Accuracy Analysis of Shunt Current Sensing by Means of Delta-Sigma Modulation in Electric Drives

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***Abstract*—This paper considers the accuracy of the shunt current measurement by means of delta-sigma modulation in electric drives. The shunt current sensing becomes more popular with the appearance of the galvanically isolated delta-sigma modulator ICs and microcontrollers with embedded demodulators. That solution is much cheaper than closed-loop Hall-effect sensor, and it is already implemented in some commercial electric drives. In this paper the accuracy of delta-sigma bitstream demodulation is considered. The dependences between oversampling ratio, digital filter type, input signal value and the maximum error were obtained from the model.**

Keywords—Current measurement, shunt sensor, delta-sigma modulation, accuracy, response time, electric drives.

I. INTRODUCTION

For many years close-loop Hall effect sensor has been the dominating method of current sensing in high-performance power electronic converters. Its benefits are well-known [1]:

- galvanic isolation between primary and secondary circuits;
- high linearity and bandwidth, small gain error and offset;
- precise and fast measurement using embedded analog-to-digital converters of modern microcontrollers.

The main drawback is high price of the sensor; and this forces researchers and designers to look for other possible solutions for current measurement. They are:

- open-loop Hall-effect current sensors;
- shunt current sensors.

The open-loop current sensors suffer from the outer magnetic fields, like the one produced by the current of other phase of the same power converter. This effect can be taken into account by precise calibration of the measurement algorithm, considering other currents flowing in the system.

Shunt current sensors are popular in low-power applications, but for industrial power converters and electric drives with more than 50 A of output current they were not usual due to absence of the convenient solution for galvanic isolation. That solution can be serial ADCs, which suffer from delay while transferring data via opto-coupling device. Existing voltage-to-frequency converter ICs [2] have poor resolution at high frequencies and unacceptable delay in measurement at low frequency modulation signals.

The next step happened when special ICs implementing delta-sigma modulation appeared together with a support of special peripheral device with demodulator and digital filters embedded into modern microcontrollers. That ICs like AMC1305 from Texas Instruments measure the voltage drop in a shunt resistor and produce delta-sigma modulated data stream. Data stream of 10 or 20 MHz has a clock and data signal and needs only two digital isolation devices; and only one if Manchester coded bitstream is used.

The manufactures, like Semikron, started to produce power modules with integrated shunt current sensors in the output circuits [3]. Texas Instruments provides a series of delta-sigma modulators [4] and microcontrollers with embedded demodulator [5]. All these components together can replace close-loop Hall effect sensor saving approximately 30 USD for each sensor (for rated sensor current of 200 A).

While researches started development of their systems using delta-sigma current measurement [6], [7], and examining accuracy of the current shunts of the modules [8], there is no clear understanding about the accuracy of the data that can be achieved by extraction from the modulated bitstream. The only documents that give some dependences between oversampling ratio, filter type and resolution are provided by manufactures and contain wrong expectations regarding efficient number of bits [9]. Also, resolution and accuracy are often confused.

The goal of this paper is to investigate the accuracy and the maximum error of shunt current measurement using an ideal delta-sigma modulator. This should be done with respect to the oversampling rate (OSR) and type of the filter used. The results are to be compared to conventional 12-bit ADC, which is commonly used in the modern power converters and electric drives. The comparison is to be done in terms of accuracy and sampling rate, which is necessary for high-performance control system with rapid current response [10].

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II. PRINCIPLES OF SHUNT CURRENT MEASUREMENT

A. Shunt

The shunt is placed in series to the circuit with flowing current (see Fig. 1). There are two options that are commonly used: 50 mV and 250 mV shunts. These voltage drops are given for the maximum current that can flow through the shunt, and usually they are twice higher than the rated value. The higher voltage drop leads to higher losses in the system. For the rated current of 400 A the dissipated power in the shunt of a single phase is 10 W and 25 W for 50 mV and 250 mV shunts respectively. That has some impact to a thermal mode of the sensing circuit, though the mitigation of overall efficiency is neglectable in any case.

B. Delta-sigma Modulator IC

The delta-sigma modulator is connected directly to the current shunt. It needs to separate supply sources — from the primary side and from the secondary side. The secondary side supply can be used from microcontroller supply circuit, while the primary side potential is floating during commutation of the power switches of the power module. This supply can be galvanically connected to the driver supply of the top-side switch.

