Direct Torque Control for Interior Permanent Magnet Synchronous Motors with Respect to Optimal Efficiency

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Abstract
Due to their high torque and power per volume ratio, interior permanent magnet synchronous motors (IPMSM) are widespread electrical machines for traction drive applications, e.g. in the drive train of hybrid electric vehicles (HEV). IPMSM exhibit a significant degree of saliency along the rotor circumference. Thus, in order to exploit the full potential of an IPMSM drive, it is mandatory to utilize the reluctance torque. As a result, using a rotor flux oriented torque control, the clear separation between flux and torque generating currents is no longer possible, i.e. that the determination of the reference currents for the subordinated current control is rather difficult. Furthermore, drive applications demand for a wide constant power range with flux weakening ratios of up to 1:5 or even higher. However, flux weakening operation demands for additional measures to ensure that the current controllers dispose of a minimum amount of voltage reserve, which is necessary to govern transients and to compensate for disturbances. In this contribution a Direct Torque Control (DTC) structure is proposed to cope with the afore mentioned problems. In a DTC structure, torque and flux are controlled directly. Hence, the approach is very well suited for operation at saturated voltage. Furthermore, with torque and flux as control variables, it is not necessary to determine any reference currents. However, the proposed structure utilizes two Look Up Tables (LUT) for the determination of efficiency-optimal set values for flux and torque. The LUT are generated based on measurement results. So, they do already account for saturation effects. The proposed DTC structure has been implemented and verified on a test bed.

1. Introduction
Requirements for electrical traction drives, e.g. for railway applications or in the drive train of hybrid electrical vehicles (HEV), are a wide constant power range as well as a high ratio of torque and power per volume. Due to the development of modern permanent magnet materials, such as NdFeB or SmCo, the power and torque density of permanent magnet synchronous motors (PMSM) increased significantly. Thus, this motor type becomes more and more attractive for drive applications. Highly utilized machines are often designed as interior permanent magnet synchronous motors (IPMSM) with the magnets embedded in the rotor structure. This results in a significant degree of saliency and in additional reluctance torque. Hence, optimal operation of IPMSM is bound to exploit not only the main torque component, which is proportional to the q-axis current, but also that extra reluctance torque, which depends on the product of d- and q-axis current components. As a result, the d-axis current of the motor must not be controlled to zero, as it is common with non-salient PMSM. Thus, the major problem is to find that combination of d- and q-axis currents, which aims for best efficiency, considering also the current and voltage limitation at a certain motor speed and DC link voltage. In [1-6] proposals for this problem have been presented.
Another characteristic requirement for traction drives is the wide constant-power range. To exploit the full torque and power potential of the drive during flux weakening, an operation at or very close to the voltage limit is mandatory. However, using a flux-oriented control structure with the voltage as actuating variable for the subordinated current control, an operation at the voltage limit is difficult, because no voltage reserve is left for the disposal of the current controllers to compensate for disturbances or to govern transients. Thus, it becomes necessary to introduce e.g. a voltage controller, which has to care about a certain amount of voltage reserve to guarantee the functionality of the current control. The overall control structure with the nonlinear torque and voltage control loops becomes rather complex and difficult to design. In [7] such a torque control structure is proposed using Look Up Tables (LUT).

In this paper, a Direct Torque Control (DTC) structure is proposed. DTC was presented first by Takahashi et al. [8]. The utilization of DTC for PMSM drives is discussed in [9-10]. Control variables of DTC are flux and torque. As the flux is controlled directly, DTC is very well suited for an operation in the constant-power range. Further on, as DTC does not comprise an inner current control loop, there is no need to determine any reference currents. However, the problem with DTC is then to determine optimal flux and torque set values with respect to optimal efficiency and accounting for the current and voltage limitation. For this purpose two LUT are utilized by the control structure proposed in this paper.

