Impact of digital signal processing on FOC current feedback in high-speed PMSM drive

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Abstract—**In applications where size and weight of the electric motor are among major design concerns, Permanent Magnet Synchronous Motors (PMSMs) with wide operational speed-range are commonly preferred. Due to limited inverter switching frequency, high-speed operation of a drive results in a low ratio between the switching frequency and the fundamental frequency of motor voltage. Such operating conditions have been recently identified as a source of errors in determining motor current feedback using the typical technique dedicated for microprocessor-based controllers. First, sampling the phase currents synchronously with the peaks of modulation carrier provides results of mean currents under an assumption of linear current changes in steady voltage intervals. This assumption is over-simplistic in high-speed drives. Second, transforming the phase currents into a rotating reference frame, required in Field Oriented Control (FOC), is carried out using discretized rotor angle. If rotor covers a substantial angular distance in the control cycle, such simplification distorts transformation results considered as mean values. This paper analyses the joint impact of both these oversimplifications on the errors of field-oriented current components derived in a microprocessor as a feedback to the control algorithm. The analysis was carried out for a high-speed PMSM drive operating at switching frequency of 5 kHz and maximal fundamental frequency of 350 Hz. Simulation results show that the considered oversimplifications lead to notable errors in digital processing of current feedback. The direct-axis current is affected by a notable offset, while the quadrature-axis current is supplemented with a high-frequency error component.**

Keywords—electric drives, high-speed drives, current control, current measurement, permanent magnet synchronous drives, digital signal processing

I. Introduction

Control methods of Permanent Magnet Synchronous Motor (PMSM) drives are continually studied, mainly in the field of mathematical algorithms for controlling currents, speed and position [1][2]. Intensive research is carried out also on methods of providing the control algorithm with feedback signals, where the focus is set on replacing rotor speed and position sensors with sensorless algorithms [3][4]. Meanwhile, the general methodology of current sampling and processing remains unchanged since microprocessors have been introduced to drive control [5], although some limitations of this methodology were identified recently. For example, measurement errors introduced by imperfections of current feedback hardware were studied in [6]. The impact of scaling and offset errors in particular phase current sensors on drive

performance was analyzed and a suitable error compensation method was proposed. Authors of [7] indicated that motor phase currents should not be approximated with linear functions when modelling motors featured by small electrical time constants. The authors analyzed how the assumption of linear current changes affects the accuracy of the mean phase currents measurement using the synchronous sampling. In turn, authors of [8] investigated the impact of currents sampling rate on drive control dynamics, proving that oversampling with a ratio of 8 to 16, combined with applying a specific PWM generator which allows for multiple reference updates within the control intervals, significantly improves the control properties of an electric drive.

In applications where size and weight of the electric motor is among major design concerns, there is a trend of extending the drive's speed-range. It may be distinctly noticed, for instance, in hybrid and electric cars [9][10]. Nearly all such cars manufactured in the last years are equipped with PMSMs, whose maximum speed exceeds 10,000 rpm. Moreover, the number of motor poles usually equals 6 or 8, leading to the requirement of high fundamental frequency of motor voltage. In turn, inverter switching frequencies are limited, as they correspond to power losses. Hence, high-speed operation of a drive results in a low ratio between inverter switching frequency and fundamental output voltage frequency (shortly: switching-to-fundamental frequency ratio, SFFR). When approaching the drive's maximal speed, this ratio can decrease below the value of 10 [11]. Furthermore, some drives use a six-step inverter mode, to shift the voltage constraint and to increase the torque [12][13]. Six-step sets the switching-to-fundamental frequency ratio into a value of 6. Operating with low SFFR has been recently identified as a source of current measurement and processing errors in Field Oriented Controlled (FOC) PMSM drives, as described in the next section.

