Direct Torque Control of Permanent Magnet Synchronous Motors – An Overview

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***Abstract*— In high-performance servo applications a rapid and accurate torque control is desired, preferably without the use of a motion-state sensor. The use of permanent magnet synchronous motors (PMSMs) combined with the direct torque control (DTC) scheme offers many opportunities to achieve this goal. Recently several authors have proposed possible implementations of direct torque control for permanent magnet synchronous motors. In this paper an overview is given. The basic principles of DTC for PMSMs are explained. Topologies and algorithms described in the literature for interior PMSMs as well as surface mounted PMSMs are discussed. Estimations of stator flux linkage and initial rotor position are needed in these control schemes. Techniques to achieve these estimations are discussed in this paper as well. The main goal of the paper is to give an outline of what is already achieved and to determine points of interest for further research.**

I. INTRODUCTION

Permanent magnet synchronous motor (PMSM) drives are replacing classic dc and induction machine (IM) drives in a variety of industrial applications, such as industrial robots and machine tools. Advantages of PMSMs include low inertia, high efficiency, high power density and reliability. Because of these advantages, PMSMSs are indeed excellent for use in high-performance servo drives where a fast and accurate torque response is required. In PMSM drives, the electromagnetic torque is usually controlled indirectly via the stator current components in a reference frame fixed to the rotor flux field. This field orientation creates the need for a position sensor, which reduces the reliability and increases the cost of the drive.

For induction motors, direct torque control (DTC) was proposed as an alternative control scheme in [1] and became very popular in the past two decades. DTC for induction machines is inherently motion-state sensorless as the calculations are executed in a stationary reference frame. Moreover DTC uses no current controller and no motor parameters other than the stator resistance, which yields a faster torque response and a lower parameter dependence than with field oriented control.

The idea of combining the advantages of DTC and PMSMs into a highly dynamic drive appeared in the literature in the late 1990's [2], [3]. In the past decade several authors have proposed ways to adapt DTC to work with PMSMs.

In this paper an overview of the research in this field is given. The possible implementations are given in section III, for interior PMSMs (IPMSMs) as well as surface mounted PMSMs (SPMSMs). Problems of implementation are discussed in sections IV and V. Points of interest for further research are summarized in section VI.

II. PRINCIPLES OF DTC FOR PMSMS

Neglecting cogging torque, the steady-state electromagnetic torque T of a PMSM can be written as

$$T = \frac{3}{4}\frac{N_p\,|\underline{\Psi}_s|}{L_d\,L_q}(2\left|\underline{\Psi}_f\right|L_q\sin\delta - |\underline{\Psi}_s|\,(L_q - L_d)\sin 2\delta), \quad (1)$$

where δ denotes the load angle. The load angle is defined as the angle between the stator flux linkage vector $\underline{\Psi}_s$ and permanent magnet flux linkage vector $\underline{\Psi}_f$, as shown in Fig.1. The number of pole pairs is denoted by N_p. Equation (1) is applicable for PMSMs with saliency, i.e. IPMSMs, where the direct axis stator inductance L_d is smaller than the quadrature axis stator inductance L_q. For PMSMs without saliency, i.e. SPMSMs, L_d is equal to L_q and (1) becomes

$$T = \frac{3}{2}\frac{N_p}{L_d}\,|\underline{\Psi}_s|\,\left|\underline{\Psi}_f\right|\sin\delta. \quad (2)$$

From (1) and (2) it can be seen that for a constant level of the stator flux linkage, the torque can be changed by altering the load angle δ.

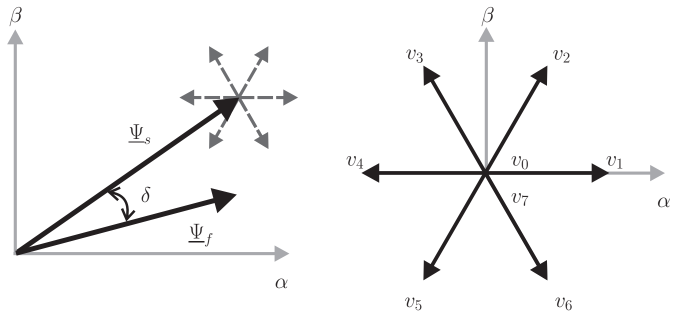

Fig. 1: Control of stator flux vector amplitude and load angle δ in a stationary (α, β) reference frame with VSI voltage vectors.

