IGBT Module with integrated Current Measurement Unit using Sigma-Delta Conversion for direct Digital Motor Control

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Abstract

System integration is one of the market driving issues in power electronics. In this paper the integration of precise shunts and complete A/D-conversion units with isolating interface into IGBT modules is demonstrated. It also provides a comparison to the often used solutions based on Hall effect sensors and additional A/D-converter chip sets. Both systems are compared based on inverter output current measurement.

1. Introduction

For speed and torque control in electrical drive systems the converter output current has to be captured for online-calculation of the PWM pattern. There are several ways to measure and digitalize the motor current. In this paper, the conventional Hall sensor current measurement and the alternative sigma-delta based current measurement are presented and compared.

1.1. Conventional Hall Sensor Current Measurement

In recent general purpose (GPD) and servo drive systems, Hall Effect sensors are often used for current measurement. Two types of single-phase Hall Effect sensors are offered on the market: The more expensive but faster closed-loop sensors and for low-cost solutions the slower open-loop types. Both types of sensors convert the magnetic flux caused by the current to be measured into an electrical, usually analogue signal that has to be internally amplified for further processing. For fast and precise operation, modern converter systems are controlled by microcontrollers or digital signal processors (DSP) in combination with powerful logic devices e.g. FPGA. However, additional and expensive analog-to-digital converter sets have to be inserted between sensor and controller unit for digitizing the current sense signal, shown in Fig. 1a).
Because of the relatively large magnetic core sensors and the position of the mass center of gravity the application of such sensors in applications suffering from vibration or high levels of acceleration becomes difficult. Recent and future trends are showing a demand towards increasing the converter's power density and beating down the costs. Latest IGBT developments allow for junction temperatures of up to T_{jopmax} = 150°C. This leads to more demanding operation conditions like higher ambient temperatures and reduced size of high power devices as well as peripheral components. Bulky, heavy, discrete Hall effects sensors with ambient temperatures limited up to 85°C don't easily allow a future-trended compact design of converter systems.

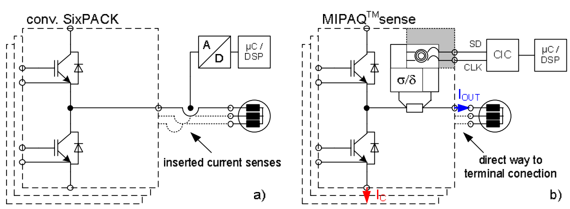

Fig. 1. Block diagrams of a) conventional Hall sensor and b) sigma-delta based current measurement

1.2. Sigma-Delta Based Current Measurement

To fulfill the above mentioned compact converter design challenges and requirements, another current measurement principle, shunt resistor combined with isolated small signal sigma-delta modulator is proposed in the present paper. Here, shunts and sigma-delta ADCs with internal isolation via CoreLess Transformer (CLT) technology are used [7], [8].

They are compact and can be operated at high ambient temperatures up to T_a = 125°C, so that they can be integrated into IGBT modules. These modules are introduced from INFINEON as 1200 V / 75 A or 100 A sixpacks and belong to the MIPAQ™ family. In Fig. 1 the block diagram of a conventional sixpack connected to an analog-digital converter including microcontroller is shown in a), an IGBT module with integrated shunts and isolated sigma-delta units is shown in Fig. 1b).

1.3. Target Application

Current measurement is an inherent part of any inverter-driven application and the sensor in use should not limit its application. From a more global point of view the precision and the bandwidth of the measurement divide applications in those with and without feedback loop. A separation can be done into open and closed loop measurements. The shunt-based Σ/Δ-measurement discussed can easily be applied as an alternative for open loop systems.

2. Comparison of the two Measurement Principles

Though the two principles coexist in the literature, the sigma-delta method has not yet widely spread in power electronic design. The following section provides a deeper insight into the details differentiating the two systems.

2.1. Investigation on the Measurement's Error Propagation

To properly control the application, its current needs to be measured

- within a proper time,
- highly precise synchronization and
- with a sufficient accuracy

The time necessary to complete the measurement mostly depends on the A/D-conversion and data transmission. Accuracy of the measurement on the other hand depends on several parameters. Investigating the error propagation is necessary to determine the final accuracy of the measurement in use.