II. Problems of digital processing of d-q currents in high-speed drives

The general scheme of FOC implemented in a microprocessor is presented in Fig. 1. Due to inverter's switching operation, the waveforms of motor voltages and currents have a compound shape. The high-frequency components related to switching transients are beyond the current control bandwidth, so the digitally executed algorithm operates based on mean voltages and currents. Consequently, the voltage modulation controller is provided with discrete reference voltages, which are transformed into Pulse Width Modulated (PWM) waveforms in a way that their mean
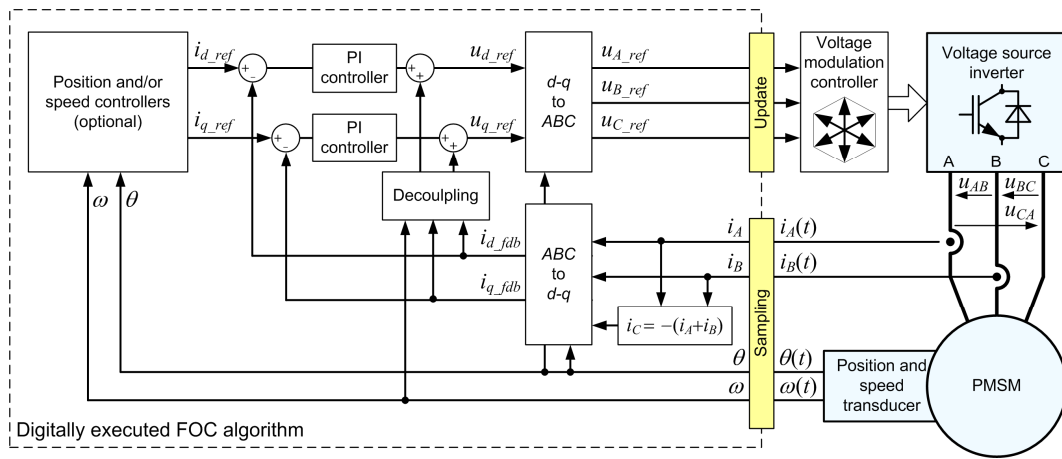
Fig. 1. Simplified scheme of microprocessor-based six-step control of PMSM drive

corresponds to the reference value. Similarly, the phase currents are sampled and processed in a manner that aims for providing mean values i_{d_fdb} and i_{q_fdb} of field-oriented currents to the current controllers.

The procedure of determining the mean d-q currents consist of extracting mean phase currents first, and transforming them into the rotating d-q reference frame afterwards. By using an assumption that the phase currents change linearly upon subintervals of steady voltage, it was proven that the instantaneous current at the midpoint of a symmetrical PWM cycle corresponds to the mean current over this cycle [5]. Hence, sampling the phase current at the midpoints, which is referred to as synchronous sampling, provides the mean value (Fig. 2a). However, the linear current changes assumption was recently reported erroneous in high-speed drives. Study [14] proves that substantial advancement in rotor position, which takes place during a PWM cycle, makes the phase currents waveforms clearly nonlinear (Fig. 2b) due to the substantial change in the electromotive force (EMF). As a result, the midpoint sample of phase current does not represent the mean value precisely. The cited paper reports on errors of synchronous sampling that approach 4% in a high-speed drive operating with SFFR of 14. The problem of current sampling under low SFFR was also in the subject of [15], where the authors propose to derive mean d-q currents by using start-point current sampling and a model-based compensation algorithm. The model reflects only fundamental current and voltage and its accuracy was verified by simulation.

Another source of error in deriving the d-q currents under high-speed operation was identified in [16]. The problem is related to the transformation between stationary and rotating reference frames. The mean phase currents $\bar{i}_a$, $\bar{i}_b$, $\bar{i}_c$, determined by synchronous sampling, are transformed first into the orthogonal x-y reference frame using Clarke transformation. Next, in order to compute the d-q currents, the outcomes $\bar{i}_x$, $\bar{i}_y$ are delivered to Park transformation along with a sampled value of rotor angular position θ:

$$\begin{bmatrix} \bar{i}_{d\_fdb} \\ \bar{i}_{q\_fdb} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \bar{i}_x \\ \bar{i}_y \end{bmatrix} \qquad (1)$$

In contrast, the mathematical definition of mean provides the following equation for mean d-q currents:

$$\begin{cases} \bar{i}_d = \dfrac{1}{T}\int_0^T i_d(t)dt = \dfrac{1}{T}\int_0^T \cos(\theta(t))\cdot i_x(t)dt + \dfrac{1}{T}\int_0^T \sin(\theta(t))\cdot i_y(t)dt \\ \bar{i}_q = \dfrac{1}{T}\int_0^T i_q(t)dt = \dfrac{1}{T}\int_0^T -\sin(\theta(t))\cdot i_x(t)dt + \dfrac{1}{T}\int_0^T \cos(\theta(t))\cdot i_y(t)dt \end{cases} \qquad (2)$$