A three-phase two-level voltage source inverter (VSI) can generate eight voltage vectors as shown in Fig.1, six active vectors ($v_1 - v_6$) and two zero vectors (v_0 and v_7). The stator flux vector can be calculated as

$$\underline{\Psi}_s = \int_0^t (\underline{V}_s - R_s\underline{I}_s)dt + \underline{\Psi}_{s|t=0}, \quad (3)$$

where R_s denotes the stator resistance, $\underline{V}_s$ and $\underline{I}_s$ denote the stator voltage and current space vector respectively. It follows that, when the stator resistance R_s is neglected, the variation of the stator flux linkage vector is given as

$$\Delta\underline{\Psi}_s = \underline{V}_s T_s, \tag{4}$$

for a switch-on time T_s of the voltage vector $\underline{V}_s$. Each of the six possible active voltage vectors has a component radially and a component tangentially to the stator flux linkage vector. From (4) thus follows that the radial component of a voltage vector changes the amplitude of the stator flux linkage while the tangential component changes the rotation speed of the stator flux vector and consequently the load angle.

This way the stator flux linkage $|\underline{\Psi}_s|$ and the torque T can be simultaneously controlled with a VSI. The instantaneous error between the reference and estimated values of stator flux linkage and torque are minimized by applying the most appropriate voltage vector. Thus a controller minimizing the error is needed, together with an estimation of the stator flux linkage and torque.

In the overview of section III different types of controllers are discussed. To make an estimation of the stator flux linkage (3) can be used. Yet, unlike IMs, in PMSMs the initial value of the stator flux vector $\underline{\Psi}_{s|t=0}$ differs from zero and depends on the rotor position. As a result the initial rotor position has to be measured or estimated.

III. POSSIBLE IMPLEMENTATIONS

A number of different implementations are proposed in the literature. One of the first papers to mention direct torque control for PMSMs is [2]. However the proposed scheme cannot be considered as a true DTC scheme as it is in fact a current control scheme. As pointed out in [4], a DTC scheme can be used to control, besides the electromagnetic torque of course, the direct-axis current or reactive power instead of the stator flux linkage. In the following these schemes are not considered, as such all the considered schemes are of the type direct torque and flux control (DTFC). In [5] an excellent overview of DTC techniques is given, but the focus is on DTC for induction machines.

In this section an attempt to summarize the different known implementations of DTC for PMSMs is given. The schemes are divided according to voltage vector selection, but are also different in terms of (initial) stator flux estimation and the use of position sensors. Some of the discussed schemes namely require the rotor position θ, thus losing the advantage of inherent motion-sensorless control.

A. Switching-table DTC

1) Basic Switching-table DTC: A classical DTC scheme has a hysteresis comparator for the stator flux linkage and a quantisizer for the torque. A typical scheme is shown in Fig.2, the quantities T^* and $|\underline{\Psi}_s|^*$ denote reference values and the optional encoder is shown as a dashed line. The instantaneous error for the stator flux linkage e_Ψ thus has two possible values (1 and -1), whereas the instantaneous torque error e_T has three (-1, 0 and 1). Furthermore the ($\alpha\beta$) plane is divided in six sections. The errors e_Ψ and e_T, together with the section number containing the stator flux vector serve as input for a switching table. The output of the switching table is one of the eight possible voltage vectors. Such a scheme is implemented in [6] for SPMSMs, with the same switching table as used in [1] for induction machines. Furthermore a first order filter is proposed as quasi-integrator to solve the problem of initial flux estimation. As the steady-state output of a first order filter is independent of the initial conditions the quasi-integrator will indeed yield good results, but not at start up of the drive.

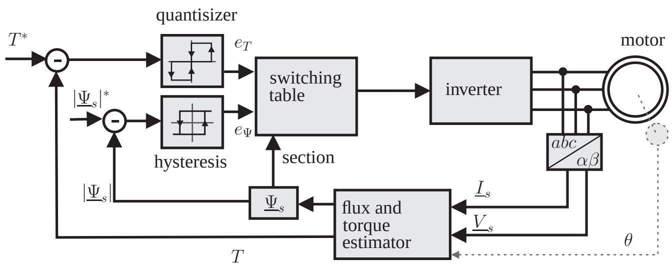

Fig. 2: Classical DTC scheme

Switching-table DTC is also implemented in [3], but no zero voltage vectors are used to control the motor. This essentially reduces the quantisizer for the torque error to a normal hysteresis comparator. The flux estimation is based on (3) and the initial flux position is assumed to be known. The method is applicable to IPMSMs and SPMSMs.

