Available online at www.sciencedirect.com

ScienceDirect

IFAC PapersOnLine 50-1 (2017) 3307–3312

Power Coordination in Variable Speed Drives using Model Predictive Control

Felix Rey * **Peter Hokayem** ** **John Lygeros** *

* *Automatic Control Laboratory, ETH Zurich, Physikstrasse 3, 8092 Zurich, Switzerland (e-mail: {rey,lygeros}@control.ee.ethz.ch).*
** *ABB Corporate Research Center, Segelhofstrasse 1K, 5405 Baden-Dättwil, Switzerland (e-mail: peter.al-hokayem@ch.abb.com)*

Abstract: Variable speed drives (VSDs) are used to convert power between electricity grids and electric machines. Typically, they are AC-DC-AC power converters consisting of a rectifier, a storage capacitor and an inverter. In this paper, we use model predictive control (MPC) to coordinate the power flow through a VSD in order to keep the stored DC energy within tight bounds, exceeding the capabilities of conventional proportional-integral (PI) control techniques. The use of MPC enables for drives with smaller storage capacity that operate close to their physical capabilities. We design an MPC procedure that is tailored to VSDs and that accounts for real-time operation aspects.

Keywords: variable speed drives, model predictive control, power coordination, real-time

1. INTRODUCTION

VSDs link power sources and electric machines. They replace mechanical controls, e.g., throttles, to allow for variable and efficient actuation at the machine load. Fig. 1 shows the setup.

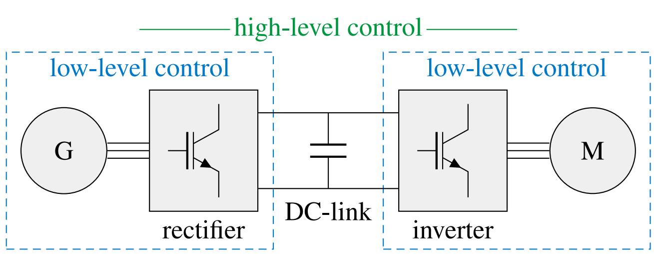

Fig. 1. Setup of the VSD between an electricity grid (G) and an electric machine (M). The rectifier and inverter perform the AC-DC-AC conversion. The DC-link buffers the power flow. Two control layers are applied to the drive.

At the power grid, the electrical energy is available at a fixed frequency, e.g., 50 Hz. The VSD rectifies the grid quantities to DC and stores the energy in the DC-link, before it inverts them back to variable frequency for the machine. We consider both converters (rectifier and inverter) to be active, making it possible to reverse the power flow and to feed energy from the machine back to the grid (e.g., for regenerative braking).

The two main tasks of the VSD are frequency conversion and power flow regulation. The frequency conversion is localized at each converter. There the electrical currents are controlled using pulse-width modulation (PWM). We call this part *low-level* control, which can be implemented as in Rodríguez et al. (2005) or Pöllänen et al. (2003) for the rectifier side, and in Trzynadlowski (2013) for the inverter side. More recently, MPC was utilized for the low-level controllers. A finite control set (FCS) MPC method is used in Rodriguez et al. (2013) and Stellato et al. (2017), which allows for fast execution times thanks to a small number of control signal choices. Similarly, Bolognani et al. (2009) and Linder and Kennel (2005) use explicit MPC techniques for the low-level controllers.

In this paper we address the second VSD task, namely managing the power flow. We call this part *high-level* control, since it relies on a functional low-level architecture. In most conventional setups, e.g. in Pena et al. (1996), the inverter directly provides the power that the machine operator demands. The rectifier monitors the DC-link voltage and regulates it using PI control. This *uncoordinated* control strategy relies on a sufficiently large DC-link and fast reaction times of the rectifier to avoid undesirable DC-link charging states. Hence, the DC-link and the rectifier are often over-sized to provide some safety margin, resulting in higher production costs for the VSD.

