Current Control of AC Drives Using Shunt Current Sensors and Delta-Sigma Modulation

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***Abstract*—This paper considers the shunt current sensing technology using delta-sigma modulation and demodulation by means of digital filters. The investigation was conducted using a model of the drive; and the open-loop system was used to examine the accuracy of the measurement, while the closed-loop control was used to study the impact of the measurement error on the stability of the control and the torque ripple of the drive. It is shown that oversampling ratios of 8 and smaller bring about very large disturbances in the control loop, even if a Sinc3 digital filter is used. Acceptable results can be obtained by using oversampling ratios of 16 and higher along with the Sinc3 filter.**

Keywords— shunt current sensing; delta-sigma modulation; current control; closed-loop control; torque ripple

I. INTRODUCTION

For many years, Hall-effect current sensors dominated current measurement technology for high-performance applications. Shunt current sensors were used only for low-power and low-cost drives in household appliances, hand tools, etc. Shunt current sensing technology for high-power applications require isolation of the analogue signal, doing which can adversely impact the cost, accuracy, and/or bandwidth. For example, linear opto-coupling ICs have poor linearity and accuracy as compared to standard closed-loop Hall-effect current sensors. Further, the voltage to frequency converter ICs, which produce digital signal that can be easily transferred to the control system via low-cost opto-couples, have large measurement delays and high costs.

This situation has changed since delta-sigma modulators became available as ICs. Delta-sigma modulators (such as the AMC1305 [2] from Texas Instruments) are currently produced by several companies to perform modulation of the input signal from the shunt current sensor and provide isolated data stream (or bitstream) transfer to the control system. Demodulation of the bitstream can be done by an internal peripheral device of the microcontroller or by the programable logic of an FPGA used for control.

Semikron was the first manufacturer to begin producing power modules with integrated shunt current sensors in the output circuits [1]. IC manufactures provide a series of delta-sigma modulators [2] and microcontrollers with embedded demodulators [3]. All these components together can replace the closed-loop Hall effect sensor, saving approximately 30 USD per sensor (for a rated sensor current of 200 A) [4]. However, the main question remaining is regarding the accuracy of the proposed current measurement system.

Published studies and manuals regarding the accuracy of shunt current sensing using delta-sigma technology have reached conclusions that are seemingly contradictory. Some datasheets [3] consider the increase of the output bitstream resolution by applying higher-order digital filters as an increase in accuracy. The problems associated with this approach are shown in [5]. The second approach explains that if the signal is very small or big (for instance, 1% of the total range), then the bitstream contains a lot of zero or one bits; and the number of consequent identical bits can exceed the sampling time. However, this problem occurs only with extreme values of the input signal, which are not typical for the normal operating conditions of the power converter [5].

As shown in [5], by analyzing the conversion of the steady signals, the information in the bitstream is represented not only by the mean value of the bits in it but also by the frequency of change between the zeros and ones in the bitstream. This information is extracted by using high-order digital filters, such as Sinc2 or Sinc3; however, the accuracy varies with the value of the input signal [6].

The use of the shunt current sensing with delta-sigma modulation was investigated in [7] and used for sensorless and predictive control in [8] and [9]. But little attention has been paid to the accuracy of the measurement and its impact on the control. The bigger the decimation is and the longer the current measurement is, the more accurate the result will be; although the estimation delay is longer too. Thus, the tuning of the digital filter is a tradeoff between the accuracy and speed of the current estimation. Therefore, the main goal of this paper is to provide recommendations regarding the required decimation ratios for digital filters.

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II. OPERATION PRINCIPLES OF SHUNT CURRENT SENSING USING DELTA-SIGMA MODULATION

The current shunt is connected between the output of the inverter and the phase of the motor. The voltage drop across the shunt should lie in the range of ±50 or ±250 mV in order to be compatible with the existing delta-sigma modulators in the market. The power supply of the top IGBT driver can be used to power the delta-sigma IC (see Fig. 1). This IC usually implements second-order delta-sigma modulation (see Fig. 2), which has better distributions of ones and zeros of the generated bitstream as compared to the first-order delta-sigma modulator [11]. The output bitstream contains information regarding current flowing through the phase of the motor. As the bitstream is a digital signal, the isolation of this signal is cheaper than that for the analogue signal.