The ICs, like AMC1303, contain second-order, switched-capacitor, feed-forward ΔΣ modulator, which produce a bitstream with information about the flowing current. The structures of the modulators presented in datasheets are usually inaccurate [4], because they lack the amplification coefficients for integrator blocks, making the structure unworkable. The structure for that research was taken from [11] and displayed in Fig. 2. The implementation of both integrators in a discrete form makes this structure time invariant regardless of the modulation frequency.

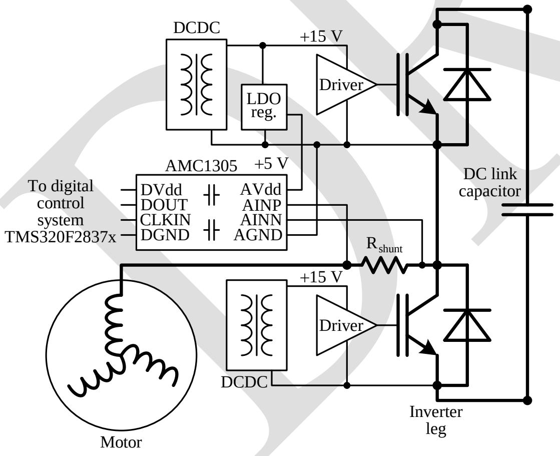


Fig. 1. Basic shunt current sensing topology for electric drives.

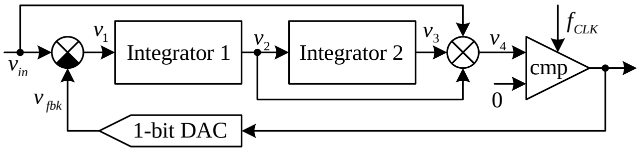


Fig. 2. Second-order delta-sigma modulator structure.

C. Demodulation of the Bitstream

The demodulation of the bitstream can be performed by means of a special peripheral device of modern microcontroller or using an FPGA. The bitstream should be filtered with low-pass filter and the usual option is Sinc filters [12] of different orders. Generally speaking, the Sinc filter of the first order is the filter of moving average; and it can be represented by IIR [9] 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 time shift operator, N represents the oversampling ratio (OSR) or the number of bitstream bit, that are used in the filter. The absolute error of the signal restored by such filter is an inverse value of number of bits processed:

$$\delta=\frac{1}{N}\cdot 100\%. \tag{3}$$

The information about the signal value represented not only by the mean value of the bits in the produced bitstream. The bit switching rate adds extra information, that can be extracted applying high-order filter. The easiest way of second- or third-order filter implementation is the series connection of three first-order filters. The simultaneous operation of Sinc, Sinc2 and Sinc3 filters with oversampling ratio of 8 bits is represented in Fig. 3. Initially the input signal is set to 60% of the entire range and in the middle of the experiment the input signal is changed to 90% of the range.

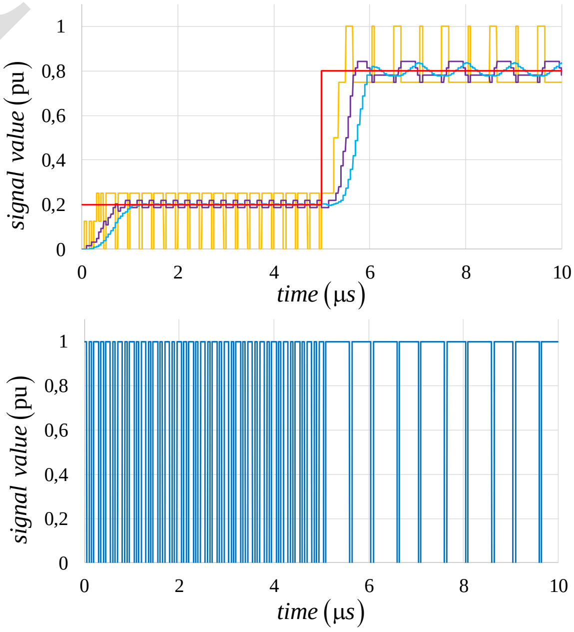


Fig. 3. Operation of Sinc, Sinc2, and Sinc3 filters for OSR equal to 8 (upper graph: red — input signal, yellow — Sinc filter output, purple — Sinc2 filter output, blue — Sinc3 filter output; lower graph: bitstream).

D. Accuracy of the Measurement

Analysis of the transient shows that the implementation of high-order filters increases the resolution of the output signal, while the accuracy is improved too. But it can be seen, that the accuracy of the output signal depends on the frequency of the bitstream. That frequency, in its turn, depends on the input signal level with respect to its maximum and minimal values.

