Abstract — This paper proposes a wide-speed deadbeat-direct torque and flux control (DB-DTFC) method associated with inverter voltage and current constraints of interior permanent-magnet synchronous motors (IPMSMs). The proposed approach has potential advantages controlling torque and flux linkage at voltage and current limits since integrators are not involved for torque control or flux weakening. An automatic transition between non-limited operation and six-step modulation can be achieved without modifying the control law. To support this, we provide a graphical and analytic analysis that naturally leads to a unique stator voltage vector selection on the hexagon. The proposed controller can maximize the available inverter voltage and generate higher output torque than conventional current vector controllers at high speeds. The method developed in this paper also maintains beneficial DTC features, such as fast dynamics and direct manipulation of the stator flux linkage for flux weakening.

Index Terms— Wide-speed deadbeat-direct torque and flux control (DB-DTFC), inverter voltage and current constraints, interior permanent-magnet synchronous motors (IPMSMs), Available inverter voltage maximization.

I. INTRODUCTION

Interior permanent-magnet synchronous motors (IPMSMs) have received wide attention in the field of automotive applications due to their unique features, such as high efficiency, high power density, and wide constant power speed range [1]. Current vector control (CVC) is the most widely used approach to achieve the desired air gap torque of IPMSMs [1-2]. However, when using current control, both air gap torque and flux linkage are open loop variables. Open loop air gap torque dynamics are limited by the current controller dynamics and accurate current regulation proves problematic when operating near the voltage limit of the inverter.

Another important issue that is relevant to operating limit control is the extension of dc-link voltage utilization since the efficiency and power density of motors and drive systems in automotive applications are crucial due to the limited power source by a battery. A number of methods for exploiting the available bus voltage for IPMSMs have been reported over the flux weakening region [2-4]. With these methods, the realization of maximum voltage utilization fails because they consider the voltage limit as a circle instead of a hexagon. Consequently, this control methodology based on the linear voltage limit increases copper loss and requires multiple control laws for transition between flux weakening and six-step operation. These adverse consequences arise due to the adherence to control structure employing the current regulator at operating limits.

Recently, some modified direct torque and flux control schemes have been reported for high performance AC motor drives [5-7]. Despite the improved control performance over that of classical direct torque control (DTC) algorithms, there exist some limitations associated with voltage limit operations. In [5-6], a variable control structure should be implemented to establish the adjustment of flux command. The drawback of using such methods is the added complexity of implementing a different control law when operating at high speeds. The system in [7] controls the stator flux magnitude and torque output by using a PI regulator and a fixed PWM switching frequency. Unfortunately, the integrators in the regulator would wind-up and cause the system to exhibit poor dynamic performance at operating limits [8].

There has been an interest in using deadbeat-direct torque and flux control (DB-DTFC) as a high performance control law for AC motors [9-11]. DB-DTFC utilizes an inverse discrete-time motor model to determine the stator voltage vector that would achieve the desired torque and stator flux magnitude at the end of the next PWM interval. However, in these works, no sufficient information is available to determine the stator voltage vector during a wide range of operation at elevated speeds.

In this paper, we investigate a wide-speed DB-DTFC method associated with inverter voltage and current constraints of IPMSMs. In the proposed approach, the drive system can provide fast and non-oscillatory dynamics under voltage limits since integrators are not involved for torque control or flux weakening. An automatic transition into a flux weakening mode is achieved with the voltage selection rule. This implies that a single control law can be used in the
voltage limits, unlike CVC methods, where the control mode has to be modified to deal with limited bus voltages. To support this, we provide a graphical and analytic analysis that naturally leads to a unique stator voltage trajectory for wide-speed DB-DTFC. The method developed in this paper maintains beneficial DTC features, such as fast dynamics and direct manipulation of the stator flux linkage for flux weakening. The control strategy has been implemented to confirm the feasibility of the method.

