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Direct sliding mode current control of feed drives

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ABSTRACT

Dealing with cascade control of electrical feed drives involves optimizing the current loop regarding precision, dynamics, robustness and energy efficiency. This is challenging using switching inverters with pulse width modulation. A direct method based on a switching controller is presented, which needs no downstream modulator. Control takes place in field-oriented as well as in phase-oriented coordinates of the machine, providing benefits compared to other direct methods. Control rules and structures are derived and a comparison between conventional and novel approach is shown. Implementation and measurement were performed in a practical setup, proving higher dynamics and less energy consumption.

1. Introduction

1.1. Common practice for current control of feed drives

Field oriented current control is nowadays the most common practice for vector control of electrical feed drives. An overview of the technique is given in [1]. Within a cascaded control structure, the current controller is typically structured as shown in Fig. 1: The outputs of two separate proportional/integral (PI) controllers for the flux (d) and the torque (q) component are transformed into motor phase coordinates (abc). Subsequently, a pulse width modulation (PWM) of the output voltage induces the corresponding current flow in the motor. This approach (further denoted as 'PI/PWM controller') was proposed by Hasse and Blaschke as summarized in [2]. It is comprehensible due to its decoupling of the different coordinate systems. However, it suffers from several disadvantages:

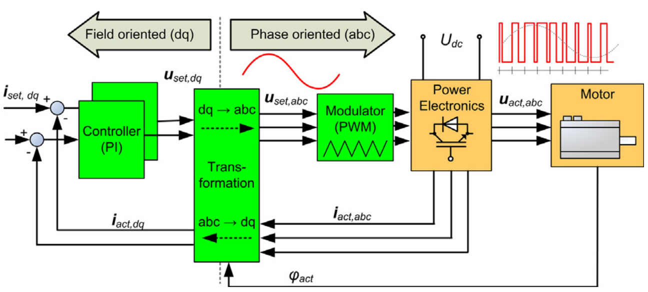

Fig. 1. Common structure of the field oriented current control for feed drives.

The semiconductors used in common power electronics (inverter) can only be switched between blocking and conducting state, therefore, the modulation output is an approximation of the calculated continuous control value and also yields to an additional time delay in the control loop. This influences the controller bandwidth negatively. Furthermore, the modulation frequency stays constant on a value adapted to the operation point with maximum dynamic requirements. For most other operation modes, this frequency is excessive and reduces the energy efficiency of the drive as the dissipation power is increased by the switching losses of the power semiconductors. This effect can even exceed the conduction losses and is further quantified in [3].

1.2. Further control techniques using a direct approach

For current control, another approach are so-called direct techniques, which do not require a modulator. They influence the motor current (Direct Current Control as in [4]) or flux and torque (Direct Torque Control, first shown in [5]) directly by a suitable switching sequence of the power semiconductors.

In general, the direct control techniques can be distinguished into two groups: those working in two-dimensional coordinates (typically d/q, flux/torque or abstract variables as α/β) and those in three-dimensional coordinates, which refer to motor phase related magnitudes. A schematic overview of the structure and functional

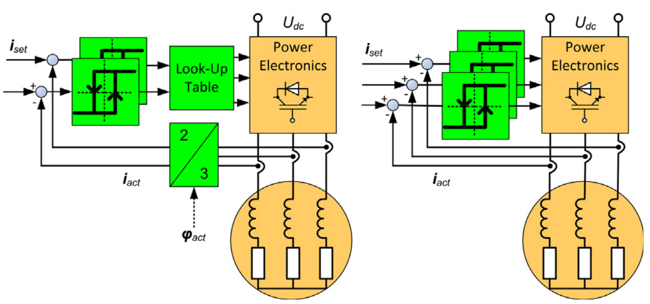

Fig. 2. Schematic illustration of the principle of direct current control techniques in two and three dimensional coordinate systems.

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Table 1
Characteristics of direct current control techniques.

	Controller designed in two-dimensional coordinates	Controller designed in phase related coordinates
Benefits	• Two decoupled controllers for two physical degrees of freedom (e.g. I_d and I_q controller)	• Control variables correspond to the switching commands, no LUT is needed • High dynamic performance
Disadvantages	• Control variables do not correspond to the switching commands. For transformation, a LUT is needed which leads to a decreased controller efficiency • Some strategies use a model based approach and result in high complexity	• Three controllers for two physical degrees of freedom lead to an over-determined system • Inaccuracy in the calculation of control variable • Nondeterministic generation of passive switching states, where all motor phases have the same electrical potential • Occurrence of superfluous high switching frequency

properties of both variants is given in Fig. 2 and Table 1, explaining the main differences regarding structure, complexity and characteristics.

The present paper shows a novel structure for a direct current controller. Main characteristic of the new approach is the combination of the benefits from both variants: By using a direct controller (without modulator) in the phase coordinate system, best dynamic behaviour and efficiency is achieved. Setpoint and tolerance parameters are given in field oriented coordinates, so the link to physical magnitudes is preserved. In addition, the generation of the passive switching vectors, where all motor phases have the same electrical potential, is done in a deterministic manner.

The design strategy is based on sliding mode control, which is a proven method for implementing switching controllers as shown in [6] and [7].