To increase accuracy of the current measurement, the higher oversampling ratio should be used. The increase of the oversampling ratio together with digital filtering results in growth of the measurement time. Longer measurement duration is undesirable for control system due to increase of delay in the current feedback. Therefore, the balance between accuracy and current measurement duration is needed to achieve maximum performance of the current control loop.

In [9] the accuracy is represented with efficient number of bits (ENOB) for each configuration of the OSR and filter type. The parameters for Sinc3 filter is displayed in Table I. The duration of current measurement or filter response time is given for 20 MHz clock. According to Table I, the acceptable OSR value lies between 16 and 32. Usually, 12-bit ADC has from 10 to 11 ENOB; therefore, there is no reason to increase OSR for the same accuracy of the current loop. But these data differ from given in [4].

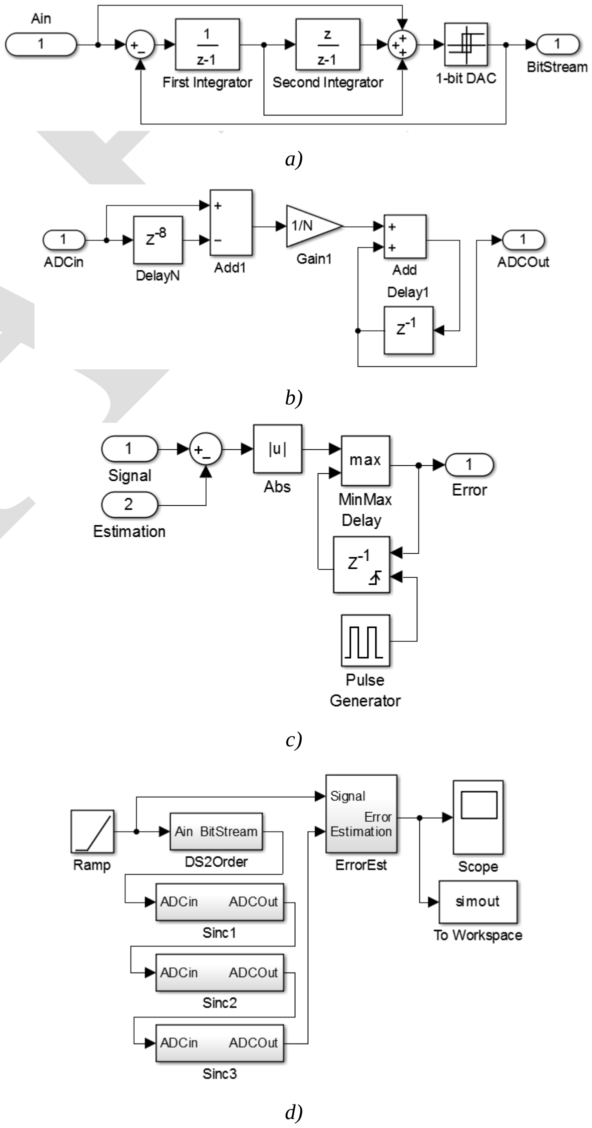
As it is difficult to evaluate the efficient number of bits due to the fact that it not only depends on number of bits but also on switching rate of the bits in the bitstream, the check of the data from Table I can be performed using some extreme case. Consider the situation when Sinc3 filter with OSR equal to 16 is in operation; and the input signal is 1/49 of the total range that corresponds to a single bit of ENOB. This means that the modulated signal has 1 positive pulse and 48 negative pulses. There may be two possible situations during current measurement. First is when one positive bit occurs together with 47 negative bits, and the measured value is not equal to zero. But the second option is that 48 negative pulses occur during measurement, and the measured signal is zero. In this case the maximum error is 1/49 of the whole range or 2%, while from ENOB it should be 0.4% according to [4] and 0.2% according to [9]. This discrepancy should be investigated by means of a model of the delta-sigma modulation and demodulation process.

TABLE I. SINC3 FILTER CHARACTERISTICS

OSR (bits)	Third-order Sinc Filter Characteristics		
	Signal to Noise Ratio (dB)	***ENOB (bits)***	***Filter response (μs)***
4	25	3.9 [9] 3 [4]	0.6
8	40	6.4 [9] 5 [4]	1.2
16	55	8.9 [9] 8 [4]	2.4
32	70	11.4 [9] 10.5 [4]	4.8
64	85	13.9 [9] 12.5 [4]	9.6