2. Modeling of IPMSM

In the rotor-fixed $d/q$ reference frame, the voltage equations of the IPMSM are given by

$$
\begin{align*}
\dot{u}_d &= R_i i_d + L_d \dot{i}_d - \omega_{RS} L_q i_q \\
\dot{u}_q &= R_i i_q + L_q \dot{i}_q + \omega_{RS} L_d i_d + \omega_{RS} \psi_p
\end{align*}
$$

(1)

The motor torque results as

$$
T = \frac{3}{2} p (\psi_p + (L_d - L_q) i_d)_q
$$

(2)

where

- $u_d, u_q$: $d$- and $q$-axis voltage components
- $i_d, i_q$: $d$- and $q$-axis current components
- $R$: Stator resistance
- $L_d, L_q$: $d$- and $q$-axis inductances
- $\omega_{RS}$: Electrical angular velocity
- $\psi_p$: Permanent magnet flux
- $I_{max}$: Maximum length of the stator current space vector
- $U_{dc}$: DC link voltage
- $p$: Number of pole pairs

Voltages and currents are restricted by the constraints given in (3) and (4). Neglecting the ohmic voltage drop, assuming steady state operation and considering that the magnitude of the voltage vector is limited to $U_{max}$, (4) can be derived directly from (1).

$$
\begin{align*}
&\dot{i}_d^2 + \dot{i}_q^2 \leq I_{max}^2 \\
&\omega_{RS} \sqrt{(\psi_p + L_d i_d)^2 + (L_q i_q)^2} \leq \frac{U_{dc}}{\sqrt{3}} = U_{max}
\end{align*}
$$

(3)

(4)

Dividing (4) by the rotor electrical frequency $\omega_{RS}$, the voltage limit for a given rotor speed can be expressed in terms of a maximum flux vector magnitude $\psi_{max}$, which is given by (5).
\[ \psi = \sqrt{(\psi_p + L_d i_d)^2 + (L_q i_q)^2} \leq \psi_{\text{max}}(\omega_{RS}) = \frac{U_{dc}}{\sqrt{3} \omega_{RS}} \]  \hspace{1cm} (5)

Looking at (5), the geometric shape of lines of constant flux in \(i_d/i_q\) coordinates are ellipses. In Fig. 1, the circle of maximum current and three constant-flux ellipses, which correspond to the voltage limit, for a constant DC link voltage, at three different rotor speeds \(\omega_1\), \(\omega_2\) and \(\omega_3\), are depicted. The center point of the constant flux ellipses is given by the short circuit current of the motor.

\[ i_d = -\frac{\psi_p}{L_d} \quad , \quad i_q = 0 \]  \hspace{1cm} (6)

The dashed green lines are lines of constant torque.

Fig. 1: Characteristic curves of an IPMSM in terms of stator currents

3. Efficiency Optimal Operation of an IPMSM Considering Current and Flux Limits

Operating the motor in a loss-minimal way means that a desired torque is generated with a current space-vector of minimum length. Each constant torque curve can be reached with a unique minimum-amplitude current space-vector. The geometric location of all minimum-amplitude current space-vectors forms the maximum-torque-per-current curve. In Fig. 1 this curve is depicted in blue.

Operating points on the maximum-torque-per-current curve

Whenever conformable with current and flux limit, operating points on the maximum-torque-per-current curve are chosen. Thus, for sufficient low rotor speeds \((\omega_{RS} \leq \omega_3)\), the maximum torque magnitude \(T_1\) is only limited by the maximum current. This maximum torque can be generated in operating point C. It should be noted that a negative \(d\)-axis current is applied to the motor in this operating point. Its purpose is not flux weakening due to the voltage limit but an optimal exploitation of the reluctance torque.
Operating points at the voltage limit

For higher rotor speeds the strategy to choose only operating points on the maximum-torque-per-current curve can no longer be sustained. Assuming that \( \psi_{\text{max}}(\omega) \) represents the voltage limit, the torque \( T_3 \) is the maximum torque, which can still be realized on the maximum-torque-per-current curve in operating point \( B \). If the desired torque exceeds \( T_3 \), the operating point has to be shifted along the ellipse of constant flux towards higher torque values. A more negative \( d \)-axis current than necessary for an optimal exploitation of the reluctance torque is introduced into the motor in order to keep the induced voltage within the allowed limit. The motor drive is now operated at the voltage limit. The maximum reachable torque is reduced to \( T_2 \) that is generated in operating point \( D \), at the intersection point of current and voltage limiting curves.

