《高阶会员专属视频》-第22期

IEEE期刊导读：无差拍控制（Deadbeat control）的动作原理为何？如何应用在电机控制上？

《高階會員專屬-第22期》IEEE期刊導讀：無差拍控制（Deadbeat control）的動作原理為何？如何應用在電機控制上？

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High-Bandwidth Current Control for Torque-Ripple Compensation in PM Synchronous Machines

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Deadbeat Predictive Current Control of Permanent-Magnet Synchronous Motors with Stator Current and Disturbance Observer

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A. The Fundamental Machine

The dynamic representation of the PM machine is based on complex state variables [8]. Space harmonics and torque ripple induced by the rotor slots are neglected in a first approach and, hence, the analysis starts from the fundamental machine model. The voltage equation in a rotor-fixed reference frame (superscript $^{(R)}$) is

$$\boldsymbol{u}_s^{(R)} = r_s \boldsymbol{i}_s^{(R)} + \boldsymbol{l}_s^{(R)} * \frac{d\boldsymbol{i}_s^{(R)}}{dt} + j\omega \boldsymbol{l}_s * \boldsymbol{i}_s^{(R)} + \boldsymbol{u}_{i1}^{(R)} \tag{1}$$

where $\boldsymbol{u}_s$ is the stator voltage, $\boldsymbol{i}_s$ is the stator current, r_s is the winding resistance, $\boldsymbol{u}_{i1}$ is the fundamental back EMF, and ω is the angular mechanical velocity of the rotor. The

The magnetic saliency of the machines is expressed in (1) by the inductance tensor

$$\boldsymbol{l}_s^{(R)} = \begin{bmatrix} l_d & 0 \\ 0 & l_q \end{bmatrix}. \tag{2}$$

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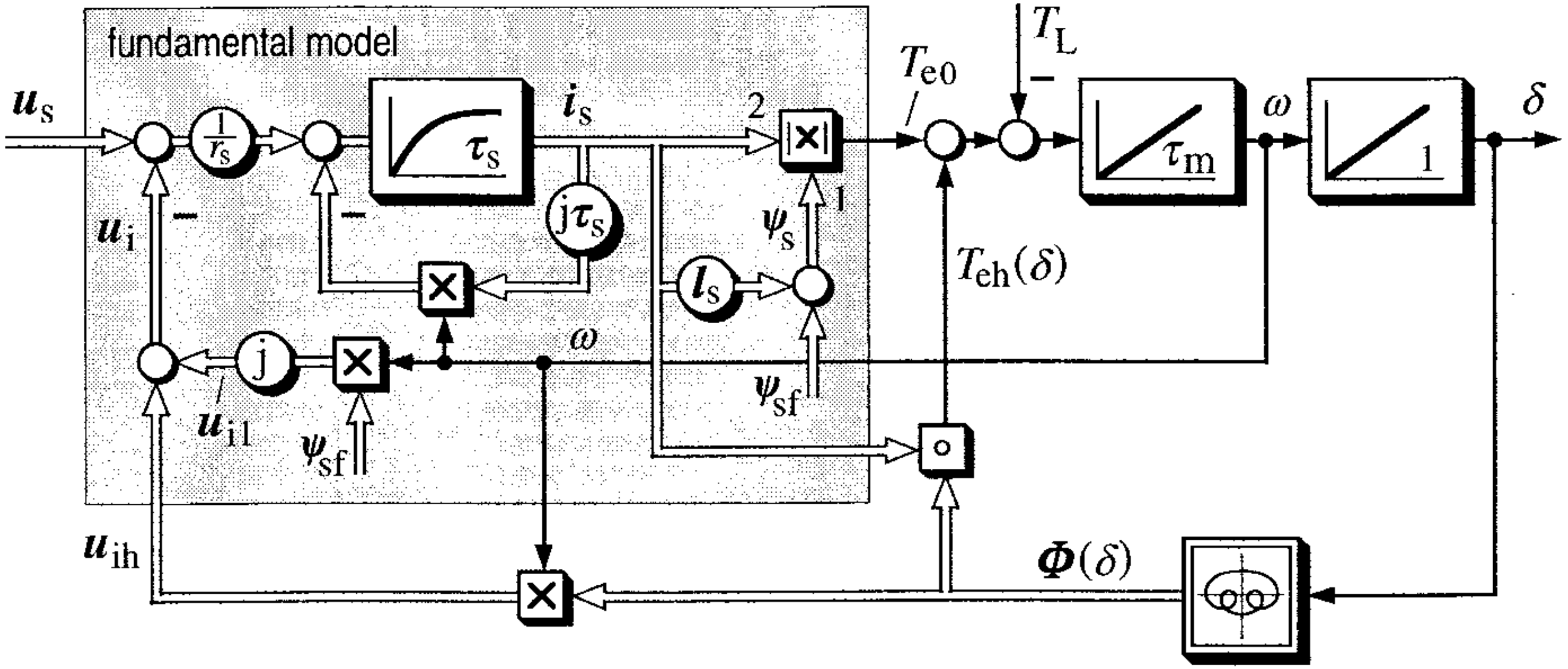