III. MODEL FOR ACCURACY EVALUATION

The model consists of input signal source, second-order delta-sigma modulator (see Fig. 4a), and serial connected Sinc filters. As the result from the first Sinc filter is a simple moving average, it does not utilize extra information from switching rate of the bitstream. Therefore, the output of first-order Sinc filter shouldn't be considered. The comparison is to be done between Sinc2 and Sinc3 outputs for the same measurement time. The filter output is to be compared with the input signal, that helps to evaluate an error as a function of input signal. The input signal varies from middle to maximum value. It is not necessary to test it in the entire range, because the operation is symmetrical. The model was implemented in Simulink MATLAB; its structure is shown in Fig. 4d. Sinc filter was implemented according to (1), and its model is represented in Fig. 4b. The error peak detector (see Fig. 4c) collects maximum error during 100 measurements.



a)

b)

c)

d)

Fig. 4. Model of the experimental setup (a — second-order delta-sigma modulator subsystem (DS2Order); b — Sinc filter subsystem (Sinc1, Sinc2, Sinc3); c — error peak detector subsystem (ErrorEst); d — model of the experimental setup).

IV. MODELLING RESULTS

The first experiment was performed with OSR equal to 8 and Sinc3 filter (see Fig. 5a) and OSR equal to 12 and Sinc2 filter (see Fig. 5b). In both cases 8*3 and 12*2 bits of the bitstream were processed. The results display that in both cases the maximum error reaches the highest values when the input signal is approaching to its maximum. Sinc2 characteristic is more flat in a region from 0 to 75%, while Sinc3 starts to grow after 50% magnitude of the signal.

For longer measurement the accuracy increases. The maximum error for Sinc3 method (see Fig. 6a) is now lower than for Sinc2 (see Fig. 6b) and has 0.25% at zero input signal and increasing to 0.5% for 75% of the maximum value. Both measurements correspond to approximately 8 efficient bits, while the accuracy of the measurement with Sinc2 filter is lower in average.

By increasing the oversampling ratio to 32 in case of Sinc3 filter, the maximum error of 0.05% for the range from 0 to 50% of the input signal was obtained (see Fig. 7a). That corresponds to 11 efficient bits. Results for Sinc2 filter and the same duration of the measurement are poorer (see Fig. 7b).

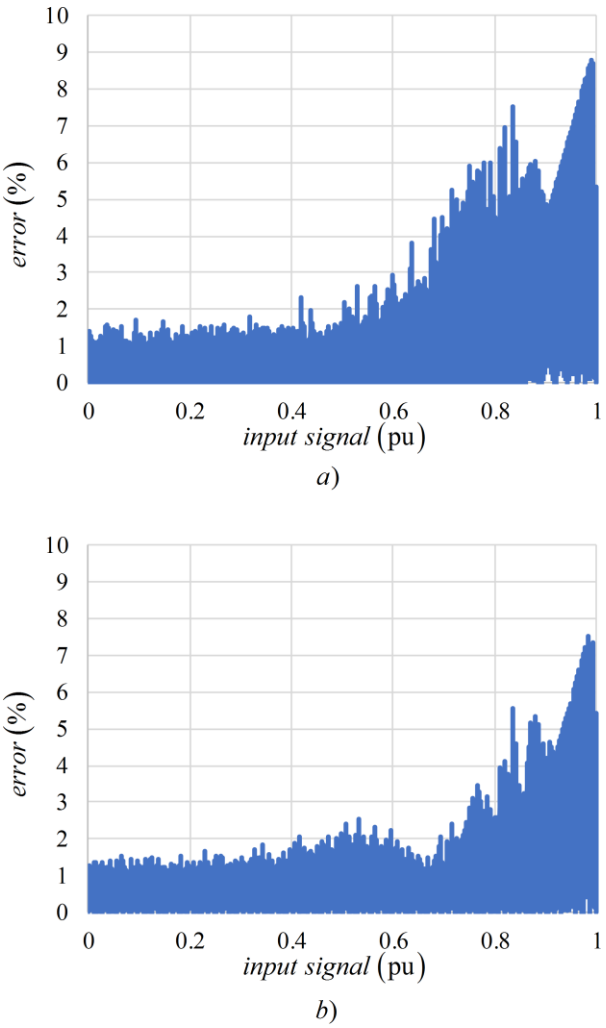


Fig. 5. Errors for a) OSR = 8 and Sinc3 filter, b) OSR = 12 and Sinc2 filter.