2. Design of the sliding mode current controller

2.1. Controller law derivation and realization structure

The primary goal of all current control techniques is to minimize the difference between the setpoint value i_{set} and the actual value i_{act} of the motor current. The error variable $\mathbf{e}_{dq}$ can be defined in field oriented coordinates:

$$\mathbf{e}_{dq} = \begin{bmatrix} \mathbf{e}_d \\ \mathbf{e}_q \end{bmatrix} = \begin{bmatrix} i_{d,set} - i_{d,act} \\ i_{q,set} - i_{q,act} \end{bmatrix} \quad (1)$$

To eliminate persistent control deviations, the time integral of the error has to be minimized as well. Therefore, the error variable is extended to σ_{dq}, where the weight of the time integral is given by λ:

$$\boldsymbol{\sigma}_{dq} = \mathbf{e}_{dq} + \lambda \int \mathbf{e}_{dq} dt \quad (2)$$

As all other system variables, σ can be expressed either in field oriented or in phase oriented coordinates by using a coordinate transformation as shown in [2]:

$$\boldsymbol{\sigma}_{abc} = \mathbf{A}_{abc}^{dq} \boldsymbol{\sigma}_{dq} \quad (3)$$

For the implementation of a sliding mode controller, σ_{abc} is selected for the switching function, giving the phase oriented control law

$$\boldsymbol{\Phi}_{abc} = \frac{U_{dc}}{2} sign(\boldsymbol{\sigma}_{abc}) \quad (4)$$

where Φ_{abc} is representing the electrical potential of each motor phase which corresponds to the switching state of the power semiconductors. The DC link voltage is denoted as U_{dc}.

The control law can be further extended by applying a passive switching vector when the error is zero for all phases:

$$\begin{cases} |\boldsymbol{\sigma}_{dq}| \neq 0, \rightarrow \boldsymbol{\Phi}_{abc} = \frac{U_{dc}}{2} sign(\boldsymbol{\sigma}_{abc}) \\ |\boldsymbol{\sigma}_{dq}| = 0, \rightarrow \boldsymbol{\Phi}_{abc} = [0,0,0]^T \end{cases} \quad (5)$$

As a result, the current controller eliminates the previously shown disadvantages by agitation in field and also in phase oriented variables in parallel. Additionally, passive switching states are applied in a defined manner, when the motor currents correspond to the demanded values.

The behaviour of sliding mode controllers is affected by the occurrence of chattering, which is further explained in [8]. Each infinitesimal deviation from the errorless state (for example caused by signal noise) leads to an undesirable switching operation which can be seen in (5). To avoid this behaviour, a hysteresis element is used instead of the Signum function. The hysteresis is applied to the phase as also field oriented part of the control. The implementation of the controller law is shown in Fig. 3. Principally, various mathematical norms can be used to define the error-free condition. A different weighting of d and q coordinates for special needs can also be realized. In this work, a maximum norm was chosen limiting the current error in both σ_d and σ_d. The result is a less conservative controller compared e.g. to a quadratic norm.

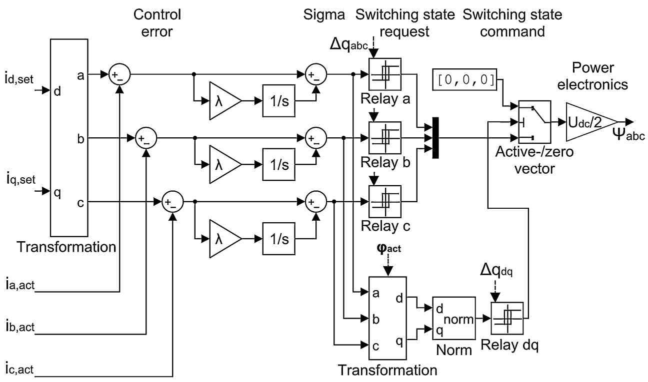

Fig. 3. Implementation structure of the current controller.

2.2. Controller parametrization

An important parameter of the direct sliding mode current controller is the tolerance range of the hysteresis elements, which influences directly the accuracy of the current control respectively the magnitude of the remaining current ripple. Therefore, parameterization aims at minimal tolerances with respect to boundary values determined by the maximum allowed switching frequency. In doing so, the current acquisition has to be considered, as the hysteresis cannot be smaller than the amount of measurement noise, the achievable gain in control bandwidth depends on sufficiently small measurement dead time.

The voltage generated by a rotating motor called 'back electromotive force (back-EMF)' is the biggest disturbance in the current control loop and directly proportional to the motor speed. Changes of the back-EMF affect the switching frequency, when the hysteresis width is kept fixed. To avoid such behaviour, the hysteresis width has to be adapted to the rotation speed of the machine. This can be done by adjusting a parameter Δq_{dq} (denoted in field oriented coordinate) so that for a given velocity value a chosen maximum switching frequency is never exceeded. It is possible to calculate the optimum correspondence between rotational speed and hysteresis width via numerical simulation, an example is shown in Fig. 4. The curve has a maximum at the point, where the back-EMF reaches half the dc-link voltage.

The hysteresis width Δq_{abc} (which can be given in phase coordinates) as well as the weighting of the integral part λ remain constant for all operation points.