slow industrial processes, e.g. the petrochemical industry (Morari & Lee, 1999). The basic idea of the MPC method is to predict the future behavior of the system based on the plant model and selects the best output signals by optimizing a cost function (Camacho & Bordons, 2007). MPC methods can handle multivariable systems and it can consider the implementation constraints very easily (Maciejowski, 2002). However, in the past decades, the heavy calculation effort made it difficult for fast industrial processes.

Fortunately, with the development of fast microprocessors such as digital signal processing (DSP) and field programmable gate arrays (FPGAs), it is not a problem anymore to use the MPC method in fast industrial processes (Naouar, Ammar Naassani, Monmasson, & Slama Belkhodja, 2008). The MPC method was introduced into the field of power electronics and electrical drive systems in 1980s (Holtz & Stadtfeldt, 1983; Kennel & Schöder, 1983). The MPC method has been approved to have fast dynamics in this field and has become an important and popular research topic in recent years (Cortesands, Wilson, Kouro, Rodriguez, & Abu-Rub, 2010; Defay, Llor, & Fadel, 2010; Geyer, Papafotiou, & Morari, 2009; Linder, Kanchan, Kennel, & Stolze, 2010; Papafotiou, Kley, Papadopoulos, Bohren, & Morari, 2009; Rodriguez & Cortes, 2012). With a modulator continuous MPC has been investigated and has shown good performance (Kennel, Linder, & Linke, 2001). Without a modulator Finite-State MPC has been developed (Rodriguez et al., 2004, 2007). Compared to continuous MPC, Finite-State MPC has the advantages of a simple system structure and the absence of a modulator (Cortes, Kazmierkowski, Kennel, Quevedo, & Rodriguez, 2008). By considering different prediction horizons, the MPC method can be divided into two categories: one-step MPC and long-step MPC (>1 step). Although the offline optimization method reduces the calculation effort during every

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http://dx.doi.org/10.1016/j.conengprac.2014.06.004
0967-0661/

sampling interval, it increases the complexity of the controller (Baotic, 2005; Kvasnica, Grieder, Baotić, & Morari, 2004; Stolze, Landsmann, Kennel, & Mouton, 2011; Tøndel, Johansen, & Bemporad, 2003). The popular FS-MPC method by using the online optimization has been investigated mostly with one-step prediction. With a one-step prediction, it shows good performance and it was comparable with field oriented control (FOC) in Rodriguez et al. (2012). It has faster dynamics but leads to large current total harmonic distortion (THD) compared to the FOC method. It can also reach very similar performance with direct torque control (DTC) and has lower torque ripples (Kennel, Rodriguez, Espinoza, & Trincado, 2010). The FS-MPC method is even used in some sensorless situations (Davari, Khaburi, Wang, & Kennel, 2012). However, long-step prediction is rarely considered and implemented, because the big calculation effort makes this almost impossible on a common test bench. By using a two-level voltage source inverter for a one-step Finite-State MPC method, the switching selection cost function needs to be calculated seven times because the inverter only has eight different voltage vectors corresponding to the eight switching state possibilities. However, with a two-step FS-MPC method, the cost function needs to be calculated 7^2 times for the best switching state selection, which needs much more calculation power.

In Preindl, Schaltz, and Thogersen (2011) a lower inverter switching frequency method is proposed. It limits the switching state selection in every sampling interval. Only one leg switching state change is allowed in the RSF-PTC method. In this way, the switching frequency can be reduced. This method is also applied in Preindl and Bolognani (2013), where maximum torque per ampere (MTPA) based on a one-step MPC method is investigated and achieves good performance. More importantly, the solution reduces the calculation time of the optimization of the cost function. It makes possible to reach a long-step prediction FS-MPC method.

