Finite-Control-Set Model Predictive Torque Control With a Deadbeat Solution for PMSM Drives

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Abstract—This paper proposes a control strategy of finite-control-set model predictive torque control (FCS-MPTC) with a deadbeat (DB) solution for permanent-magnet synchronous motor drives. By using a DB solution, the process of selection of the best switching vector is optimized. The predicted DB voltage sector consisting of the desired voltage vector (VV) avoids the complete enumeration for testing all feasible VVs, which relieves the big calculation effort of the traditional FCS-MPTC method. The proposed system is experimentally carried out both in the steady state and in the transient state.

Index Terms—Deadbeat (DB), model predictive control, optimization, permanent-magnet machines, torque control.

I. INTRODUCTION

The DIRECT torque control (DTC) method for electric drives is a widely accepted control method. The DTC method selects the estimated stator flux magnitude and the estimated air-gap torque as the two control state variables and applies a closed-loop feedback control structure to regulate these states [1], [2]. However, the traditional DTC method has a drawback of considerable torque ripples. As possible alternative control strategies, model predictive torque control with a finite control set (FCS-MPTC) [3]–[5] and deadbeat (DB) direct torque and flux control (DB-DTFC) [6] have been recently getting more attention. Both control strategies offer significant improvements over the traditional DTC method. FCS-MPTC is a direct control method that predicts the future system states in discrete time using a predictive model. It utilizes the inherent discrete nature of the power converter without a modulator to solve the optimization problem using a single cost function [7]. The switching vector that minimizes the cost function is selected as the output of the controller. The advantages of the FCS-MPTC method are its intuitive concept and straightforward implementation [4]. Furthermore, the system constraints can be easily added in the cost function. The system is verified as having comparable performance with the field-oriented control method [3]. One of the main drawbacks or challenges of FCS-MPTC is the high calculation effort. In particular, for long steps prediction and for the application of multilevel or irregular topology inverters, the calculation effort rises exponentially. On a common test bench, a large calculation effort burden means long sampling intervals and a low switching frequency, which will increase the torque ripple and reduce the quality of stator currents.

In order to reduce the calculation effort, some methods have been developed to solve or optimize the exploration problem offline. As presented in [8], FCS-MPTC is implemented as the search tree to reduce the calculation effort. In [9] and [10], sphere decoding is utilized to reduce the calculation time and to enable long horizon prediction for FCS-MPTC. As introduced in [11], a heuristic strategy is applied offline. It utilizes multiparametric programming with the Multiparametric Toolbox (MPT) from Matlab. However, a well-known disadvantage of these offline strategies is that the optimization can be no longer affected while the system is running, unless it is stopped or its operating point resets.

As another direct control strategy, DB control [12], [13] is one special discrete-time case. It should cause the system to fully respond to a feasible command after one sample (switching) period. It requires a model inverse solution that makes it feasible to calculate the value of the manipulated input. Referring to the DB control for electric drives, a complete modeling and implementation of DB-DTFC with a stator flux linkage observer was first proposed by Kenny and Lorenz for induction machine control [6]. DB-DTFC utilizes an inverse machine model to calculate the desired voltage vector (VV) based on...
the torque and the stator flux linkage reference. With the applied VV, the desired torque and stator flux linkage can be achieved in the next sampling instant when the torque and stator flux commands are feasible according to the power supply capacity. Recently, DB-DTFC has been transplanted to interior-permanent-magnet synchronous motor (IPMSM) control in [14] and [15]. However, the DB-DTFC method requires a space vector modulator and an accurate observer that increase the complexity of the system.

The basic idea of the proposed FCS-MPTC method with a DB solution is that the cost function for selecting the procedure for the best VV is optimized by using a DB solution. By means of the proposed method, the best switching vector can be selected without evaluating all the feasible vectors of the applied inverter. Based on a two-level voltage source inverter (VSI), the procedure exploration of FCS-MPTC with DB is depicted in Fig. 1(b) and compared with that of the conventional FCS-MPTC method shown in Fig. 1(a). As shown in Fig. 1, the normal FCS-MPTC method tests all the seven VVs (black dotted line) during each predictive step. However, the FCS-MPTC with DB method only needs to test two active VVs (red solid line) and two zero VVs (the origin of the coordinate). The reason is that the DB solution has already achieved the expected VV. Based on the DB VV (DB-VV), only the VVs near the DB-VV are necessary to be tested by the cost function. Thus, with the DB solution, the exhaustive exploration is avoided.