The delta-sigma IC must be synchronized by a microcontroller with a 20 MHz clock—f_{clk}. 20 MHz is the most common maximum synchronization frequency for these ICs. The lower frequency is not desirable, as it increases the measurement time. The demodulation of the bitstream can be performed by means of a special peripheral device of modern microcontroller such as TMS320F28377D from Texas Instruments. The bitstream should be filtered using a low-pass filter, the usual option for which is Sinc filters [6] of different orders. In general, the Sinc filter of the first order is the moving average filter and can be represented by an IIR [10] or FIR equation, while the result of operation remains the same:

$$H_{IIR}(z)=\frac{1}{N}\cdot\frac{\left(1-z^{-N}\right)}{\left(1-z^{-1}\right)}, \tag{1}$$

$$H_{FIR}(z)=\frac{1}{N}\left(1+z^{-1}+z^{-2}+\ldots+z^{-(N-1)}\right), \tag{2}$$

where z is the time shift operator; N represents the oversampling ratio (OSR) or the number of bitstream bits used in the filter.

The accuracy of the current measurement depends on the number of bits in the bitstream used for a single measurement and on the digital filter used. The bigger the number of bits or oversampling ratio is and the higher the filter order is, the higher the accuracy will be. Whereas, increasing the accuracy by the number of the bits processed the measurement duration increases as well. Hence, the tuning of the digital filter is a tradeoff between the accuracy and measurement speed. The current measurement times can be evaluated using the following equation:

$$t=\frac{OSR}{f_{clk}}\cdot F_{order}, \tag{3}$$

where F_{order} is the Sinc-filter order.

Usually, two different filters are used for each channel. One is used for precise current measurement—Sinc2 or Sinc3 filter with a large OSR—and another is used for protection—Sinc1 filter with a small OSR.

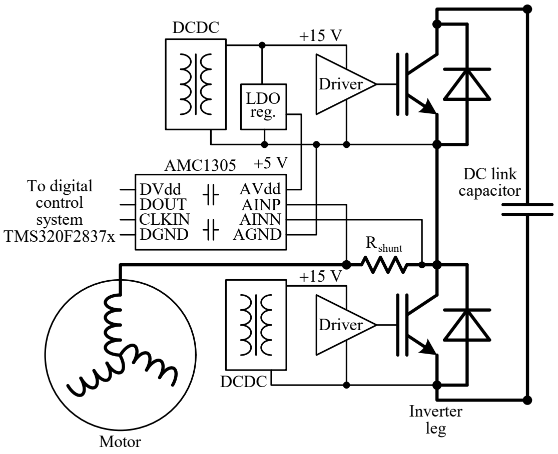
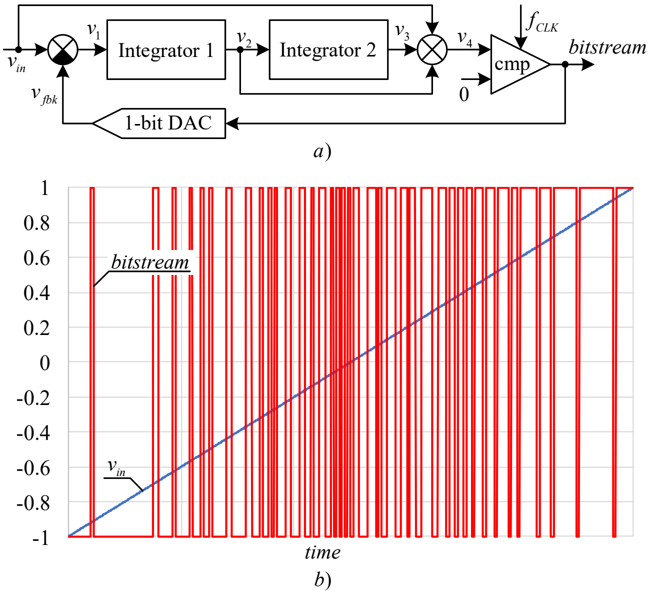


Fig. 1. Basic shunt current sensing topology for electric drives.



a)

b)

Fig. 2. Second-order delta-sigma modulator structure (a) and its operation (b).

III. SYSTEMS UNDER INVESTIGATION

The investigation of the shunt current sensing is split into two parts corresponding to the open-loop system and the closed-loop system. It is performed using a model of the induction motor drive fed from the 2-level inverter. Shunt current sensor has the full range of ±100 A peak current. The accuracy of the current measurement will be investigated under the open-loop control. Further, the sustainability of the closed-loop control will be checked using various tunings of the digital filter. The oversampling ratio (OSR) varies between 8, 16, and 32 bits and the digital filter used is Sinc3 (filter order; $F_{order} = 3$). This gives the duration of the current measurement according to (3) 1.2, 2.4, and 4.8 µs respectively. PWM frequency is set to 2000 Hz in order to obtain visible current deviation.