To optimize the online cost function, a TB-PTC method is proposed in this work. The TB-PTC method is an FS-PTC method which is designed by pre-considering a torque-band. A reduction of the inverter switching frequency is also considered in its cost function design. It does not reduce the calculation time. In every sampling interval all possible switching states are evaluated. The one which minimizes the cost function will be selected as the output. The optimization method focuses on the flux error and the switching frequency for switching states which constrain the torque error within the torque-band. When the value of torque error is within the torque-band, the cost function will neglect the torque error term. Therefore, better flux response and less switching frequency can be expected by using the TB-PTC method. In this work, the RSF-PTC method and the TB-PTC method are investigated experimentally and compared to the conventional FS-PTC method. The RSF-PTC method with one-step and two-step predictions are developed and compared. With the RSF-PTC the cost function only needs to be calculated four times. Therefore, it needs to be calculated 4^2 times with a two-step prediction, which is acceptable for the used common test bench. The dynamics, the switching frequencies, the calculation time, the torque ripples, the stator flux response and the stator current THD are considered in comparisons.

The paper is structured as follows: Section 2 introduces the mathematical model of an induction machine (IM). Section 3 presents the FS-PTC methods. The experimental results are shown in Section 4. The conclusions are presented in Section 5.

2. IM mathematical model

An induction machine can be described by a well-known set of complex equations using a stator reference frame (Holtz, 1994):

$$\vec{v}_s = \vec{i}_s \cdot R_s + \frac{d}{dt}\vec{\psi}_s, \tag{1}$$

$$0 = \vec{i}_r \cdot R_r + \frac{d}{dt}\vec{\psi}_r - j \cdot \omega \cdot \vec{\psi}_r, \tag{2}$$

$$\vec{\psi}_s = L_s \cdot \vec{i}_s + L_m \cdot \vec{i}_r, \tag{3}$$

$$\vec{\psi}_r = L_r \cdot \vec{i}_r + L_m \cdot \vec{i}_s, \tag{4}$$

$$T_e = \frac{3}{2} \cdot p \cdot \mathrm{Im}\left\{\vec{\psi}_s^* \cdot \vec{i}_s\right\}, \tag{5}$$

where $\vec{v}_s$ denotes the stator voltage vector, $\vec{\psi}_s$ and $\vec{\psi}_r$ represent the stator flux and rotor flux, respectively. $\vec{i}_s$ and $\vec{i}_r$ are the stator and rotor currents, respectively. R_s and R_r are the stator and rotor resistances, respectively. L_s, L_r and L_m are stator, rotor and mutual inductances and ω is the electrical speed, respectively. p is the number of pole pairs, and T_e denotes the electromagnetic torque.

3. Finite-state PTC method

An FS-PTC method includes three steps: variable estimations, predictions and optimizations. For variable estimations, all observers which provide accurate values of the variable estimation can be applied. The future required states must be predicted. Finally, the inverter switching signal which minimizes the cost function will be selected. The block diagram of FS-PTC method is shown in Fig. 1.

3.1. Estimations

The first step for FS-PTC method is to observe the required variables which cannot be measured. The quality of the estimated

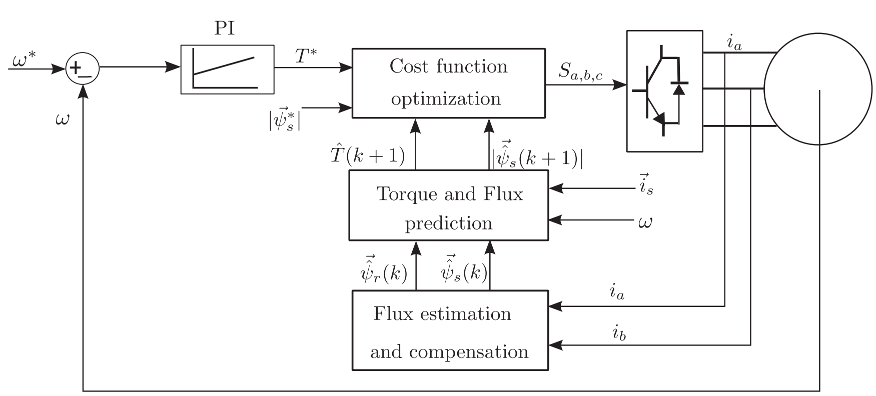

Fig. 1. Block diagram of FS-PTC method.