Fig. 1. Complex signal flow graph of a PM synchronous machine. The factor j advances a complex vector by $\pi/2$ in space.

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IV. Deadbeat Current Control

Since the frequency of the harmonic torque components increases with speed, the efficient compensation by a counteracting electromagnetic torque requires a high-bandwidth current control system. Digital signal processing limits the achievable bandwidth owing to the inherent signal delay. The combination of a deadbeat current controller and a current predictor appears an appropriate approach to solve this problem.

The space-vector notation [5] will be used for the controller design, as it corresponds to the representation of the machine model [7] used in Fig. 1. The notation has been found expedient for the dynamic analysis of ac drive systems [10].

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A. Principle of Deadbeat Current Control

Ideally, a deadbeat controller would establish zero current error within one sampling interval T_s. In a digital control system, the controller algorithm computes the required stator voltage vector such that the stator current error $\Delta \boldsymbol{i}_{s,k} = \boldsymbol{i}^*_{s,k} - \boldsymbol{i}_{s,k}$ at sampling instant k is eliminated in the next sampling instant, $\Delta \boldsymbol{i}_{s,k+1} = 0$. Referring to (1), (4), and (7), the required stator voltage at any next sampling instant $k+1$ is

K時刻的電流命令

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$$\boldsymbol{u}^*_{s,k+1} = r_s \boldsymbol{i}_{s,k} + \boldsymbol{l}_s * \frac{\boldsymbol{i}^*_{s,k} - \boldsymbol{i}_{s,k}}{T_s} + j\omega \boldsymbol{l}_s * \boldsymbol{i}_{s,k} + \boldsymbol{u}_{i,k}(\delta) \tag{12}$$

K+1時刻才會作用的電壓命令

which is the defining equation of the deadbeat controller. To verify (12), it is assumed that there is no change of current commanded at sampling instant k, $\boldsymbol{i}^*_{s,k} - \boldsymbol{i}_{s,k} = 0$. Then, the reference voltage need not change in the next