Equation (1) approximates the accurate definition of mean (2) under an assumption that the rotor position $\theta(t)$ is constant. Hence, the continuous advancement of rotor position is not included in the practical approach of determining i_{d_fdb} and i_{q_fdb}, which consists of synchronous sampling followed by Clarke and Park transformations. The resulting error develops with the increase in rotor position advancement that takes place during the PWM cycle. The reference [16] investigates the considered error of deriving the d-q currents for a case of six-step drive's operation. According to this study, the error is
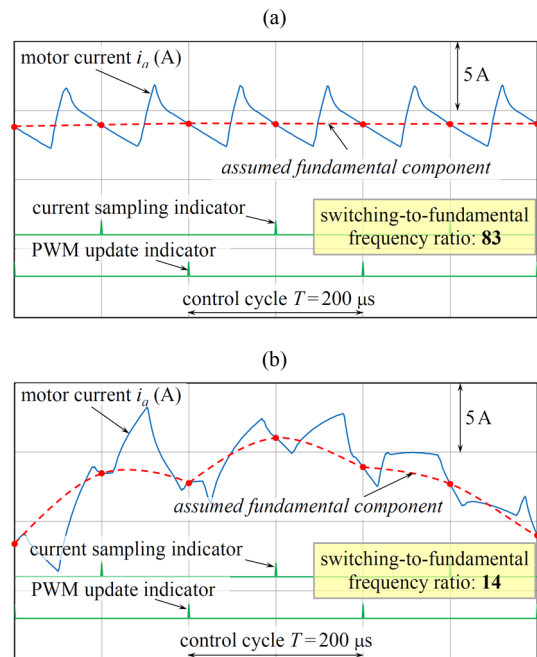

Fig. 2. Phase current waveforms recorded in a laboratory PMSM drive operating with: (a) high switching-to-fundamental frequency ratio, (b) low switching-to-fundamental frequency ratio

at a level of 5% in steady state and becomes higher during transients. Similar investigation was carried out for an induction motor drive [17], and the derived error is at comparable level.

III. AIM OF THE PAPER

As reviewed in the previous section, two sources of error in deriving feedback of mean d-q currents appear under low SFFR operation. The first source is the linear current approximation, which is in the background of synchronous sampling. The second source corresponds to the use of discretized rotor position in the transformation between stationary and rotating reference frames. Both sources were investigated in the previous papers [14] and [16]. However, the errors were investigated independently from each other and by using different assumptions. The study [14] discusses on how the error of synchronous sampling changes with SFFR, but it does not include any analysis on d-q currents. In turn, the work [16] deals with the problem of discretizing rotor position, but the analysis is limited to six-step operation. Therefore, only the lowest SFFR of 6 is investigated and no PWM transients are included. Moreover, study [16] assumes the linear current changes at steady voltage intervals, which is in conflict with the main conclusion from [14].

The aim of this paper is to analyze the joint effect of both errors on derivation of d-q currents in a high-speed FOC PMSM drive that operates in linear PWM region (no six-step). Concluding from the previous works, the errors depend on application-specific features like motor parameters, as well as on random conditions like PWM timings in particular control

TABLE I. MAIN PARAMETERS OF THE PMSM DRIVE

Parameter	Value
Switching (PWM) frequency	f = 5 kHz
Rated phase current	I_r = 10.5 A
Rated DC-bus voltage	U_{DCr} = 300 V
Rated speed (electrical)	ω_r = 2200 rad/s
Flux linkage due to permanent magnets	ψ_f = 75 mWb
Stator resistance	R_s = 0.1 Ω
Stator inductance	$L_d = L_q$ = 1.0 mH

cycles. Thus, their analytical description would be very complex. This paper investigates a case study of specific high-speed drive consisting of non-salient PMSM, whose SFFR declines to 14 at the maximal speed of 2200 rad/s. The error analysis is carried out based on a simulation model.

IV. SIMULATION MODEL

In order to investigate the errors of deriving the d-q currents, a simulation model of high-speed PMSM drive (Table I) was developed in Simulink software [18]. The model consists of both continuous- and discrete-time subsystems in order to reflect the behavior of electric motor as well as the execution of microprocessor-based control and PWM voltage generation.

