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Embedded Model Predictive Direct Switching Control for High Performance Electrical Drives - A Quantitative Comparison

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Abstract: This paper presents a quantitative comparison of state of the art model predictive direct switching control (MPDSC) methods for electrical drives. In MPDSC the switching states of the inverter are directly computed via model predictive control (MPC). This eliminates the need for modulators and presents an attractive alternative to classical field oriented control (FOC) approaches. Three classes of MPDSC methods are compared to field oriented model predictive control (FOMPC). The investigated MPDSC approaches are: hysteresis-based MPDSC, finite control set MPC (FCS-MPC) and model predictive pulse pattern control (MP^{3}C). The comparison is based on transient and stationary simulations of a permanent magnet synchronous machine (PSM) driven by a voltage-fed two-level inverter, representative for high-performance automotive applications.

Keywords: automotive control, model predictive control, electrical drives, embedded optimization, model predictive direct torque control

1. INTRODUCTION

High performance electrical drives can be found in plenty of industrial applications, in which they play an increasingly important role. Especially in automotive applications, where this development is driven by the trends towards electric mobility and electrification of auxiliaries. Typically, these drives are three-phase machines – e. g. permanent magnet synchronous machines (PSM) and asynchronous (induction) machines (ASM) – driven by two-level voltage-fed inverters in small to medium voltage range. These inverters can set one of two voltage-levels at each of the three terminals, which yields 2^3 discrete switching states.

Basically, there are two classical control approaches for electrical drives, that yield fast dynamic response. One is field oriented control (FOC), the other is direct torque control (DTC). With FOC, the inverter switching states are not considered directly. Instead, a continuous control set is introduced, which allows to apply standard methods like PI-control to compute a desired voltage vector. Then, this continuous voltage is approximated by a sequence of switching states using pulse width (PWM) or space vector modulation (SVPWM) [Leonhard, 2001]. With DTC, the modulation scheme is replaced by a controller that directly selects a specific switching state at each sample time instant. Thus, the finite inverter control set becomes an explicit degree of freedom for the controller. Typically, the selection is based on hysteresis methods and off-line precomputed look-up tables [Tiitinen and Surandra, 1996].

The quality of a control method for electrical drives depends on various factors. Common requirements are a fast dynamic response, small total harmonic distortions (THD), and minimal losses from both switching actions and the machine itself. In addition, the ability to operate close to constraints – maximal voltage and current – is important for efficient operation with either maximum torque per voltage (MTPV) or per ampere (MTPA).

In the past, advanced methods came up in order to capture the afore mentioned aspects. Amongst these approaches, basically two branches can be identified. On the one hand, standard modulation schemes can be combined with model predictive control strategies. Subsequently, this approach will be named field-oriented model predictive control (FOMPC). FOMPC works in a rotating dq-frame with the continuous input voltage $u_{dq} \in \mathcal{R}^2$, subject to quadratic state (max. current) and input constraints (max. voltage). The modulation approximates the continous voltage u_{dq} by a switching sequence over a duty cycle. By the predictive and optimal nature, the FOMPC scheme allows to operate the electrical drive close to voltage and current limitations which results in overall efficiency improvements.

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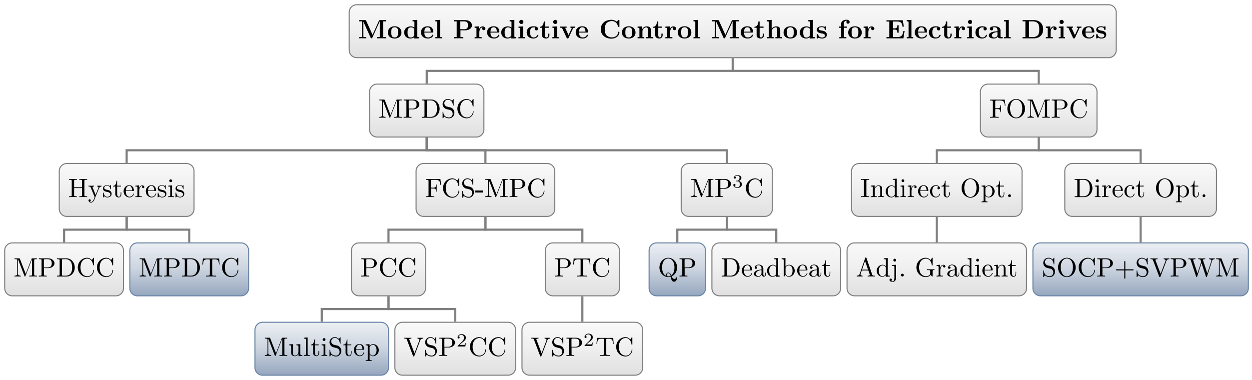