In [7] and [8] this scheme with reduced switching table is applied for IPMSMs and the initial rotor position is known from a low resolution encoder. It is shown that by varying the stator flux linkage reference either maximum torque per ampere (MTPA) or field weakening operation of the drive is possible. Recent papers have further reported on the use of these reference-flux-generating methods. In [9] a maximum torque per flux (MTPF) scheme is discussed, based on switching-table DTC. A method to optimize efficiency under switching-table DTC of PMSMs is given in [10], where the stator flux linkage is selected to yield maximum efficiency. In all of these reference-flux-generating methods off-line calculations are needed to determine the look-up tables for the reference stator flux.

2) Extended Number of Voltage Vectors: One of the main drawbacks of DTC is the ripple in torque and stator flux linkage. This ripple can be reduced by using more, different voltage vectors. When motoring in basic DTC there is only a limited number of voltage vectors available per sector, the switching table chooses the most appropriate. However it is very unlikely that both the radial and tangential components of the vector are aligned with the desired components. With adding more voltage vectors and/or adding sectors, a closer match for both components can be achieved. In [11] a DTC scheme is proposed which allows, by means of space vector modulation (SVM), to use 24 voltage vector directions at three amplitude levels. With the quantization of torque and flux error and the availability of 72 voltage vectors a different switching table is constructed. As a result a lower torque ripple is achieved. In [11] SVM is used to generate more, different voltage vectors during the entire operation of the drive. It is however also possible to use a hybrid algorithm, making more voltage vectors available during certain operating conditions. In [12] a method is proposed to ensure a fast torque response during start-up of IPMSMs. At start-up SVM is used to generate the optimal voltage vector, i.e. the voltage vector allowing the fastest rise in torque. However the calculations are dependent on the rotor position, thus the initial rotor position has to be known from an encoder and during the torque development duration the rotor position is assumed to be constant. Once the torque reference value is reached, a regular switching table (containing only voltage vectors $v_0 - v_7$) is used and there is no further need for the encoder.

Multilevel converters make more voltage vectors available to control flux and torque, hence reducing ripple and achieving a less variable switching frequency. As a disadvantage more power switches are needed, thus increasing system cost and complexity as well as switching losses. In [13] such a DTC is proposed for induction machines, but application to PMSMs is not reported in literature.

B. Constant Switching Frequency DTC

To further eliminate torque and stator flux ripples and to obtain a fixed switching frequency, it is possible to use a model of the PMSM to calculate the most appropriate voltage vector during the next switching interval. This most appropriate voltage vector can then be realised by SVM. Furthermore the use of SVM permits avoiding some other disadvantages of switching-table DTC, such as violating polarity consistency rules, high sampling frequency for digital implementation of the comparators and distortions due to sector changes. However there are several ways of calculating the most appropriate voltage vector and the required motor parameters and computational complexity have to be taken into account when comparing the different schemes.

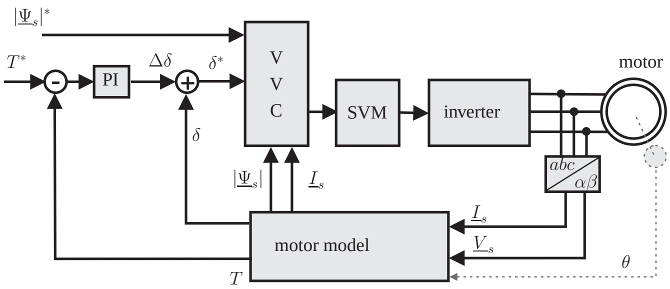

Fig. 3: SVM-DTC with closed loop torque control, VVC denotes Voltage Vector Calculation

1) SVM-DTC with Closed Loop Torque Control: A typical scheme of this type is shown in Fig.3. In [14] the difference between actual and reference torque is supplied to a PI-controller resulting in a desired change of load angle $\Delta\delta$. This signal, together with the measured currents and the actual and reference flux are used in a predictive controller to calculate, based on (3), the desired voltage vector in polar coordinates. The stator voltage command is supplied to a space vector modulator. However, this method uses a motion-state sensor.