General structure of the simulation model is presented in Fig. 3. The blue blocks in the figure represent operations,
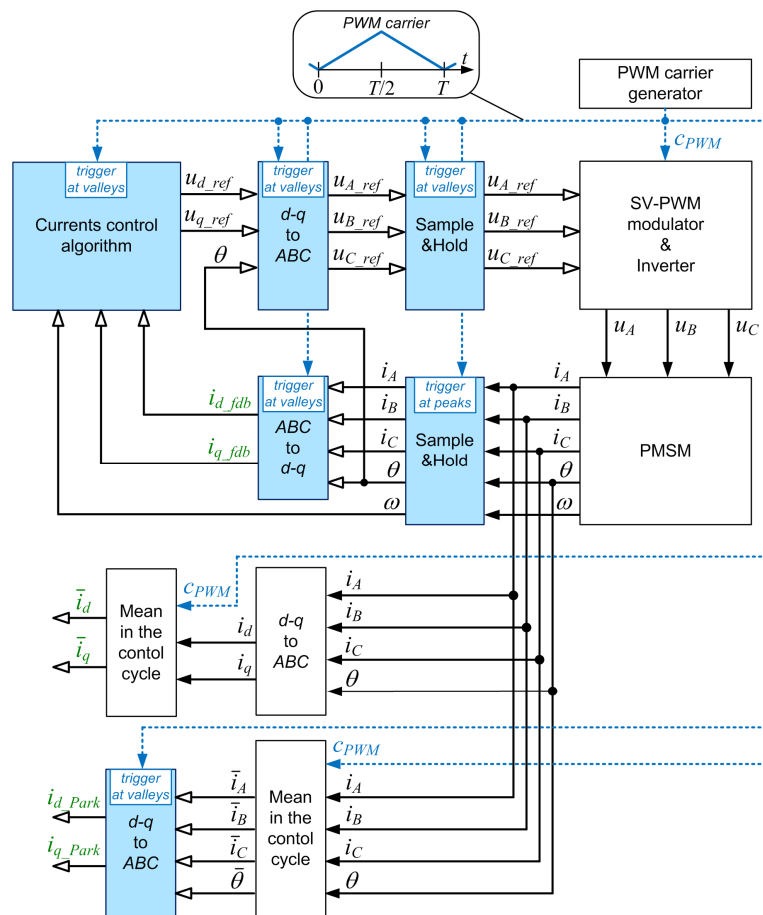
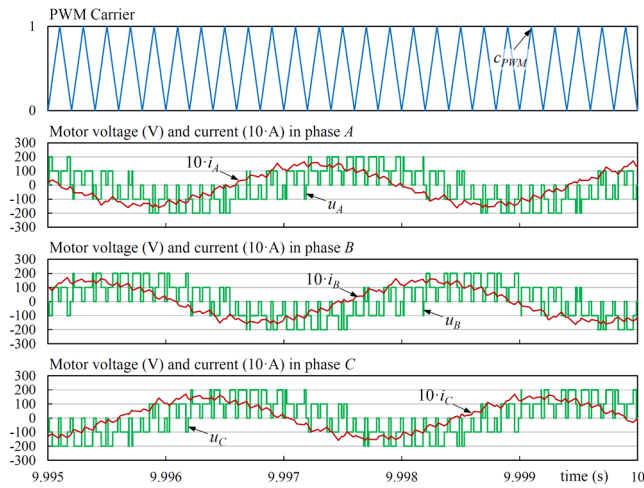

Fig. 3. Structure of the simulation model

Fig. 4. Exemplary simulation results including PWM transients, recorded at maximal speed

V. SIMULATION RESULTS

The investigated errors are related to low switching-to-fundamental frequency ratio. Thus, the focus of the analysis is set on operating with maximal rotor speed, as the SFFR is the lowest then. Nevertheless, it is also considered interesting to observe how the errors change with increasing speed. Hence, the test scenario consists of acceleration from a standstill to the maximum speed.