II. PRINCIPLE OF DB-DTFC UNDER NON-LIMITED CONDITION

The output torque of the IPMSM based on the flux linkage is simply given by

$$T_e = \frac{3}{4} P \left( \lambda_{dqs}^r i_{qs}^r - \lambda_{qs}^r i_{ds}^r \right)$$

where \( \lambda_{dqs}^r \) and \( i_{dqs}^r \) represent the d-q axis stator flux linkage and the current vector in the rotor reference frame, respectively, and \( P \) denotes the number of poles.

In order to form the DB-DTFC law, the following torque differential equation can be written as

$$\dot{T}_e = \frac{3}{4} P \left( \lambda_{dqs}^r i_{qs}^r + \lambda_{dqs}^r i_{q}^r - \lambda_{dqs}^r i_{ds}^r - \lambda_{qs}^r i_{ds}^r \right).$$

The rate of change of torque can be modeled over a PWM period, \( T_s \), as a discrete time system with latched voltage input. This forms the basis for the DB-DTFC regulator [11] as

$$v_{qs}^r(k)T_s = M v_{ds}^r(k)T_s + B$$

where

$$M = \frac{\left( L_q - L_d \right) k_{qs}^r(k)}{\left( L_q - L_d \right) \lambda_{dqs}(k) - L_q \lambda_{pm}}$$

$$B = \frac{L_d L_q}{\left( L_q - L_d \right) \lambda_{dqs}(k) - L_q \lambda_{pm}}$$

and

$$\Delta T_e(k) = T_e(k + 1) - T_e(k).$$

Combining (3) and (4) provides a unique stator Volt-sec solution that produces both the desired change in output torque and stator flux magnitude at each discrete time step. Fig. 1 shows a graphical representation of the stator voltage solution in the d-q Volt-sec plane.

The desired change in torque of (3) forms a dotted line in the complex stator Volt-sec plane and is shown in red. The stator flux linkage of (4) forms a big circle in pink, where a part of the circle is shown. The solution of (3) and (4) lies within current (ellipse in black) and voltage limit (hexagon in blue) under the non-limited condition. Here, the stator flux command can be modified by a given Maximum Torque Per
Ampere (MTPA) strategy. The increase of the motor speed forces the operating point on the voltage limit boundary as shown in Fig. 2. This speed is called a base speed ($\omega_b$), where the flux weakening operation starts.

III. DB-DTFC AT OPERATING LIMITS

The desired change in torque of (3) forms a straight line in the complex stator Volt-sec plane and is shown in red. The stator flux linkage of (4) forms a big circle in pink, where a part of circle is shown. The solution of (3) and (4) lies within current (ellipse in black) and voltage limit (hexagon in blue) under the non-limited condition. Here, the stator flux command can be modified by a given Maximum Torque Per Ampere (MTPA) strategy. The increase of the motor speed forces the operating point on the voltage limit boundary as shown in Fig. 2. This speed is called a base speed ($\omega_b$), where the flux weakening operation starts.

Above the base speed as shown in Fig. 3(a), the deadbeat command voltage vector, the intersection of (3) and (4), exists outside of the voltage limit. For this case, the command voltage vector should be scaled back to the physical limits. Here, three other vectors are shown in Fig. 3(a). The point “a” is on the voltage limit and can achieve the maximum torque increase, but it does not satisfy the current limit condition. The point “b” satisfies both physical constraints, but it does not utilize the full current capacity. The point “c” (labeled $v_{dqs}^{c}(k)T_{s}$) is the best option to develop the largest torque while the flux decreases at a given rotor speed.

As shown in Fig. 3(b), this modification implies that the stator flux circle moves toward the new voltage vector in the next step. Then, the stator current at the next sample time will exist on the current limit as

$$i_{ds}^{r}(k+1)^2 + i_{qs}^{r}(k+1)^2 = I_{s_{max}}^2$$

where $I_{s_{max}}$ represents the maximum current limited by the inverter current rating.