A very much related scheme is proposed in [15] for IPMSMs, but without the use of a position sensor. The estimated stator flux linkage position, the load angle correction (from a PI-controller) and the reference flux amplitude are used to calculate a reference flux vector. The error between this reference flux vector and the actual vector, both in amplitude as angle, is then corrected by applying the required voltage vector through SVM. A lower ripple and fixed switching frequency are reported to be obtained in [14], [15]. However one has to notice that the use of a PI-controller may deteriorate the performance of the drive as the PI-controller is sensitive to detuning.

2) Stator Flux Oriented Control: Direct stator flux linkage control for SPMSMs as proposed in [16] is related to the previous SVM-DTC schemes. Again the pulse width modulator is used to generate an increment of stator flux linkage (both in amplitude as angle), but the torque control is open loop. The scheme controls the load angle and amplitude of the stator flux linkage. The reference value for the load angle can be calculated from the torque reference. In the proposed scheme a position sensor is used.

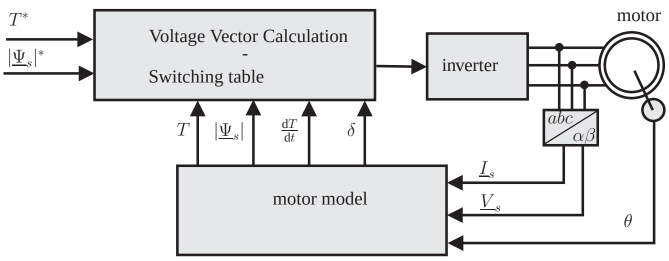

Fig. 4: Predictive DTC

3) Predictive Control: A predictive direct torque controller for SPMSMs is discussed in [17] and schematically shown in Fig.4. By using the equations of the PMSM, the calculation of the trajectory of the torque in a given time is possible. In this way an optimum switching sequence can be calculated. In a constant switching interval a suitable voltage vector is applied for the time required to reach the border of the calculated ripple band, then the zero voltage vector is applied for the remainder of the switching interval so that the torque reaches the minimum of ripple band.

In steady state this yields a constant switching frequency and a constant torque ripple. The selection of the voltage vector and switching time is based on the prediction of torque and flux at the beginning of every sampling interval. For the prediction of the torque, the time derivative of the torque $\frac{\mathrm{d}T}{\mathrm{d}t}$ is calculated as function of the stator voltages, stator currents, permanent magnet flux and rotor position. It is clear that the motor parameter dependence in this scheme is larger than in basic DTC. Nevertheless the scheme needs a position encoder to obtain the rotor position θ.

4) Variable Structure Control: A variable structure controller (VSC) for DTC of IPMSMs is proposed in [18] where the sliding surfaces and VSC law are derived. The torque and stator flux linkage errors, together with the flux components, rotor speed and the extended flux are used by the variable structure controller to calculate the voltage vector driving the system states to the sliding surface. By means of SVM this voltage vector is realized. A lower ripple and fixed switching frequency is obtained, but a speed encoder is used. The calculations for the VSC result in a larger dependence on motor parameters for the drive performance.

IV. STATOR FLUX LINKAGE ESTIMATION

The basic principle of DTC is to control the torque by altering the stator flux vector in such a way that instantaneous torque and stator flux linkage errors are minimized. As such the estimation of the stator flux linkage vector is very important for a correct operation of the DTC drive. A method to estimate the stator flux linkage is to measure stator voltages and currents and equation (3). The only motor parameter needed is the stator resistance R_s. The use of an integration however has its disadvantages: any dc offset in the measurements of voltages or currents lead to large drifts in the estimated stator flux linkage. Several compensation techniques have been reported and a short overview is given in [19].

To overcome this problem a programmable cascade of low-pass filters (LPF) is proposed as alternative to an integrator in [19]. Each of the low-pass filters has a transfer characteristic $\frac{1}{1+j\tau\omega}$ with τ the filter time constant and ω the frequency of the signal. The cascade can achieve the same phase lag and gain as a pure integrator if the time constant and gain G are programmable and adjusted to the rotor speed.