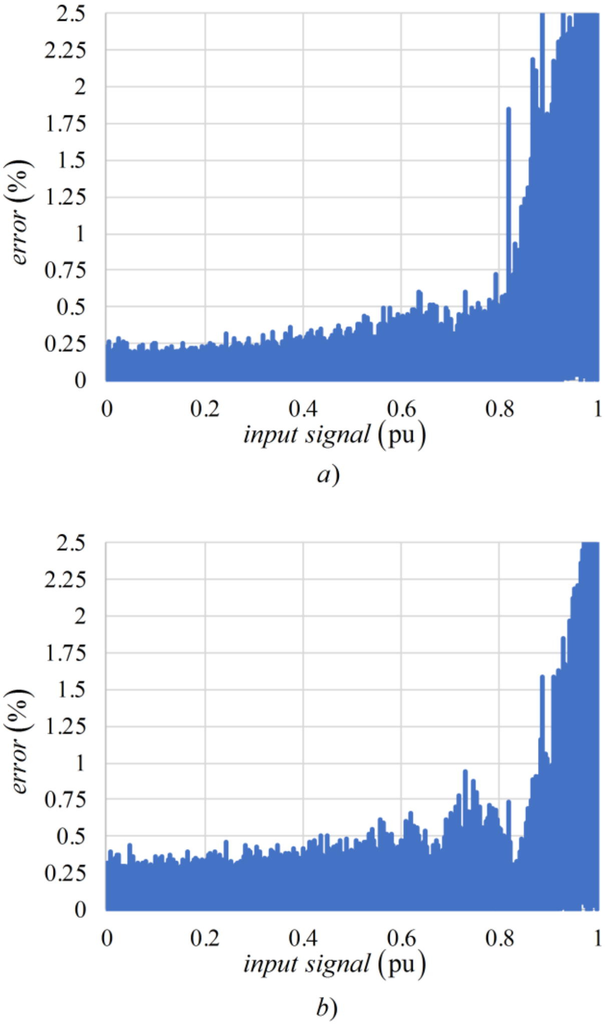
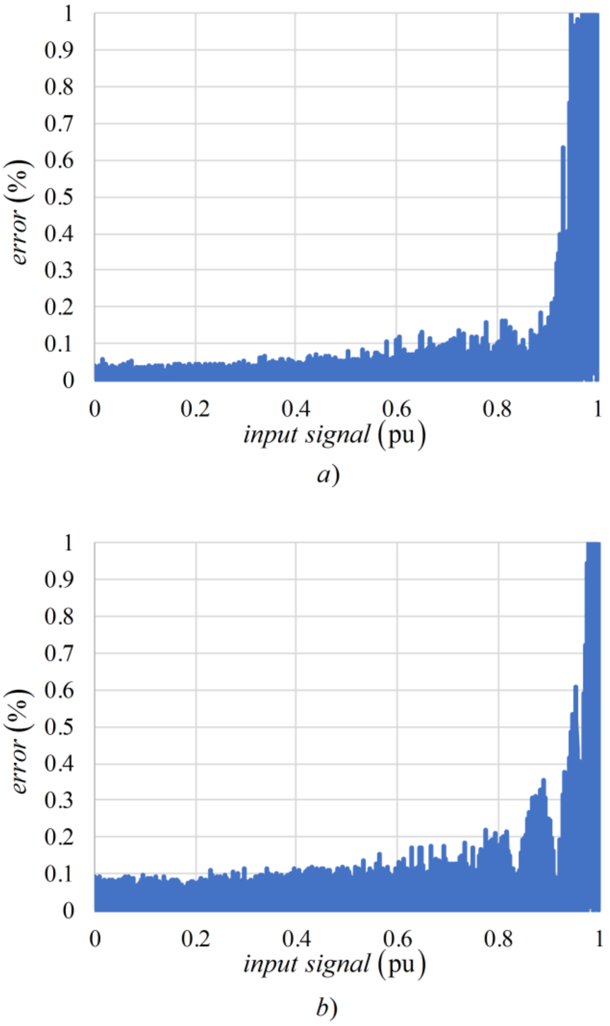


Fig. 6. Errors for a) OSR = 16 and Sinc3 filter, b) OSR = 24 and Sin2 filter.

The increase of the error in the area of high input signals has no actual impact on the performance of the close-loop control. That values are only reachable under overload conditions when the demands to the quality of the current regulation are not applicable.

V. CONCLUSIONS

In this paper the question of accuracy for the shunt current sensing by means of delta-sigma modulation and digital filtering was considered. Shunt current sensing using delta-sigma modulation is a cheap and accurate method of current measurement in the control systems. It provides higher accuracy at the small input signals, while under overload conditions accuracy is reduced. Another advantage of this method is its immunity to commutation noises in the power converter. The measurement time is comparable with conventional ADCs and lies in the range between 2.4 and 4.8 µs for the same resolution.



a)

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Fig. 7. Errors for a) OSR = 32 and Sinc3 filter, b) OSR = 48 and Sinc2 filter.

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