If the center point of the ellipses of constant flux is located within the circle of maximum current, i.e. if the maximum current of the motor exceeds the short circuit current, there is no electrical limitation for the rotor speed. In this case, for sufficient high rotor speeds, the maximum torque reachable will just be limited by the voltage, and the operating point, in which this torque is generated, is located on the cyan maximum-torque-per-voltage curve. Assuming that \( \psi_{\text{max}}(\omega) \) represents the voltage limit, a maximum torque \( T_4 \) can be generated in operating point \( E \). Thus, the dashed yellow maximum-torque-per-voltage-and-current curve comprises all operating points, where maximum torque for a given voltage limit can be generated.

4. Implemented DTC Structure

Based on the considerations of the last chapter an efficiency-optimal torque control structure, which considers voltage and current limit and uses DTC, can be deduced. The resulting structure, which provides torque and flux reference values to the actual DTC, is shown in Fig. 2. It utilizes two LUT. The first LUT \( \psi_{\text{opt}}(T) \) comprises all combinations of torque and flux values on the optimum-torque-per-current curve, where a desired torque is generated with a minimum length current space-vector. The second LUT \( T_{\text{max}}(\psi) \) comprises all combinations of torque and flux values on the dashed yellow maximum-torque-per-voltage-and-current curve. With that LUT the maximum producible torque \( T_{\text{max}} \) for a given flux limit \( \psi_{\text{max}} \) can be determined.

The function of the control structure can be explained as follows: Given a desired torque \( T^* \), the respective efficiency optimal flux value on the maximum-torque-per-current curve is obtained from the LUT \( \psi_{\text{opt}}(T) \). It is then limited to \( \psi_{\text{max}} \), which represents the voltage limit at a given DC link voltage and rotor speed. The resulting flux value \( |\psi|^* \) is the reference flux for the actual DTC structure. The reference torque is limited to a maximum value producible with a flux magnitude of \( |\psi|^* \) using the LUT \( T_{\text{max}}(\psi) \). The complete control structure is depicted in Fig. 3. The actual torque and flux values are obtained from an observer structure labeled with “Flux and Torque Observer”.

![Fig.2: Reference torque and flux determination with respect to optimum efficiency](image-url)
Fig. 3: Overall Control Structure

**Generation of the look up tables**

The proposed control structure has been implemented on a test bed, using an IPMSM with the following data:

**Table I: Parameter of the IPMSM**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pole pairs</td>
<td>$p$</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>$R$</td>
</tr>
<tr>
<td>Magnet flux linkage</td>
<td>$\psi_p$</td>
</tr>
<tr>
<td>$d$-axis inductance</td>
<td>$L_d$</td>
</tr>
<tr>
<td>$q$-axis inductance</td>
<td>$L_q$</td>
</tr>
<tr>
<td>Maximum phase current</td>
<td>$I_{max}$</td>
</tr>
</tbody>
</table>

For the generation of the necessary LUT, information about the generated torque and flux for all reasonable $i_d/i_q$ current combinations is required. This information could be generated using the data of the motor parameters $L_d$, $L_q$, $\psi_p$. Particularly, if iron saturation has to be regarded, the data should be obtained either by detailed FEA calculations or directly by experiment. For this purpose, a grid of $i_d/i_q$ current combinations has to be generated and applied to the IPMSM, while a fixed rotor speed is impressed to the machine. For each applied current combination, the generated torque is measured. The flux values can be obtained indirectly by evaluating the steady state stator voltages, which are necessary to sustain the applied currents. The advantage of this method is that the generated LUT do already account for saturation effects, which usually must not be neglected for highly utilized IPMSM. Fig. 4 shows the flux and torque values obtained. The generated LUT $\psi_{opt}(T)$ and $T_{max}(\psi)$ are depicted in Fig. 5.
5. Measurement Results

Fig. 6 to 10 show experimental results of the implemented control structure.

