Indirect Measurement of Motor Current Derivatives in PMSM Sensorless Drives

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Abstract—Motor current derivatives contain useful information for control algorithms, especially in sensorless electric drives. The measurement of motor current derivatives in electric motors supplied by voltage source inverter can be performed using di/dt transducers. However, in such a solution additional sensors have to be installed, e.g. Rogowski coils. Another approach is to measure current derivatives indirectly – by oversampling the motor currents. In such a method special attention must be paid to determination of current sampling instants. Measurement triggering times must be recalculated in each voltage modulation period with regard to transistors switching. The paper presents different current sampling approaches. Considered oversampling algorithms were experimentally tested in sensorless PMSM drive. The impact of different sampling approaches on the accuracy of rotor position estimation has been discussed.

Index Terms—Current measurement, sensorless control, signal sampling, space vector pulse width modulation, variable speed drives.

I. INTRODUCTION

In recent years increased research has been conducted in variable speed drives control algorithms which use motor phase currents derivatives. The main field is sensorless control of Permanent Magnet Synchronous Motors (PMSM) [1]–[5]. Estimation of rotor position at high speeds is performed by determination of the electromotive force (EMF) vector [6]. The use of motor current derivatives instead of the current values alone significantly simplifies the mathematical calculations. At low speeds the rotor position is estimated by the analysis of motor saliency or saturation [7], [8]. In most methods an additional high-frequency signal component is generated by the inverter in order to detect the PMSM stator inductance variation. The use of current derivatives takes advantage of the standard pulse width modulation (PWM) transient excitation. Therefore, the ripples of electromagnetic torque and power losses can be minimized. The current derivatives can also be used for rotor position estimation in other drives, i.e. induction motor [9] or reluctance motor drives [10]. The values of current derivatives may also be exploited for motor parameters identification [11], [12].

The current derivatives are determined between the inverter transistors switching, i.e. during a modulation subperiod. They can be measured directly or indirectly. In

the first case Rogowski coils can be used [2]. In such a solution the gain resulting from removing the rotor position and speed sensor can be easily overweighed by the cost of additional feedback.

Indirect measurement of current derivatives is based on current oversampling with the use of standard transducers. Considering single modulation subperiod, the inverter output voltages are constant. The motor currents change according to exponential, but the duration of a subperiod is very short with respect to the time constant of the circuit. Therefore, it is assumed that the current changes linearly (Fig. 1). The calculation of current derivative requires two current measurements in a single modulation subperiod. The current derivative is calculated as differential quotient

$$\frac{\mathrm{d}i}{\mathrm{d}t} \cong \frac{\Delta i}{\Delta t}. \tag{1}$$

The research in the field of sensorless drives using measurement of current derivatives focuses on the mathematical algorithms for estimation of rotor angular position. The method of current sampling, if considered, is assumed *ad hoc*, without a proof of its superiority [2–5], [10]. A research concerning an influence of shifting the current sampling instants with respect to inverter control signals has not been reported.

The paper discusses different approaches to current oversampling for determination of current derivatives. The standard methods presented in the references are summarized, followed by the proposal of a new approach to accumulated current change calculation. The assessment of the discussed methods was performed experimentally by the analysis of rotor position estimation errors in PMSM sensorless drive, with the use of the previously presented mathematical algorithm [13].
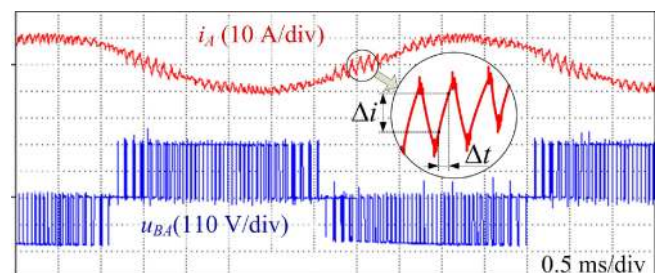

Fig. 1. Phase current i_A and line-to-line voltage u_{BA} in PMSM motor supplied by Voltage Source Inverter (VSI).