For replacing the conventional PI technique, we use MPC to enforce upper and lower bounds on the energy that is stored in the DC-link. To achieve this, the actions of the rectifier and the inverter are *coordinated* to jointly manage the DC-link energy, avoiding undesirable charging states and enabling for a reduction of the DC-link size. Hence, instead of having an over-sized VSD, we get a more cost efficient drive that can safely operate close to the bounds of its physical capabilities.

Our key concepts to handle the high computational burden of MPC are *rate constrained prediction models* and *move-blocking*. The rate constraints allow us to describe the converter behavior with a simple linear system, instead of a nonlinear or switched-linear system approach. Move-blocking reduces the number of decision variables in the MPC optimization program. The combination of both concepts enables for control reaction times of just 250 μs, opening the road for a real-time implementation. Here we rely on interior point methods to solve the MPC optimization programs, and in Rey et al. (2017) we present an extension to more sophisticated solver strategies.

The rest of the paper is divided into three parts. In Section 2 the VSD setup and conventional control techniques are shown. In Section 3 we introduce the MPC procedure and in Section 4 we compare MPC to the conventional PI technique.

2405-8963 © 2017, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd. All rights reserved.
Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2017.08.507

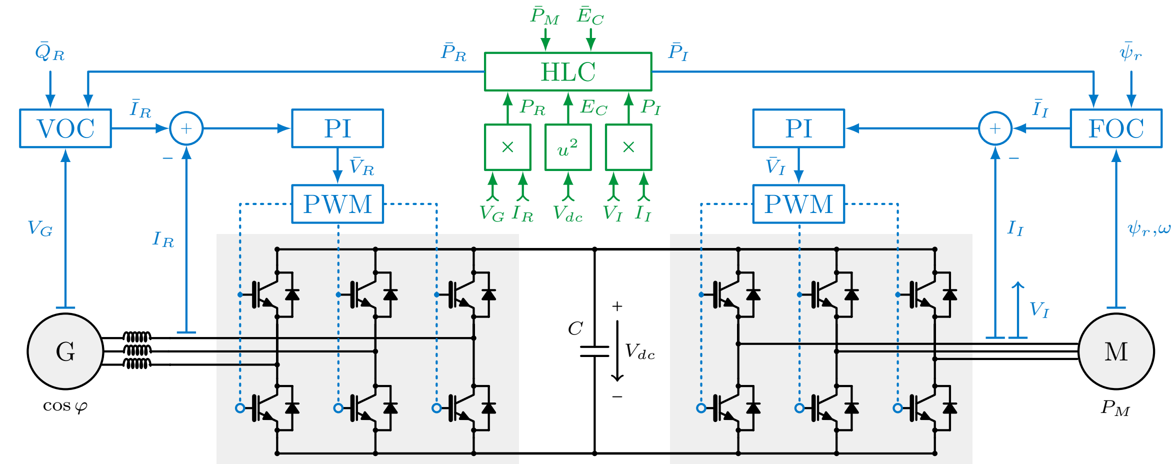

Fig. 2. Detailed setup of the VSD. Rectifier (left) and inverter (right) consist of six transistors each. The DC-link is a storage capacitor placed in between. The grid is denoted with ‘G’, the machine with ‘M’. On both sides, the low-level controllers (blue) drive the current I towards its reference $\bar{I}$ by using a PI controller that determines the voltage reference $\bar{V}$. The PWM translates this reference into transistor switching signals. The desired rectifier current is obtained by voltage oriented control (VOC), while the inverter current is obtained by field oriented control (FOC), making it possible to assign desired active power values $\bar{P}$ independent of the demanded reactive rectifier power $\bar{Q}_R$ and the assigned machine rotor flux $\bar{\psi}_r$. The high-level controller (HLC), together with its peripherals, is shown in green. It is guided by the machine power demand $\bar{P}_M$ and the nominal DC-link energy $\bar{E}_C$, assigned by the VSD operator. The HLC determines target power values $\bar{P}$ for both converters, based on the operator demand $\bar{P}_M$, $\bar{E}_C$ and the measurements P_R, E_C and P_I.