For the full utilization of the physical resource, both voltage and current constraints should be considered, maintaining the DB-DTFC features, to modify a command voltage vector on the point “c”. The modified voltage will satisfy the hexagon-shaped voltage limit as shown in Fig. 4.

![Fig. 3. The proposed flux weakening strategy ($\omega_0 > \omega_b$).](image)

![Fig. 4. Space vector diagram in the synchronous d-q Volt-sec plane.](image)
given dc link voltage $V_{dc}$ when the rotating angle is zero ($\theta_r = 0$). It has six equilateral triangles in the synchronous d-q Volt-sec plane. Here, each triangle is called a sector numbered as $\text{sec}_n$ ($n=1, 2, ..., 6$). An adjacent sector shares the vertex defined as $p_n = (p_{nd}, p_{nq})$.

The voltage limit hexagon rotates in the reverse direction with respect to the rotor angle, as shown in Fig. 4(b). The rotation results in the variation of the d-q vertex components. For the calculation of $p_n$, it is useful to consider a transformation of the vertex as

$$p_n = R^{-1}(\theta_r) \left[ \begin{array}{c} p_{nd0} \\ p_{nq0} \end{array} \right]$$

(6)

where $p_{nd0}$ and $p_{nq0}$ are the tip value at $\theta_r = 0$.

Identification of the sector adjacent to the current limit is the first step for a modified stator voltage selection. Then, the boundary of each sector can be obtained as

$$v_{qs}^*(k)T_s = M_n v_{ds}^*(k)T_s + B_n$$

(7)

where

$$M_n = \frac{p_{nq} - p_{nq}}{p_{nd} - p_{nd}}$$

and

$$B_n = -M_n p_{nd} + p_{nq}.$$

The modified stator flux linkage can be rewritten as a function of stator currents as

$$\lambda_{ds}^*(k+1) = L_d i_{ds}^*(k+1) + \lambda_{pm}.$$  

(8)

$$\lambda_{qs}^*(k+1) = L_q i_{qs}^*(k+1)$$

Substituting (8) into (5), the current limit is given by

$$\left\{ \frac{\lambda_{ds}^*(k+1) - \lambda_{pm}}{L_d} \right\}^2 + \left\{ \frac{\lambda_{qs}^*(k+1)}{L_q} \right\}^2 = I_{smax}^2.$$  

(9)

Combining (7) and (9), a new stator flux linkage command ($\lambda_{s}^* = \lambda_{qs}^*(k+1)$) can be obtained. Then, a unique modified stator Volt-sec solution $v_{dqs}^*(k)T_s$ is also obtained as (10) to maximize the output torque under this physical constraint.

$$v_{qs}^*(k) = -\beta - sgn(\omega_r) \sqrt{\frac{\beta^2}{2} - 4\gamma}$$

$$v_{ds}^*(k) = \frac{v_{qs}^*(k) - \beta}{M_n}$$

(10)

where

$$\alpha = L_d^2 M_n^2 + L_d^2,$$

$$\beta = \left[2\omega_n \lambda_{pm} L_q M_n^2 + 2B_n L_d^2 \right],$$

$$\gamma = \left(\omega_n \lambda_{pm} L_q M_n^2 \right)^2 + \left(L_d B_n \right)^2 - \left(I_{smax} \lambda_{pm} L_d L_q M_n \right)^2.$$

Here, it is not possible to achieve deadbeat torque response for the desired value, but it is possible to achieve part of the desired change in torque. With this algorithm, though a deadbeat torque response can be partly achieved, the maximum voltage and current utilization are always guaranteed during the flux weakening region. The basic principle of the wide-speed DB-DTFC ensures direct control of the actual flux over the whole speed range and also a smooth transition between the constant flux region and the flux-weakening region, without the need of the base speed calculation. The selected voltage trajectory automatically moves toward the intersection of current and voltage limit with the speed elevation as shown in Fig. 3(b). The proposed scheme self-regulates the stator flux without adjusting extra tuning parameters, allowing a satisfying operation in the whole speed range. Based on the selected voltages, the system can naturally transition into six-step modulation without changing the control law. This is advantageous as only one control law needs to be developed.