During acceleration (Fig. 5a), the drive follows the current constraint of 10.5 A (rms). Until $t = 5$ s the controller sets the currents according to maximum-torque-per-ampere strategy. For a non-salient motor, this corresponds to maintaining the value of i_d current at zero. Afterwards, the drives switches into flux-weakening operation, which uses negative i_d to keep the electromotive force below the inverter's voltage constraint. At the end of the test, the drive reaches the maximum speed of 2200 rad/s, which corresponds to fundamental frequency of 350 Hz and SFFR of 14. The current errors are shown in the two last waveforms included in Fig. 5a. In addition, their part corresponding to the last 50 ms of the test is magnified and presented in Fig. 5b.

The errors related to discretizing the rotor position Δi_{d_Park}, Δi_{q_Park} are featured by evident high-frequency components, while their mean values are small. These high-frequency components did not appear in [16], where six-step operation was analyzed and linear current changes were assumed. Hence, this high frequency component is presumably related
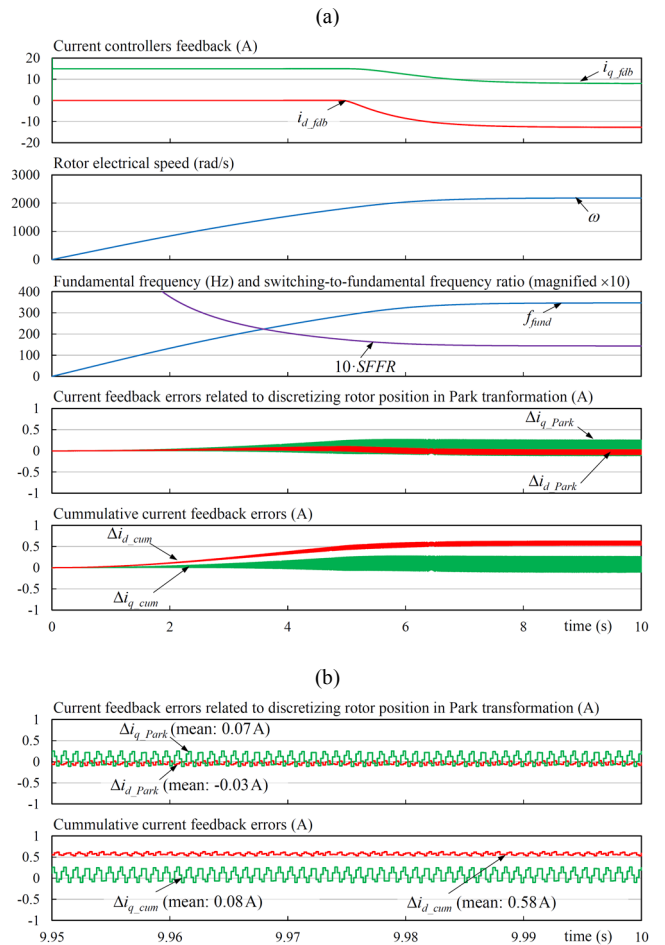
which are executed discretely, once per control cycle. Their execution is triggered either by valleys or by peaks of PWM carrier signal, so it takes place at the start-points or midpoints of PWM cycle. The carrier signal is marked with the blue dashed line. The white blocks in Fig. 3 correspond to subsystems that are running in continuous time. White and black arrowheads are used to differentiate between discrete and continuous signals, respectively.

The most essential control events of current sampling and PWM update are reflected using the sample-and-hold blocks, where the first is executed at the midpoints of control cycles and the latter is triggered at the start-points. The reference frame transformations and the main control algorithm computations must be executed between the above-mentioned instants. As the computing time is not reflected in the simulation, the computations are executed infinitely fast with respect to the simulation time. Thus, it was assumed that these computations are executed at the start-points of control cycle, but they precede the update of PWM reference signals.

The subsystem representing modulator reflects the SV-PWM method [3] as shown in Fig. 4. Transistors and diodes in the inverter model are assumed ideal. Voltage drops, switching disturbances and dead times are not reflected in this model.

In the model, the d-q currents are computed in several ways. The accurate mean currents $\bar{i}_d$, $\bar{i}_q$ are computed according to the definition (2), and they are used as reference values for deriving errors. The i_{d_fdb} and i_{q_fdb} values are computed in a manner that reflects the microprocessor implementation, i.e. by synchronous sampling of the phase currents and transforming the results into the d-q frame using (1). The differences between the reference currents and the i_{d_fdb} and i_{q_fdb} currents are considered as cumulative errors Δi_{d_cum}, Δi_{q_cum} that include both the considered oversimplifications. In addition, the i_{d_Park} and i_{q_Park} currents are derived by computing the errorless mean of the phase currents, and transforming the results into the d-q frame using the discrete rotor position that corresponds to the midpoint of PWM cycle. These currents, which do not consist of errors related to synchronous sampling, are used to compute errors Δi_{d_Park}, Δi_{q_Park} related solely to the use of discretized rotor position in Park transformation.