This paper is organized as follows. Section II introduces the predictive control for permanent-magnet synchronous motors (PMSMs). Section III explains the proposed FCS-MPTC with DB method. Section IV gives the experimental results, and this paper is concluded in Section V.

II. Predictive Control for PMSMs

A. Discrete Model of PMSMs

Predictive control presents similar dynamic response and reference tracking than other well-established control methods, and it has wide applications recently [16], [17]. An internal discrete-time model of an electric drive is necessary in order to predict the future evolution of the controlled output variables for a sequence of control inputs over a prediction horizon (one sampling period $T_s$) [18]. Here, the following normal forward Euler approximation will be used to achieve the discrete machine model:

$$\frac{dy}{dt} = \frac{y(k + 1) - y(k)}{T_s}. \quad (1)$$

Omitting the lengthy derivation step, a standard discrete model of a PMSM can be described as follows [19]:

$$\dot{i}_s(k + 1) = Ai_s(k) + Bu_s(k) + C \quad (2)$$

$$\dot{\Psi}_s(k + 1) = L_xi_s(k + 1) + \psi_{PM} \quad (3)$$

$$\dot{T}_e(k + 1) = \left(\frac{3}{2}\right)p\left(\hat{\psi}_s(k + 1) \cdot \dot{i}_s(k + 1)\right) \quad (4)$$

where

$$A = \begin{bmatrix} 1 - R_sT_s/L_d & L_qT_s\omega_e(k)/L_d \\ -L_dT_s\omega_e(k)/L_q & 1 - R_sT_s/L_q \end{bmatrix} \quad (5a)$$

$$B = \begin{bmatrix} T_s/L_d & 0 \\ 0 & T_s/L_q \end{bmatrix} \quad (5b)$$

$$C = \begin{bmatrix} 0 \\ -\psi_{PM}T_s\omega_e(k)/L_q \end{bmatrix}. \quad (5c)$$

B. FCS-MPTC Method

The cost function of the FCS-MPTC method is the criterion for selecting the best VV among the feasible VVs. Here, a traditional two-level VSI is used, as shown in Fig. 2. The switching state and the output voltage can be described as follows:

$$S = \begin{bmatrix} 3 \\ 2 \end{bmatrix} \begin{bmatrix} S_a + e^{2j\pi}S_b + e^{4j\pi}S_b \end{bmatrix} \quad (6)$$

$$V = SV_{dc} \quad (7)$$

Since the torque and flux are directly controlled in the FCS-MPTC methods, the following is used as the cost function:

$$g_i = \sum_{n=1}^{N} \left[ T_{ref} - \hat{T}_e(k + n) \right]^2 - Q_1 \left| \psi_{ref} - \hat{\psi}_s(k + n) \right|^2 + Q_2 \left| S(k) - S(k + n) \right| + I_{max} \quad (8)$$
where \( i = 1, \ldots, 7 \) represents the available number of the switching states of the two-level VSI. \( g_i \) is the cost value corresponding to the \( i \)th VV at the \( (k + N) \)th sampling time, and \( T_{ref} \) and \( \psi_{ref} \) are the torque and flux linkage references at the \( (k) \)th sampling time, respectively. \( T_e(k + n) \) and \( \psi_e(k + n) \) with a superscript are the estimated torque and flux at the \( (k + n) \)th sampling period, respectively. \( Q_1 \) and \( Q_2 \) are the weighting factors that determine the relative importance of each control objective. Based on the iterative evaluation method [20], \( Q_1 \) and \( Q_2 \) are set as 429 and 0.182 in this paper, respectively. As a protection, the current limitation term is important. The following is used to limit the phase current:

\[
I_{max} = \begin{cases} 
0, & \text{if } |i(k + n)| \leq |i_{max}| \\
\infty, & \text{if } |i(k + n)| > |i_{max}|
\end{cases}
\]  

(9)

where \( |i| = \sqrt{i^2_a + i^2_b} \). When the calculated \( I_{max} \) value corresponding to a VV is less than the limitation, the value of \( I_{max} \) is zero, which means that this VV will not generate an overcurrent problem. When a tested VV induces a current over the limit, the value of \( I_{max} \) is infinitive. Therefore, the calculated value of the cost function corresponding to this VV will be infinitive too. According to the principle of the minimization of a cost function, this VV will never be selected as the output, which makes the whole implementation system safe. It is well known that the output VV of FCS-MPTC without DB is selected by exploring all feasible VVs, which is a major advantage of FCS-MPTC in terms of the intuitive algorithm design [3]. However, when the number of feasible VVs is large, such as the case for a multilevel converter or for a long predictive horizon \( (N > 1) \), the big calculation effort is unacceptable, and it will limit the implementation of the original FCS-MPTC method. As shown in Fig. 3, the algorithm with a long prediction horizon cannot be completed during one sampling interval.