II. PMSM Rotor Position Estimation Algorithm

Motor torque control in sensorless drive involves accurate rotor position estimation at any speed. This requirement is fulfilled by the use of different estimation algorithms switched according to actual speed. The considerations were limited to an algorithm designed for medium- and high speed range presented in [13], [14]. The estimator uses motor current derivatives measured when motor terminal voltages are zero to track the angle of EMF vector. Rotor position θ_E is calculated from

$$\theta_E = \arctan\left(\frac{\dfrac{di_\alpha(0)}{dt}}{\dfrac{-di_\beta(0)}{dt}}\right) - k \cdot i_q =$$

$$= \arctan\left(\frac{\Delta i_\alpha(0)}{\Delta i_\beta(0)}\right) - k \cdot i_q, \qquad (2)$$

where $di_{\alpha(0)}/dt$, $di_{\beta(0)}/dt$, are motor current derivatives transformed into α-β stationary reference frame; k is a constant calculated from the motor parameters; i_q is q-axis motor current expressed in d-q rotating reference frame. The second term of (2) was added to cancel the error caused by the motor saliency in Interior PMSM (IPMSM) [13].

III. Current Sampling Algorithms

For PMSM rotor position estimation with the use of (2) it is necessary to measure the current derivatives when a passive (zero-voltage) vector is generated on the inverter output, i.e. when all lower or all higher transistors are turned on, so the motor terminals are connected (Fig. 2).
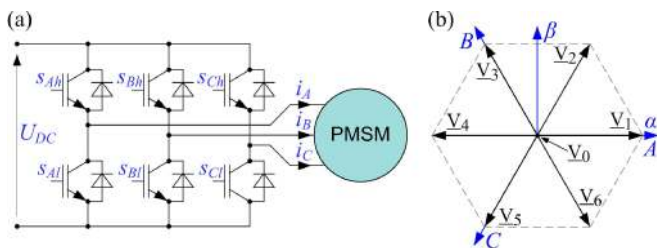

Fig. 2. VSI: electrical diagram (a) and output voltage vectors (b).

An exemplary sequence of transistor control signals in a modulation period using Space Vector method (SV-PWM) [15] is presented in Fig. 3. The i_A and i_B are motor phase currents, s_{ADC} is Analog to Digital Converter (ADC) start of conversion signal (falling edge). The transistors control signals were labeled according to Fig. 2. The ouput voltage vectors are marked at the bottom of the figure. In general, every SV-PWM period includes three passive subperiods ($\underline{V}_0$) – at the beginning, in the middle and at the end. Between them active subperiods ($\underline{V}_m$, $\underline{V}_n$) take place.

Every transition between subsequent subperiods requires switching in an inverter leg. One of the transistors is turned off and, after a short delay (i.e. dead time), another one is turned on. The switching process results in disturbances in current waveforms. The measurements can be triggered simultaneously with the change of control signal which turns

off a transistor. Current sampling is performed quickly enough not to be affected by the current disturbances [5]. This approach is easy to implement since ADC triggering requires no special event. The measurement can be initiated synchronously with PWM signals change.
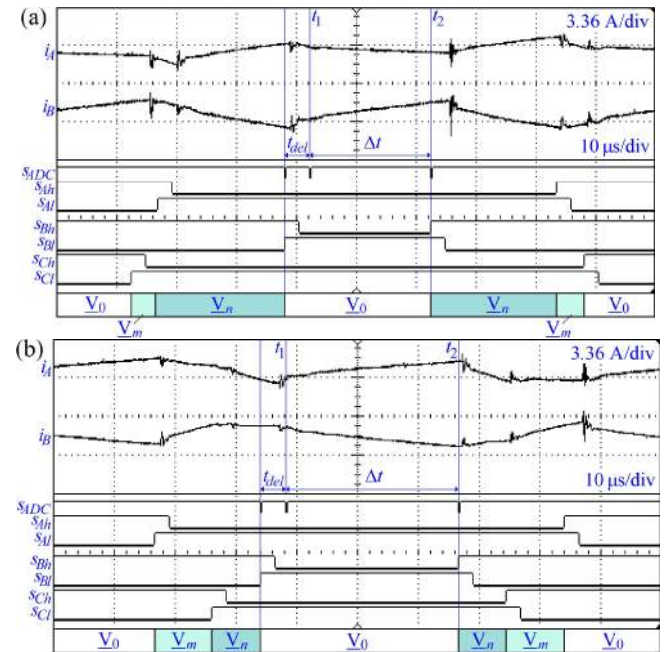