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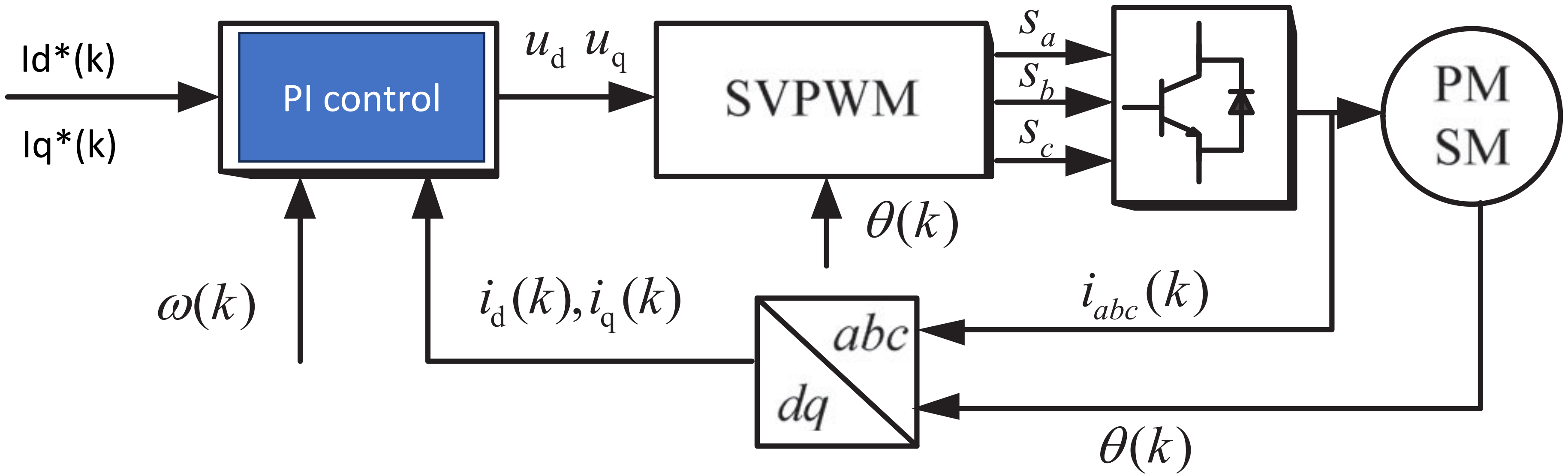

Fig. 1. Block diagram of PMSM DPCC system.

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B. Current Predictor

To eliminate the time delay in (12), the system state variables are required one sampling interval ahead in time. The predicted current is computed with reference to (1) as

K時刻的電壓命令

$$\hat{\boldsymbol{i}}_{s,k+1} = \boldsymbol{i}_{s,k} + (\hat{\boldsymbol{u}}_{s,k} - r_s \boldsymbol{i}_{s,k} - \boldsymbol{u}_i(\delta)_k - j\omega \boldsymbol{l}_s * \boldsymbol{i}_{s,k}) T_s * \boldsymbol{l}_s^{-1} \quad (13)$$

to replace the value $\boldsymbol{i}_{s,k}$ in (12):

$$\boldsymbol{u}^*_{s,k+1} = r_s \hat{i}_{s,k+1} + \boldsymbol{l}_s * \frac{\boldsymbol{i}^*_{s,k} - \hat{\boldsymbol{i}}_{s,k+1}}{T_s} + j\omega_k \boldsymbol{l}_s * \hat{\boldsymbol{i}}_{s,k+1} + \boldsymbol{u}_i(\delta + \omega_k T_s). \quad (14)$$