III. FCS-MPTC Method With DB Solution For PMSM Drives

The key point of the FCS-MPTC with a DB solution is the optimized exploration. The conventional exhaustive exploration is introduced [16]. Based on the calculation of a DB-VV and the definition of a DB sector, the novel design of the FCS-MPTC with DB system is introduced and analyzed.

![Fig. 3. Execution of the conventional FCS-MPTC.](image)

![Fig. 4. Simplified DB sector of a two-level VSI.](image)

A. Optimized Exploration of FCS-MPTC With DB Solution

As aforementioned, the DB-DTFC system is an inverse-model-based solution. It calculates the desired VV according to the required torque and stator flux linkage references. The desired voltage is defined as DB-VV. With the applied VV, the desired torque and stator flux linkage can be achieved in one switching interval if the commands are feasible according to the power supply capability. In [21], an approximate discrete-time state equation of torque is formed, as described in the following:

\[
\Delta T_e(k) = \frac{3}{2} \left[ u_d(k)\psi_q(k) \left( \frac{(L_d - L_q)}{(L_q L_q)} \right) + u_q(k) \left( \frac{(L_d - L_q)\psi_d(k) + \psi_{PM} L_q}{(L_d L_q)} \right) + \left( \frac{\omega_r(k)}{L_d L_q} \right) \left( L_q - L_d \right) \left( \psi^2_d(k) - \psi^2_q(k) \right) \right] - L_q \psi_q \psi_{PM} - \frac{(R_s \psi_q(k))}{(L_d L_q^2)} \left( \frac{L_d^2 - L_q^2}{L_d L_q} \right) \psi_d(k) - L^2_q \psi_{PM}
\]

\[
\Delta T_e(k) = T_e(k + 1) - T_e(k).
\]

Equation (10) can be linearly rewritten with a slope and a constant that includes the required change of torque in one switching period, as shown in the following:

\[
u_q(k)T_e = mu_d(k)T_e + b
\]

(12)

where

\[
\begin{align*}
\mu & = \left( \frac{(L_q - L_d)\psi_q(k)}{(L_q - L_d)\psi_d(k) - L_q \psi_{PM}} \right) \\
b & = \left( \frac{(L_q L_q)}{(L_q - L_d)\psi_d(k) - L_q \psi_{PM}} \right) \times \left[ (2\Delta T_e(k)) / (3\beta) - (\omega_r(k)T_s) / (L_q L_q) \right] \\
& \times \left( L_q - L_d \right) \left( \psi^2_d(k) - \psi^2_q(k) \right) - L_q \psi_d(k) \psi_{PM} \\
& = (R_s T_s \psi_q(k)) / \left( L_d L_q \right) \left( L^2_d - L^2_q \right) \times \left( \psi_d(k) - \psi_{PM} \right)
\end{align*}
\]

Based on (12), multiple possible VVs can achieve the required change of torque in the next sample instant, and each of the
solutions yields the DB torque control. Due to the limitation of the reference stator flux, the solution of the expected voltages (the DB-VV) in the \(dq\) frame is shown in the following [21]:

\[
\begin{align*}
\begin{cases}
    u_d(k) = (-\bar{A} \pm \sqrt{\bar{C}^2 - (m^2 + 1)\bar{B}})/(m^2 + 1)T_s \quad (13)
    \\
    u_d(k) = m\bar{u}_d(k) + b/T_s
\end{cases}
\end{align*}
\]

where

\[
\begin{align*}
\bar{A} &= m\psi_q(k) + \psi_d(k) - m + mb \\
\bar{B} &= \psi_q^2(k) + \psi_d^2(k) + b^2 + 2b\psi_q(k).
\end{align*}
\]