Fig. 5 shows a block diagram of the torque control system.

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### Fig. 5. Proposed wide-speed DB-DTFC strategy.
augmented to include the wide-speed DB-DTFC algorithm. For the stator flux linkage estimation, a discrete time Gopinath-style stator flux linkage observer for IPMSMs is employed [12]. The stator current in next sample time instant is also estimated with the discrete time version of the stator current observer to enhance the control performance.

IV. EXPERIMENTAL RESULTS

The proposed DB-DTFC algorithm was implemented on a 900W IPMSM, as described in Table I, coupled to a 1.0 kW servo motor as shown Fig. 6. An encoder of 2500-pulse-per-revolution was mounted to one end of the test motor to measure the actual position. Fixed MTPA curve was implemented to utilize both the electromagnetic and the reluctance torque available in the IPMSM below the base speed [2]. The CVC and the DB-DTFC were implemented in the inverter with 10 kHz of constant PWM sampling frequency.

<table>
<thead>
<tr>
<th>Ratings and Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated torque</td>
<td>2.9</td>
<td>Nm</td>
</tr>
<tr>
<td>$L_d$</td>
<td>8.5</td>
<td>mH</td>
</tr>
<tr>
<td>$L_q$</td>
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<td>mH</td>
</tr>
<tr>
<td>$\lambda_{pm}$</td>
<td>0.115</td>
<td>Wb</td>
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</table>

The test result of the conventional CVC method [11] is depicted in Fig. 7, where the $x$-$y$ plot of the stator voltage, the air-gap torque, the rotor speed, the stator voltage magnitude, and the current magnitude are displayed from top to bottom. In this test, the dc-link voltage was set to 150 V and the IPMSM drive was operated with an infeasible speed command to saturate the speed controller. Here, the voltage feedback flux weakening control scheme was applied above the base speed [8]. It can be observed from the $x$-$y$ plot that the stator voltage moves along the voltage limit circle ($V_{dc}/\sqrt{3}$) during the flux weakening region. Even though the controller fully uses the available voltage and current during wide speed operation, the realization of maximum voltage utilization fails due to the linear voltage limit. The flux weakening begins about 1200 r/min and the maximum speed reaches 2860 r/min.

The same experiment was repeated using the proposed wide-speed DB-DTFC in the testing system, as shown in Fig. 8.
8. The x-y stator voltage locus almost reaches its maximum voltage in limited conditions. In this test, the drive enters the flux weakening region around 1300 r/min. The maximum speed is 3250 r/min that is amount to the 13.6% elevation compared to the CVC result. It is seen from the waveform of the air-gap torque and the stator flux that a smooth transition occurs between the non-limited operation and the flux weakening mode. The result indicates that the developed voltage selection approach has been successfully applied to IPMSMs at current and voltage limits. The resulting controller was proven to work without requiring any extra control gains or sophisticated anti-windup techniques over the entire operating space.

The results in Fig. 9 show the maximum torque and the output power versus rotor speed of the proposed control and the CVC method. It shows that the proposed method utilizes more torque and power at a given speed than its counterpart in the flux-weakening region. Here, the 12% increase of air-gap torque and output power can be obtained with direct manipulation of stator voltages.

The experimental results clearly show that we achieve the maximum voltage utilization and improved torque production with a single control law.

V. CONCLUSIONS

In this paper, we investigate a wide-speed DB-DTFC method associated with physical constraints of IPMSMs. In the proposed approach, the drive system can provide fast and non-oscillatory dynamics under voltage limits since integrators are not involved for torque control or flux weakening. This implies that a single control law can be used in the voltage limits, unlike current vector control methods, where the control mode has to be modified to deal with limited bus voltages. To support this, we provide a graphical and analytic analysis that naturally leads to a unique stator voltage trajectory for wide-speed DB-DTFC. This allows for an objective voltage vector choice extending the operational ranges.

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