Notation

We denote the sets of natural and real numbers as $\mathbb{N}$ and $\mathbb{R}$. The set of n-dimensional, positive semi-definite matrices is denoted as $\mathbb{S}^n_+$. The identity matrix of dimension $n \times n$ is I_n. $0_{n\times m}$ or $1_{n\times m}$ are $n \times m$ matrices with all elements 0 or 1 respectively; the subscripts are omitted when the dimension can be determined from context. Finally, for $x \in \mathbb{R}^n$ and $Q \in \mathbb{S}^n_+$ we write $x^\top Q x$ as $\|x\|^2_Q$.

2. DRIVE SETUP AND CONVENTIONAL CONTROL

In this section we explain the control structure and go step by step through the VSD setup as shown in Fig. 2. Moreover, the conventional PI technique for high-level control is presented.

2.1 Control Setup

The rectifier and the inverter have separate low-level control structures, while the high-level controller acts on both converters. Fig. 3 shows the control hierarchy.

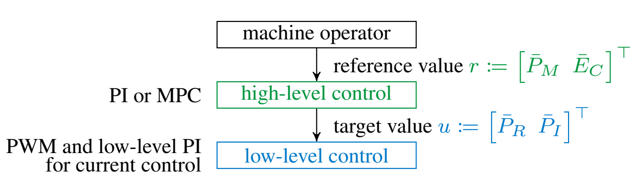

Fig. 3. VSD control architecture. The machine operator issues reference values for the machine power $\bar{P}_M$ and the DC-link energy $\bar{E}_C$. The high-level controller assesses the plant state and assigns target values for the rectifier power $\bar{P}_R$ and the inverter power $\bar{P}_I$. The low-level control determines the currents and drives the transistors.

The low-level controller handles fast and local control actions. Therefore, the high-level controller can focus on more complex tasks, such as constraint satisfaction.

2.2 Converter and Pulse-Width Modulation

Rectifier and inverter are identical voltage source active front ends as treated in Rodríguez et al. (2005), however mirrored around the DC-link as shown in Fig. 2. The PWM blocks convert the normalized voltage reference $\bar{V}$ to the transistor gate signals. For both converters we use asynchronous double-edge sinusoidal triangular carrier modulation. Details on the PWM can be found in Vasca and Iannelli (2012). The normalized voltage reference signals are determined by a PI controller that acts on the difference between desired and measured current.

2.3 Grid and DC-Link

The grid is modeled as an ideal AC voltage source, followed by inductors to smoothen the distortions caused by the rectifier switching. The DC-link capacitance C has the voltage V_{dc} and energy $E_C = \frac{C}{2}{V_{dc}}^2$. The operator assigns a (possibly time-variant) energy reference $\bar{E}_C$, which is then tracked through actuation of the high- and low-level controllers.

2.4 Rectifier Current Control

Voltage oriented control (VOC), as treated in Malinowski et al. (2003), is used to determine the rectifier current reference $\bar{I}_R$. We express the voltage and current (V, I) as vector components (v, i) in a rotating $dq0$-coordinate system aligned with the grid voltage ($v_q = 0$). The 0-component is absent since the three-phase system is balanced. The resulting dependencies are

$$v_G = v_d + iv_q = v_d \quad (1a)$$
$$P_R = \tfrac{3}{2}(v_d i_d + v_q i_q) = \tfrac{3}{2} v_d i_d \quad (1b)$$
$$Q_R = \tfrac{3}{2}(v_d i_q + v_q i_d) = \tfrac{3}{2} v_d i_q. \quad (1c)$$

From (1) we can derive the desired currents $(\bar{i}_d, \bar{i}_q)$ using the targeted active and reactive powers $(\bar{P}_R, \bar{Q}_R)$ and measuring or estimating the grid voltage v_G. VOC also decouples the active