However, due to the absence of a modulator, the DB-VV is hard to be applied using the FCS-MPTC method. In addition, the DB-VV can supply a datum to decrease the scope of the expected VV of the FCS-MPTC with DB system. In order to fix the scope that includes the DB-VV, the desired DB VV based on the \(dq\) frame in (13) has to be transformed to the \(\alpha\beta\) frame, and the result is shown in the following:

\[
\begin{bmatrix}
    u_\alpha(k) \\
    u_\beta(k)
\end{bmatrix} =
\begin{bmatrix}
    \cos \theta & -\sin \theta \\
    \sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
    u_d(k) \\
    u_q(k)
\end{bmatrix}.
\]

(14)

Then, the position of the desired DB-VV (\(\theta_{DB}\)) can be calculated by

\[
\theta_{DB} = \arctan u_\alpha(k)/u_\beta(k)
\]

(15)

and the desired DB sector that includes the desired voltage is achieved. Furthermore, an insightful graphical solution for the DB sector in the VV plane of a two-level VSI is shown in Fig. 4. In Fig. 4, it can be seen that each DB sector consists of two active VVs (red solid line) and one zero VV (the origin of the coordinate). Based on the position of the DB-VV, the six DB sectors are defined, which are described in Table I.

### B. Implementation of FCS-MPTC with DB Solution

The basic idea of the FCS-MPTC with DB method is that the DB control idea is used to reduce the exploration process. The basic block diagram of the FCS-MPTC with DB system is shown in Fig. 5. In the proposed FCS-MPTC with DB method, the optimized exploration is based on the DB-VV calculation and the DB-sector definition, which is different from the original FCS-MPTC method proposed by Rodriguez et al. [4]. In a real implementation, the microprocessor needs time to execute the algorithm. It takes one sampling cycle to generate the optimum switching state if the variables are measured at the \(k\)th sampling period. In order to obtain the exact flux or torque at the next sampling period \((k + 1)\), the system computation delay has to be taken into account. To compensate for this time delay, a model-based compensation method is applied, as proposed in [22]. The flowchart of the proposed algorithm is described in Fig. 6. It mainly includes the following steps.

- Measure the current and the voltage at the \(k\)th sampling period.
- Estimate the flux and the torque by an observer at the present sampling period \(k\).
- Compensate for the system computation delay, and predict the flux and the torque at next sampling period \((k + 1)\).
- Estimate the accurate output VV by (13), which is called the DB-VV.
Search for the exact sector (the DB sector) into which the accurate DB-VV falls, and reduce the number of tested VVs to 3.

Predict the torque and flux of the three potential VVs, where the number of the feasible VVs is 3.

Calculate the cost function for all the feasible VVs at the next sampling period \((k + 1)\).

Select the VV that has the minimum value of the cost function.

Apply the selected VV as the gate signal of the inverter.

### IV. Experimental Implementation

The proposed FCS-MPTC with DB strategy has been tested and experimentally compared with the conventional FCS-MPTC strategy for a novel designed concentrated windings (CW)-IPMSM [23]. The machine parameters are summarized in Table II. In order to evaluate the validity of the proposed strategy, both the FCS-MPTC with DB method (hereafter referred to as the MPTC-DB method for a simple description) and the conventional FCS-MPTC (hereafter referred to as MPTC) will be based on the same speed proportional–integral controller \((K_p = 0.219, \text{ and } K_i = 0.16)\) and the same cost function (8). Their performance is shown and analyzed in this section.
A. Simulation of Computation Time

The computation results are shown in Table III. In Table III, MPTC and DB represent the MPTC method and the MPTC-DB method, respectively. Time means the turnaround time of the control system, which includes the communication time between dSPACE and Control Desk, the \( A/D \) and \( D/A \) conversion time, the time of the pure code implementation, and the data saving time. It can be seen that, compared with the MPTC method, the computation burden of the proposed MPTC-DB solution method achieves a significant reduction.

B. Experimental Results

The CW-IPMSM is driven by a modified 2-kVA inverter that provides full control over the MOSFET gates, and the maximum switching frequency of the inverter is 50 kHz by taking into account the computation delay and the communication time, as shown in Table III. For example, both the sampling times of the MPTC method and the MPTC-DB solution method are set as 40 \( \mu \)s. When the sampling time is set as 40 \( \mu \)s, the average switching commutations can reach 4.5 kHz per MOSFET. Fig. 7 shows the construction of the test bench.