Fig. 3. Waveforms of phase current and control signals recorded in PMSM drive during motoring (a) and braking (b).

In abovementioned approach the motor voltages change between sampling which is contrary to the formulated assumption. This leads to certain errors when calculating the value of current derivative. Another solution is to delay the first current measurement so that it is performed after the current disturbances (see t_{del} in Fig. 3) [3], [4], [10]. The delay has to be long enough for the disturbances to fade out. On the other hand, increasing the t_{del} value leads to lower Δt and Δi values. This decreases the indirect measurement accuracy due to measurement noise and limited ADC resolution. Moreover, deterioration of the accuracy is expected in braking mode as mentioned in [3]. This is caused by different delay between turning off a transistor and the occurrence of current disturbances, which can be noticed when comparing Fig. 3(a) and Fig. 3(b). Therefore the optimal value of the delay is a subject to experimental research.
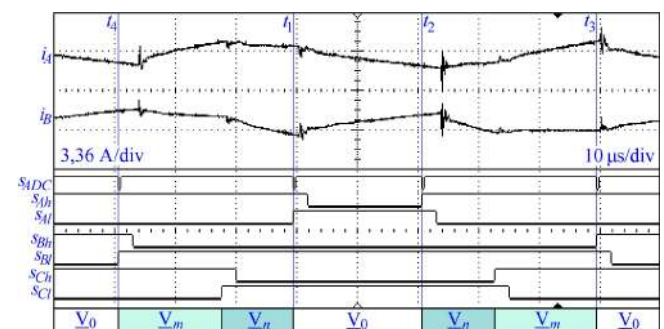

Fig. 4. Waveforms of phase current and control signals recorded in PMSM drive with sampling algorithm dedicated to accumulated current change calculation.

Standard sampling approaches presented in the references

consider current derivative determination for a single modulation subperiod, both with and without $t_{del} > 0$. However, a SV-PWM period includes three passive subperiods. Accumulation of the current changes Δi for a set of three subperiods may lead to increased accuracy. Such an attempt still allows rotor position in every PWM period to be calculated [13]. There is no transient between the last passive subperiod in $k-1$ modulation period and the first passive subperiod in k period. Consequently, only four current samples are necessary to calculate the accumulated current change Δi_Σ after a PWM period (Fig. 4)

$$\Delta i_\Sigma = \left(i_{t3(k)} - i_{t2(k)}\right) + \left(i_{t1(k)} - i_{t4(k-1)}\right), \quad (3)$$

where $i_{t1} \div i_{t4}$ are subsequent current measurement values (Fig. 4), k is a number of PWM period. To enable rotor position estimation algorithm with the use of (2), the Δi_Σ has to be determined for each of the motor phases *ABC* and transformed into an orthogonal coordinate frame α-β [16].