A. Open-loop v/f control

The first experiment was performed under v/f control and rated load. The block diagram for the drive structure is represented by Fig. 3a. It implemented rotating the voltage vector of the rated magnitude and frequency.

B. Closed-loop control: step response

The investigation of the closed-loop control began with the step response tests of the current loops when the motor is stopped. The current controllers were executed at the beginning and in the middle of each PWM cycle, and hence, the references of the PWM were updated twice during a single PWM cycle. It was assumed that the control is implemented using FPGA without a delay between the execution and application of the references. The controllers were tuned in order to achieve maximum performance of the current loop and to attain the steady state value in a single PWM cycle. The corresponding block diagram is presented in Fig. 3b.

C. Closed-loop control: rated speed under rated load

The last simulation was performed under field-oriented control with the motor running at the rated speed and torque. This test enabled investigating the stability of the current loop at various tunings of the digital filter and torque pulsations, which occur due to errors in the current feedback and PWM. The block diagram of the drive structure for this test is shown in Fig. 3c.

IV. SIMULATION RESULTS

For the first test, the loci of the continuous currents, instant values of the current in the sampling points, and measured currents in the stationary quadrature α,β axes were obtained (see Fig. 4). The digital filter was set to the OSR of 8 and 16. The measurement of the current with the OSR equal to 8 was the most rapid, but the error was visible, and some points lay further away from the actual values. The OSR equal to 16 leads to more precise results.

The second test with the step response showed that depending on the oversampling ratio used, the accuracy of the measurement changed as well as the deviation of the current was affected by the feedback noise (see Fig. 5). For OSR equal to 8, visible errors in measurement and current deviations were presented in the transient. The acceptable quality of the transient was achieved for OSR equal to 16. The best results were obtained for the largest OSR, when the sampling time equaled 4.8 μs. The system remained stable, but the increase of the delay in feedback potentially could render it unstable for the same tuning of the current controller. For this particular case, the ratio between PWM cycle duration and the current measurement was more than 1000; but for higher PWM frequency, the current measurement delay could become significant and hence, should be considered.

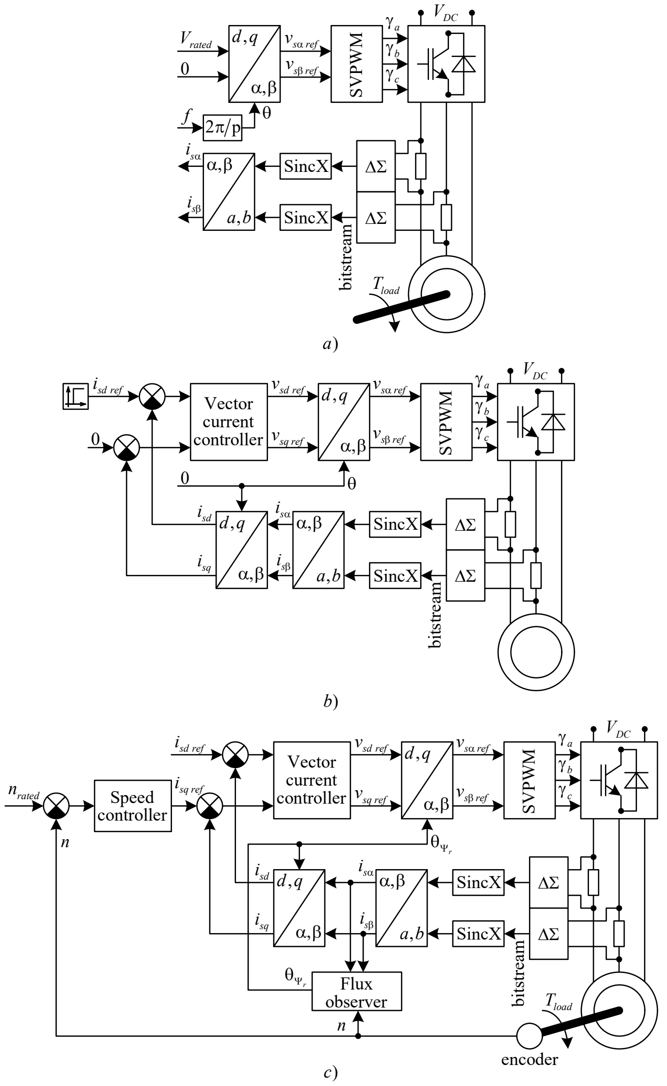


Fig. 3. Block diagrams for various configurations of the drive control: a) open-loop control of the induction motor drive; b) step response test; c) field-oriented control under rated conditions.