**Transient behavior of the control structure**

In Fig. 6 and 7 the transient response with respect to a reference torque step is depicted. The results of Fig. 6 were recorded in the constant torque range at a rotor speed fixed to 1000rpm. A torque reference step from 0Nm to 150Nm was applied to the motor drive. Reaching the reference torque in less than 2ms, the torque step response proves the superb dynamic performance of the DTC. As the drive is operating in the constant-torque range, the flux reference values are obtained from the LUT $\psi_{opt}(T^*)$. 

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**Fig. 4:** Characteristic curves of IPMSM

**Fig. 5:** Generated Look Up Tables
So, simultaneously with the torque reference step, the flux reference changed according to the maximum-torque-per-current-curve. It can be seen, that during the torque and flux step response the $d$-axis current increases temporarily. This results on the one hand in a poor exploitation of the reluctance torque during the transient process making the flux step response considerably quicker than the torque step response. On the other hand it ensures that during the transient process the length of the flux vector suffices for the generation of the desired torque. Hence, unstable operating conditions are avoided.

In Fig. 7 a torque step response during flux weakening with fixed rotor speed of 2300rpm is shown. The flux reference value is determined by the voltage limit and given by the maximum available flux $|\psi_{\text{max}}|$, which is only influenced indirectly via a non constant DC link voltage by the torque reference step (see Fig. 2). Due to the operation in the flux weakening range, the torque step response is considerably slower compared to Fig. 6.

**Steady state behavior of the control structure**

In Fig. 8 and 9 the steady state behavior of the control structure is examined.

In Fig. 8 the reference torque is increased linearly, while the rotor speed is kept constant at 500rpm. As the drive is not operated at the voltage limit, the reference flux is chosen according to LUT $\psi_{\text{opt}}(T)$. The currents develop accordingly in an efficiency-optimal way. The torque is limited to a maximum value, so that the maximum current $I_{\text{max}}$ is not exceeded.

In Fig. 9 the reference torque is increased linearly again, but this time the constant rotor speed is chosen to 2300rpm. From the flux development in Fig. 9 can be obtained that due to the rising flux in $q$-direction at time $t=0.9s$ the flux limit $\psi_{\text{max}}$ is reached. A further increase of torque is realized by shifting the operating point along the flux limit ellipse towards higher torque values. From the development of the $d/q$-currents can be concluded, that the motor is operated in an efficiency-optimal way, accounting for current and voltage limit.

![Fig. 6: Torque Step Response at 1000rpm](image1)
![Fig. 7: Torque Step Response at 2300rpm](image2)
6. Conclusions

In this contribution a DTC structure is presented, which allows an efficiency optimal operation of an IPMSM in the constant torque as well as in the flux weakening range. It utilizes two Look Up Tables (LUT) to generate the set values for flux and torque in a way that the reluctance torque is optimally exploited, while current and voltage limit are considered. As the LUT are generated based on measurement results, they do already account for saturation effects, which often must not be neglected for highly utilized IPMSM. The developed DTC structure has been implemented on a test bed. Steady state and transient measurement results are presented, which prove its ability, to operate the motor in an efficiency optimal way in both the constant-torque and flux weakening range. Stable operation and a satisfying torque rise time were achieved in the complete area of operation. As the flux step response is considerably quicker than the torque step response, unstable operating conditions are avoided. Compared to field-oriented solutions the proposed control structure is very well suited for flux-weakening operation, which is a major advantage in traction drive applications. Another considerable advantage of the proposed control structure is its easy implementation.

References