IV. EXPERIMENTAL SETUP

The considered current sampling strategies were tested on laboratory 3-kW PMSM drive presented in Fig. 5.
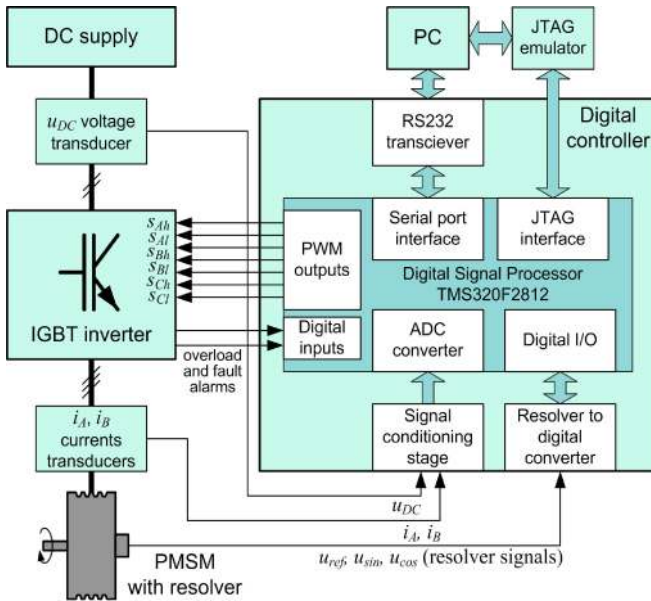

Fig. 5. Overall structure of the sensorless drive with control system.

The digital controller is based on the TMS320F2812 Digital Signal Processor (DSP). The controller performs the current control algorithm according to the FOC method [16]. The drive works in a torque control mode. Maximum Torque Per Ampere (MTPA) strategy is applied to calculate the i_d and i_q reference values. Control software variables are transmitted to the PC via serial port interface. The standard SV-PWM voltage modulation method is used [15] at the frequency of 10 kHz.

LEM LTS-15NP transducers with 100 kHz bandwidth were chosen for motor phase currents measurement. The signal conditioning stage consists of operational amplifiers for signal scaling and analog low-pass filters with cut-off frequency set to 100 kHz to filter out the interference peaks.
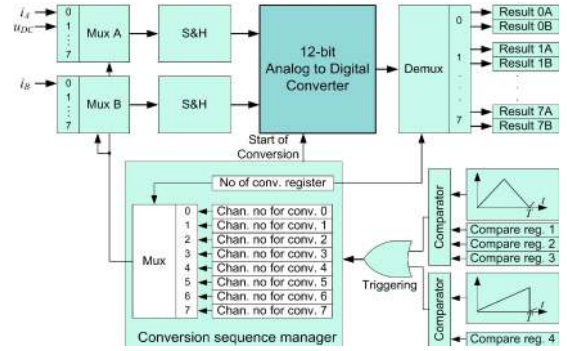

Fig. 6. Functional diagram of ADC module configured for indirect current derivatives measurement.

The ADC module integrated into the DSP was set to perform multiple sampling in a PWM period. A functional diagram of the configured ADC module is presented in Fig. 6. The measurement is triggered by the event of matching values of a counter and a compare register. For the measurements synchronised with the transistors control signals the same compare registers and up-down counter is used as for PWM switching. Introducing the delay between the change in inverter control signal and measurement triggering requires the use of an additional counter which counts up. The delay between measurement triggering and latching the analog value in sample&hold circuit equals approximately 0.4 μs.
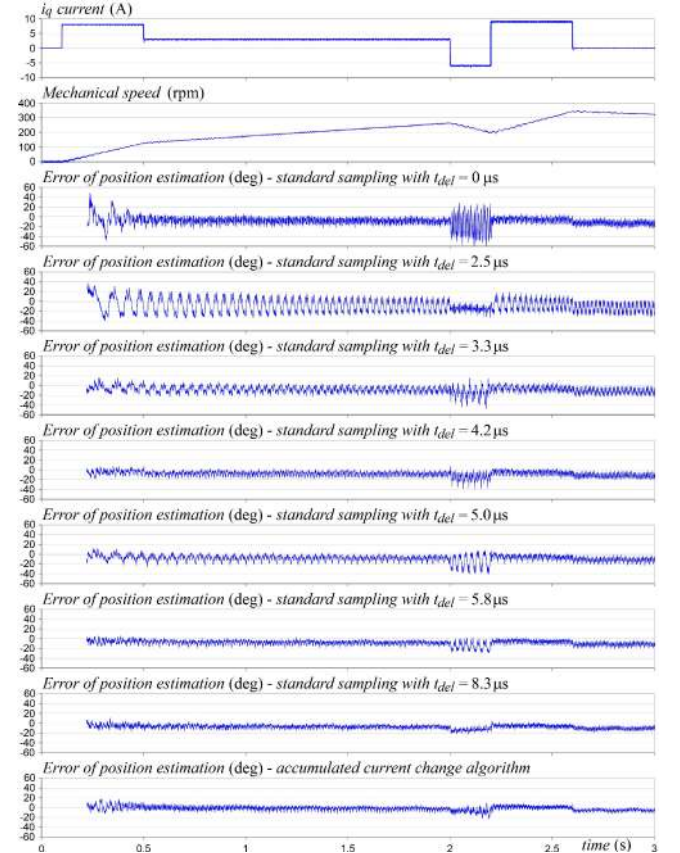
V. EXPERIMENTAL RESULTS