For the last test, the field-oriented control was run under the rated load. Its operation point was the same as for the experiment with the open-loop control, but current controllers were regulating the motor currents and affected by the current measurement errors. These errors resulted in errors in the flux estimation and higher current ripple, which consequently resulted in torque pulsations. Oscillograms with the currents of the phases a and b and torque are presented in Fig. 6. Smaller oversampling ratios lead to disturbance in the torque control, where deviations of the torque were considerable. By increasing the OSR to 16 and finally to 32, the error of the current measurement was reduced. This affected not only the shape of the phase current but also the torque pulsation. Now, the torque ripple was caused mostly by the PWM component in the q-axis current.

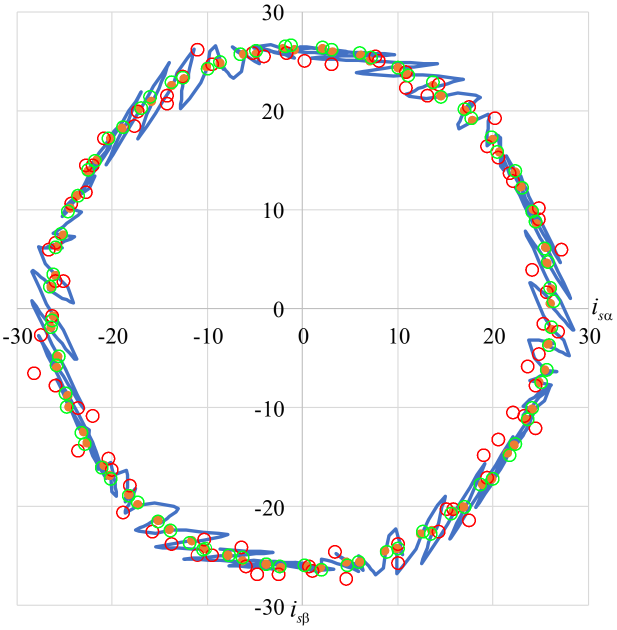


Fig. 4. Loci of the current in open-loop control system (blue—continuous current; orange—current at the sampling points in the middle and the beginning of the PWM cycle; lime—measured current with OSR = 16; red—measured current with OSR = 8).

V. CONCLUSIONS

The shunt current sensing with delta-sigma modulation is a low-cost solution for closed-loop control in modern electric drives and power converters. The accuracy of the current measurement can be adjusted by changing the oversampling ratio (OSR). Although increasing the accuracy increased the sampling time as well, this is a tradeoff between obtaining small errors and fast responses.

The conducted research showed that OSRs of 8 and smaller lead to large errors in current measurement, which resulted in oscillations in the current loop and torque ripple on the shaft. The acceptable OSR value is 16, which allows achieving performance comparable to the conventional closed-loop Hall-effect sensor and 12-bit ADC. Higher OSRs significantly increased the accuracy along with the growth of the measurement delay.