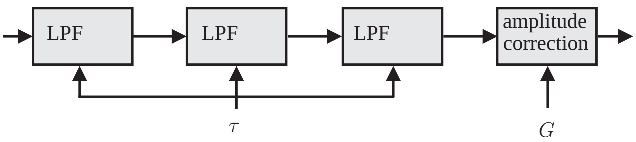

Fig. 5: Cascade of three LPFs, τ and G are programmable

Another problem for the estimation of the stator flux linkage based on the voltage equations is the stator resistance variation. Due to skin effect and temperature changes, the stator resistance can have significant variations. Using the wrong value for R_s in (3) will give rise to large errors. A technique for stator resistance estimation is described in [19] and [20]. It is based on the relationship between the change in resistance and the change in current, which allows a PI-controller to determine the stator resistance correction. The algorithm has no need for the rotor position. Despite the dependency of the reference current on L_d and L_q, the influence of saturation on this method is not discussed.

An alternative method of estimating the stator flux linkage is presented in [21]. The method is based on the monitoring of the scalar product of estimated stator flux and the measured stator current. The ac part is extracted, filtered and used for the correction of the estimated stator flux linkage. Both simple LPF and adaptive filtering are discussed.

Other methods to estimate the stator flux linkage are extended Kalman filtering (EKF) as in [22], which allows also to estimate the mechanical state of the considered SPMSM, and observers based on sliding mode as in [23].

V. INITIAL ROTOR POSITION ESTIMATION

As mentioned earlier in section II, the initial rotor position must be known in a DTC drive as it is required for the estimation of the initial stator flux linkage. If the initial-position information in the controller is too inaccurate, the motor may initially rotate in the wrong direction.

In [19] and [24] a technique is discussed to estimate the initial rotor position of an IPMSM. The method is based on the relation between the amplitude of a high-frequency (300 Hz) stator current and the angular position of the rotor due to the saliency. The magnetic-pole orientation is found by the effect of saturation on the stator currents. A method using rectangular pulsed voltages is described in [25] and is valid for salient PMSMs, i.e. IPMSMs, only.

For nonsalient PMSMs the sensorless estimation of the initial rotor position is more difficult. Methods as described in [19] and [24] possibly can be adapted to work with SPMSMs, when saturation effects are considered.

VI. FUTURE RESEARCH

The influence of saturation and parameter-estimation errors on the performance of DTC for PMSMs, especially on model-based estimators and controllers has to be investigated. A focus on sensorless controllers and estimators is intended. Sensorless position estimation also has applications other than DTC PMSM.

Digital implementation of DTC PMSM and associated discrete modelling of PMSM, together with new DTC schemes offers many opportunities for more research. In conjunction with the research on DTC schemes, research into the most appropriate switching strategies has to be undertaken.

Many implementations are reported in literature. However, apart from [26], the stability of the DTC PMSM drive has not much been studied yet, in spite of the fact that instability can occur due to the maximum in the torque-load angle characteristic. With δ_m the load angle corresponding with maximum torque, a load angle $\delta > \delta_m$ will result in a lower torque. If the direct torque controller tries to increase the torque by increasing the load angle, the torque will decrease further thus resulting in instability. Two methods of avoiding this instability are discussed in [26]. Both are based on controlling the load angle δ. However besides this static instability, the overall stability of the drive should be considered as well. In [27] a mathematical analysis of the stabilization mechanism of DTC for induction machines is given and used to understand the observed behaviour of DTC schemes. As such a thorough investigation concerning the stability of DTC for PMSMs still has to be undertaken.

VII. CONCLUSIONS

This paper gives an overview of the existing implementations for DTC with PMSMs. The overview divides these implementations in two main categories, based on the differences in vector voltage selection and generation of the schemes. Firstly the switching-table based DTC excels in simplicity and ease of implementation. However, as a consequence of the quantisized input to the controller, only a limited set of voltage vectors can be applied. As such significant torque and stator flux ripples are observed. Secondly the constant switching frequency DTC (SVM-DTC) schemes allow full usage of the inverter capabilities in constructing voltage vectors, but at a cost of a higher computational burden and parameter dependence. In each main category there are variations in the way of selecting and generating voltage vectors.

Apart from voltage selection and generation, the possible DTC schemes differ in the estimation of stator flux linkage and torque. A discussion on possible estimation techniques is given. As DTC is inherently a motion-state sensorless technique, the use of a position encoder (be it during run-up or at normal working conditions) has to be considered when evaluating a DTC strategy. To this end some initial rotor position estimation techniques are discussed as well.

The overview of possible implementations and the related estimation problems clearly determine points of interest for further research, which are summarized in this paper.

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