Fig. 7. Experimental results of rotor position estimation errors for different sampling algorithms.

A compound drive operation cycle was proposed to validate different sampling algorithms. The cycle consists of

motoring with varying torque (i_q current), braking and freewheeling. Experimental results are presented in Fig. 7. To evaluate the accuracy of current derivatives the value of estimated rotor position was used. The error of position estimation can be determined by comparison with the value measured by the resolver. Since the estimation algorithm is dedicated for medium- and high-speeds range, the error waveforms were registered when drive reached 50 rpm.

In case of standard sampling with $t_{del} = 0$ (see Fig. 3) the accuracy of rotor position estimation is on an average level. However, great errors occur during braking (negative i_q). This disqualifies such an approach in certain applications, e.g. traction drive. Introducing the delay between the change in inverter control signal and the first measurement can improve the estimation accuracy. However, the relation between the t_{del} value and rotor position estimation errors is complex and depends on drive operation mode. Increasing the t_{del} does not always result in accuracy improvement, e.g. t_{del} change from 4.2 μs to 5 μs in Fig. 7. The best estimation accuracy, both in motoring and braking mode, was obtained for $t_{del} > 8$ μs. In this case the error for motoring mode is significantly smaller than with $t_{del} = 0$. The estimation accuracy during braking is also at a low level. Accumulated current change algorithm refers to the sampling sequence shown in Fig. 4 and calculations performed in accordance with (3). The estimation accuracy during motoring and freewheeling is similar to the one for the standard sampling with $t_{del} > 8$ μs slightly bigger error occurs during braking.

VI. Conclusions

The use of motor current derivatives measurement in PMSM sensorless drive leads to simple rotor position estimation calculations. The derivatives can be measured indirectly by multiple current sampling in a PWM period. However, special attention must be paid to implementation of specialized current sampling algorithm. The instants of measurement triggering have to be calculated on basis of transistor switching times – for each modulation period.

Different sampling approaches suggested in the references were tested experimentally. The best accuracy was achieved for current sampling performed with $t_{del} > 8$ μs in a single passive modulation subperiod. However, such a delay leads to additional limitation of minimal duration of inverter passive states. This results in significant limitation of the modulus of inverter output voltage vector. Assuming minimal sampling interval $\Delta t = 5$ ms and modulation frequency $f_{PWM} = 10$ kHz, the maximum inverter output voltage has to be reduced by 25 %. In comparison, using the accumulated current change calculation leads to slightly worse accuracy, but introduces much smaller limitation of inverter output voltage – 10 % for the same Δt and f_{PWM} values. Moreover, it is easier to implement since only PWM generation events are necessary for measurement triggering.

The experimental tests, performed for an adopted drive setup, enabled to draw general conclusions about the impact of current sampling approach on the error of rotor position estimation. However, the results are influenced by the selected hardware, e.g. transistor switching times, ADC resolution etc. Therefore, the sampling algorithm should be returned after any change in the hardware.

Recent improvement in DSP processors enabled the use of current-derivative-based control algorithms in low-budget electric drives. The experiments validated the possibility of rotor position estimation with indirect measurement of current derivatives in a relatively low-cost controller. Internal 12-bit ADC module of the used DSP has sufficient accuracy and triggering possibilities to perform indirect measurement of motor current derivatives without any additional devices, e.g. FPGA or external ADCs.

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