Fig. 1. Hierarchical overview of selected model predictive control methods for electrical drives

On the other hand, the recently upcoming model predictive direct switching control (MPDSC) procedure is the combination of the predictive nature of MPC and the direct choice of switching states known from DTC. This procedure computes the optimal switching sequence based on the solution of an online optimization problem, which is discussed in detail in the following.

The paper is structured as follows: Section 2 presents an overview and some mathematical background of selected MPDSC methods, that can be used for electrical drive systems. Section 3 deals with the quantitative comparison of these methods. A brief summary and a conclusion are given in Section 4.

2. MODULATION BASED VERSUS DIRECT SWITCHING - A TREE OF APPROACHES

MPDSC is a new and fast growing field with a corresponding diversity in methods. All these methods have in common, that they use a model predictive scheme that exploits the discrete nature of the control input.

The MPDSC method directly computes the switching state, thus offering a simple design and exploiting the discrete structure to improve performance, instead of treating it as an obstacle. In the following a short overview over MPDSC methods for electrical drives is given. Due to the vast number of schemes, only the most promising methods are presented and grouped by their common characteristics, in order to highlight the main approaches without going into details. With out loss of generality, we focus on two-level inverters and only allow one switch at a time. We focus only on PSM, even though most methods are equally applicable to ASM.

A graphical summary of the relationship of the different methods is illustrated in Figure 1. The selected methods, which will be used in the comparison are marked.

2.1 Hysteresis based MPDSC

Hysteresis based MPDSC methods can be viewed as an improved version of DTC. These methods force the control variables to be contained in some set, like DTC, while additionally minimizing the required switching effort [Geyer et al., 2009]. This is accomplished in a MPC like fashion, where infeasible input sequences are discarded and feasible outputs are extrapolated until a constraint violation occurs. Two variants can be distinguished: Model Predictive Direct Torque Control (MPDTC) [Geyer et al., 2009] enforces constraint on the torque T_e and stator flux Ψ_s, while Model Predictive Direct Current Control (MPDCC) [Martinez et al., 2010] focuses on the stator current $\mathrm{i_s}$. The concept has also been extended to enable longer prediction horizons by using consecutive sequences of switching and extrapolation steps in the prediction [Geyer, 2009].

MPDTC is implemented with the generalized switching extrapolation horizon 'eSSESE' as described in [Geyer, 2009]. Hereby, each 'e/E' stands for an extrapolation step whereas 'S' stands for a switching action. Thus, 'eSSESE' means that starting from the current state x and switching position u an extrapolation is carried out until a constraint is violated. At this point, it will be decided on two switching actions and so on. The control algorithm can be expressed with the following pseudo code:

function: MPDTC - eSSESE($x, T_{\max}, T_{\min}, \Psi_{\max}, \Psi_{\min}$)
- **e:** extrapolate trajectory till a constraint is hit $\rightarrow t_s$
- **SS:** predict output for all input sequences for two consecutive switching steps ($4^2 = 16$ possibilities)
- **E:** determine candidate sequences (feasible) and extrapolate candidates until a constraint is hit
- **S:** predict candidates with one switching step ($4 \cdot$ #candidates possibilities)
- **E:** Extrapolate all candidate sequences (still feasible) until constraint is hit
- **Opt:** Choose sequence with minimal switching frequency: $f_{\text{switch}} = \frac{\#\text{switches}}{\text{prediction horizon}}$
- **U:** Apply first switch of input sequence at time t_s.

The basic idea of this generalized prediction horizon is illustrated in Figure 2 with different torque candidate trajectories. This method generates a relatively long prediction horizon of variable length via extrapolation, while keeping the computational demand low by discarding infeasible trajectories. It is also possible to incorporate the maximum current constraint by defining an additional constraint.

2.2 Finite Control Set MPC

Finite Control Set MPC (FCS-MPC) can be viewed as the discrete counter part to standard MPC with a continuous control set. Like in standard MPC a fixed prediction