Fig. 5. Simulaton results: (a) including the process of accelerating from a standstill to the maximal speed; (b) for operating at the maximal speed

to the current nonlinear changes and PWM transients. In the cumulative errors, the high-frequency components are repeated. However, the mean of the Δi_{d_cum} error is elevated with respect to Δi_{d_Park}, which must be related to the inaccuracy of synchronous sampling. This mean reaches 0.58 A, i.e. 4% of the rated current. In turn, mean of the Δi_{q_cum} error is a few times smaller. Such relation between Δi_{d_cum} and Δi_{q_cum} can be explained analytically. The assumption of constant rotor position during a control cycle causes that the actual EMF varies with respect to the unmoving d-q co-ordinates. The angular position of the EMF vector is close to the q axis. Thus, the changes of electromotive force E in d and q axes can be estimated by $E \cdot \sin(\Delta\theta)$ and $E \cdot \cos(\Delta\theta)$, respectively. For small values of $\Delta\theta$, the derivative of sine is close to 1, while the derivative of cosine can be approximated with 0. Hence, the changes in the EMF are noted mainly in the d-axis. Consequently, the i_d current becomes substantially non-linear, and the regular sampling errors are much higher for i_d than for i_q.

Computation time related to the control algorithm is infinitely short in the simulation time domain. This provides an opportunity to use the accurate mean currents as a feedback for current controllers. Fig. 6 presents a comparison between torque waveforms obtained in control systems that use feedback from standard i_{d_fdb}, i_{q_fdb} and precise $\bar{i}_d$, $\bar{i}_q$ signals. For the exemplary drive (Table I), featured by low inductances and low switching frequency, there is no notable impact of the high-frequency Δi_{q_cum} component on rms of torque ripples.

VI. Conclusion

Whilst both the considered sources of errors have been already investigated, the analysis of their cumulative effect brings new insight on the inaccuracies in digital processing of the d-q currents in high-speed PMSM drives. The investigated errors are related to the current control method, PWM scheme, motor ratings etc. This poses problems to formulate a versatile analytical description. Hence, the analysis in this paper is based on the simulation study performed for the exemplary drive. This gives a general insight on the errors, but does not represent the maximal possible errors, as other drives may use e.g. lower SFFR than considered in this paper.

The use of discretized rotor position in Park transformation causes that the derived d-q currents consist of a high frequency error component, which is larger in the q-axis current. As the mean of error signal is negligible, this error may potentially increase torque ripples, but it should not notably influence the mean torque.
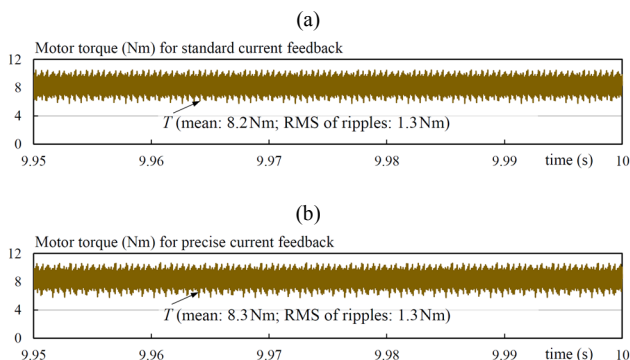

Fig. 6. Torque waveforms recorded at maximum speed for:
(a) standard current feedback; (b) precise current feedback

The error of deriving the mean current by synchronous sampling causes a DC-like error in the field-oriented currents, which affects mainly the d-axis current. The consequences of this error in controlling the i_d current may include, for instance, deviating from the assumed ratio between i_d and i_q currents that assures maximal motor efficiency. Under flux weakening operation, the error can disturb balancing on the voltage constraint. As the derived current is less than the actual one, the flux would be over-weakened, which is safe in regard to control stability, but decreases the available torque.

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