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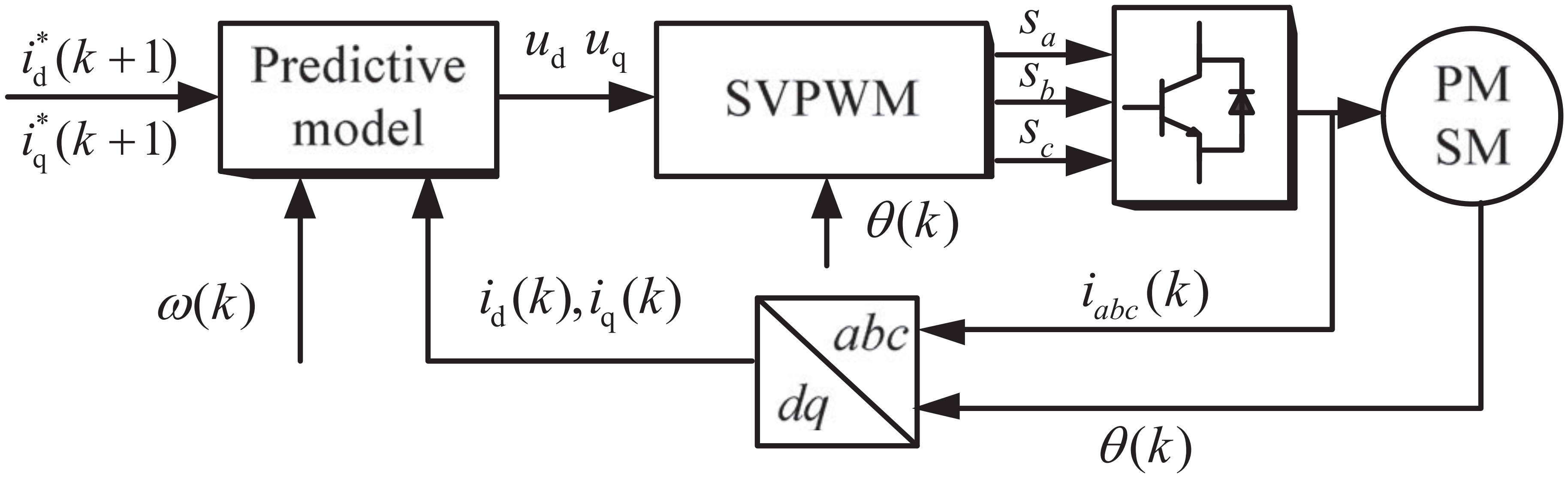

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If the sampling period T_{sc} of control system is short enough, the discrete time model of PMSM can be described by the means of a first-order Taylor series expansion. Then the discrete current predictive model of PMSM is shown in (2), where $\boldsymbol{F}$, $\boldsymbol{G}$, and $\boldsymbol{M}$ are given in (3)

$$\begin{bmatrix} i_d(k+1) \\ i_q(k+1) \end{bmatrix} = \boldsymbol{F}(k) \cdot \begin{bmatrix} i_d(k) \\ i_q(k) \end{bmatrix} + \boldsymbol{G} \cdot \begin{bmatrix} u_d(k) \\ u_q(k) \end{bmatrix} + \boldsymbol{M}(k) \tag{2}$$

$$\begin{aligned} \boldsymbol{F}(k) &= \begin{bmatrix} 1 - \dfrac{T_{\mathrm{sc}} R}{L} & T_{\mathrm{sc}} \omega_e(k) \\ -T_{\mathrm{sc}} \omega_e(k) & 1 - \dfrac{T_{\mathrm{sc}} R}{L} \end{bmatrix} \\ \boldsymbol{G} &= \begin{bmatrix} \dfrac{T_{\mathrm{sc}}}{L} & 0 \\ 0 & \dfrac{T_{\mathrm{sc}}}{L} \end{bmatrix} \\ \boldsymbol{M}(k) &= \begin{bmatrix} 0 \\ -\dfrac{T_{\mathrm{sc}} \psi_f}{L} \omega_e(k) \end{bmatrix}. \end{aligned} \tag{3}$$

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III. Deadbeat Predictive Current Control Method

A. Conventional Deadbeat Predictive Current Control

In conventional DPCC method, according to discrete predictive model (2), the stator voltage of motor that allows the actual current vector to reach the reference currents after a modulation period can be obtained as follows [32]:

$$\begin{bmatrix} u_d(k) \\ u_q(k) \end{bmatrix} = \boldsymbol{G}^{-1} \left\{ \begin{bmatrix} i_d^*(k+1) \\ i_q^*(k+1) \end{bmatrix} - \boldsymbol{F}(k) \cdot \begin{bmatrix} i_d(k) \\ i_q(k) \end{bmatrix} - \boldsymbol{M}(k) \right\} \tag{4}$$

where $i_d^*(k+1)$ and $i_q^*(k+1)$ are the current references.

The structure diagram of PMSM DPCC system is shown in Fig. 1. The voltage vector is computed using the predictive model (4) and then is converted to switching signals through SVPWM modulation.