The first test shows the validity of the developed MPTC-DB method at the steady state. The experimental results are obtained with a load torque of 1.6 N·m (0.8 p.u.) at \( n = 1300 \text{ r/min} \) (0.65 p.u.). The comparisons of the torque between the MPTC-DB method and the MPTC method are shown in Fig. 8. It can be seen that the torque performance of the MPTC-DB solution method is similar to that of the MPTC method. This means that, compared with the MPTC method, the MPTC-DB strategy has almost the same steady-state performance but optimizes the computational burden. The second test is to verify the transient response of the MPTC-DB method. One of the advantages of the MPTC method is the torque implementation of responding in time that is through selecting only active VVs. Thus, the selection of the VVs of the MPTC-DB solution method must be analyzed and verified. In the experiment, the switching states of the MPTC method are represented by seven Arabic numbers, e.g., switching state = 1 means 000, ..., switching state = 7 means 110. However, in the MPTC-DB method, every DB sector consists of one zero VV and two active VVs. In order to avoid missing the zero VVs as a potential VV, a novel initial voltage sequence is formed as \([001, 000, 010, 000, 011, \ldots, 000, 001]\). Thus, in the MPTC-DB method, switching state = 1 means 001, 2 means 000, 3 means 010, 4 means 000, 5 means 011, ..., 12 means 000, and 13 means 001. This means that all the even numbers represent zero VVs. The switching states of the MPTC method and the MPTC-DB method are shown in Fig. 9. It can be seen that, during a torque step of the MPTC method and the MPTC-DB method, only the active states are selected.

In order to evaluate the dynamic control behavior, different speed reference steps have been applied to the system in the third test. The first speed reference is 0–1000 r/min at 0.52 s; the second speed reference step is from positive 1000 to negative 1000 r/min at 2.05 s. The experimental results are shown in Fig. 10. The reference and measured electrical torque values, the reference and measured mechanical speeds, and the stator current are given. It can be seen that the actual electrical torque can track the reference torque very well during both the startup and reversal processes; thus, the actual mechanical speed can also track the speed command very well.

The fourth test is developed to analyze the robustness of the system. The test motor runs at 1300 r/min (0.65 p.u.) with 19% of the rated load. A partial load step (0.19–0.7 p.u.) is added to the control system, which is taken into account as a disturbance. The experimental results are shown in Fig. 11. The results show that the actual electrical torque can track the reference torque over a torque disturbance. The actual speed can also follow the reference speed after 0.6 s. It shows that the system has good dynamic performance. Furthermore, the parameter sensitivity of the MPTC-DB method is investigated. As well known, it is difficult to implement accurate parameters in practice due to the variations injected by noise or temperature. However, the DB solution relies on precise machine parameters to calculate the appropriate VV to apply. Thus, it is necessary to evaluate the parameter sensitivity of the MPTC-DB method. The control
performance under different parameter variations is shown in Figs. 12 and 13. At a time instant \((t = 0 \text{ s})\), \(R_s\) and \(L_s\) increase with a 150% magnitude. From the experimental results, it is shown that the parameter variation influences the system stability (e.g., the torque and the speed). However, after a transient vibration, the system can track the command slowly. The reason is that the MPTC-DB method can select the expected VV to satisfy the system stabilities, although the calculated DB-VV has a relative wide error range. Thus, it can be concluded that the proposed strategy relatively minimizes the influence of parameter variations, and the proposed system has good robustness.

V. CONCLUSION

In this paper, the MPTC-DB method has been developed and implemented. A DB-based exploration approach reduces the calculation effort for the control system. An optimized cost function has been also used to evaluate and choose the appropriate VV. The proposed algorithm has been carried out experimentally. The overall control results verify the steady-state and dynamic effectiveness of the developed strategy because the system of the MPTC-DB method works as well as that of the MPTC method under significant speed reference or torque disturbance steps. Furthermore, the time for the code implementation of the proposed concept in a real-time system is reduced significantly under a DB solution.

In future work, the multilevel topology application of the MTPC-DB method will be investigated. Then, the impact of the switching sequence of the inverter on the efficiency will be considered by optimizing the switching sequence. The overall machine loss (iron losses and copper losses) will be optimized by applying an online algorithm with dynamic programming.

REFERENCES

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