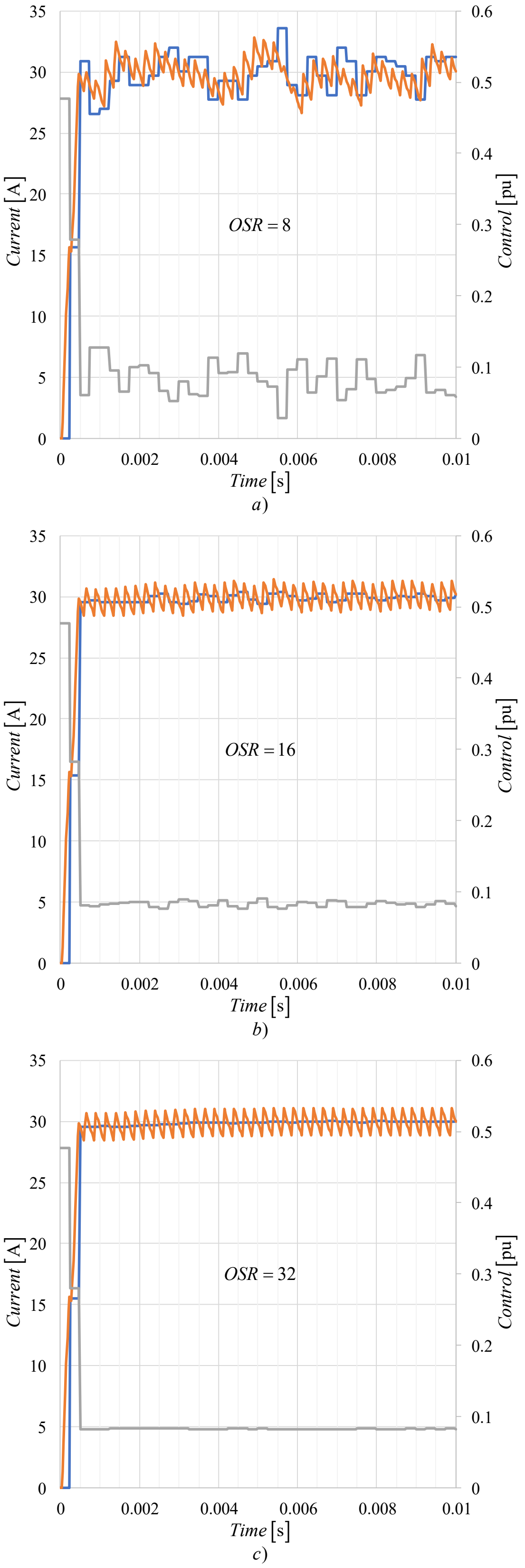
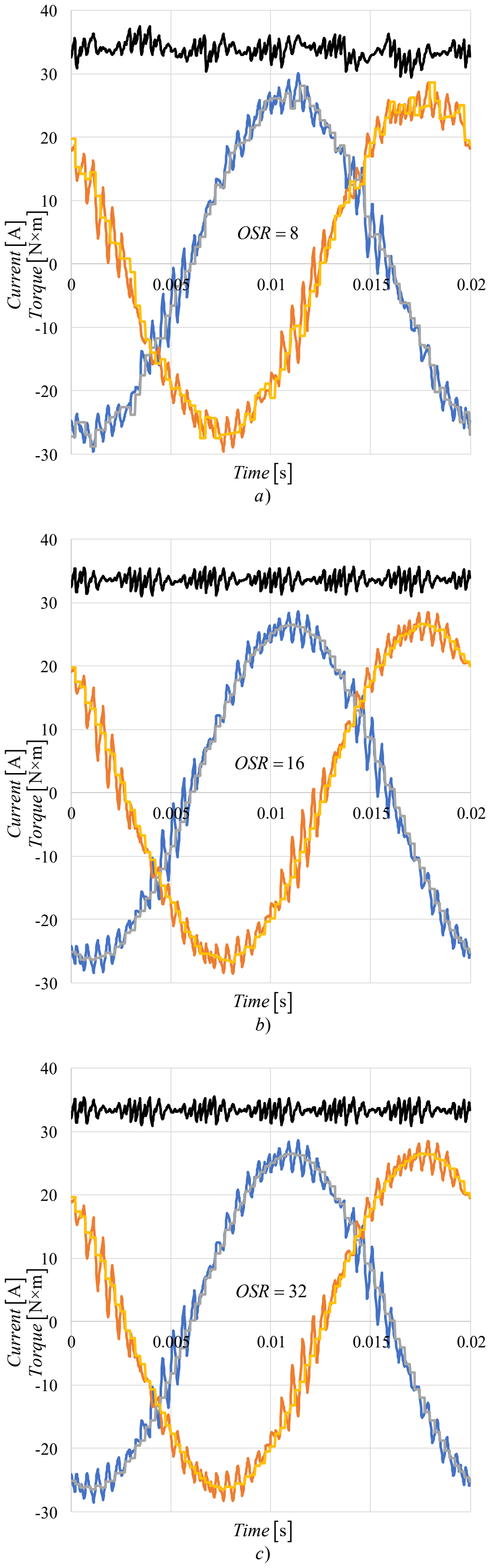


Fig. 5. Step response with 30 A current reference in the closed-loop control system at zero speed: orange—continuous current of axis d, blue—measured current, gray—control of the axis d.



a)

b)

c)

Fig. 6. Operation under field-oriented control and rated conditions: black—torque, orange—phase *a* current, yellow—measured current of phase *a*, blue—phase *b* current, gray—measured current of phase *b*.

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