Hall Sensor Measurement

Sensors based on Hall Effect suffer from several influences. Besides linearity of the sensor, temperature stability, offset and hysteresis have to be considered.

Based on the information given in the datasheets describing state-of-the-art current transducers the error propagation can be estimated. For a specific 100A open loop Hall sensor the deviations are:

- Accuracy: ±1% of I_N@25°C =±1A
- Linearity: ±0.5% of I_N
- Thermal Drift: ±0.05%/K

With an allowed operating temperature of up to 85°C the temperature swing can be 60K leading to a possible thermal drift of 3%. The sum of errors for the complete range regarding the application can add up to exceed 5% at rated current. If however smaller currents are measured, the relative error increases as shown in Fig. 2:

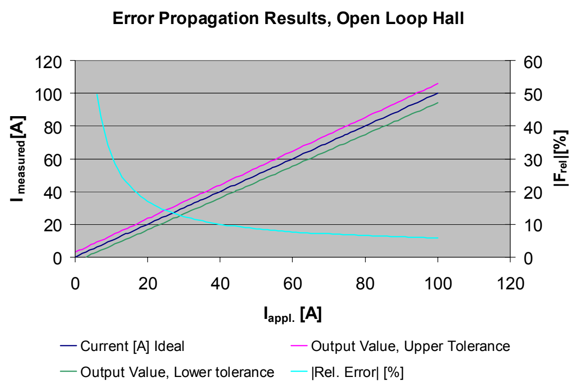

Fig. 2. Open Loop Hall, Error Propagation

Magnetic offset as a further aspect is not considered in this results. However, it has to be considered that compensating a magnetic offset turns out to be difficult.

Sigma-Delta Measurement

The typical sigma delta converter has an overall accuracy of a few percent. There are a number of error terms that combine to create this error in the temperature range from -40°C to 125°C.

The deviation caused by the shunt's temperature drift is less than ±0.3%. The measurement presented in Fig. 3 displays the outstanding temperature stability of the shunt in use:

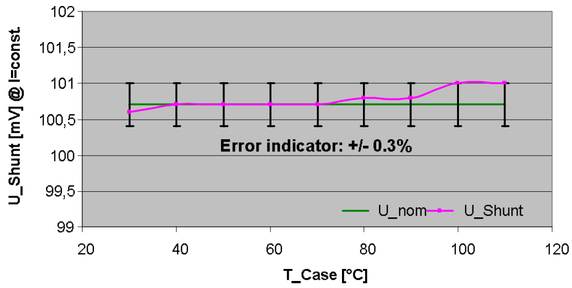

Fig. 3. 1mΩ Shunt @ I=100A, changing with T_{case}; 120°C < T_{Shunt} < 200°C

The sigma delta converter unit also contributes to the deviation:

• offset error 1mV,

• gain error 1,55% ,

• THD- ,INL-, linearization error 0,1%

(THD = total harmonic distortion, INL = integral nonlinearity)

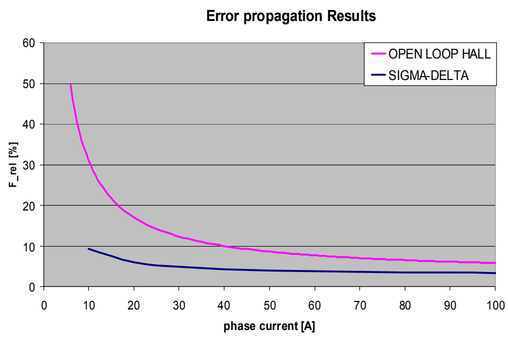

Fig. 4. Sigma Delta Method, Error Propagation

This result in Fig. 4 shows an improved behavior compared to the open loop Hall sensor.

2.2. Pros & Cons

The most beneficial aspect of the Hall sensor is the inherent isolation quality. If sample & hold A/D conversion is utilized, excellent synchronization to the PWM pattern can easily be achieved.

Size, weight, layout effort and thermal dependency are drawbacks of the Hall sensors. Additionally an adaption to different current ratings requires different sensors in varying dimensions and costs.

Getting familiar with digital hardware or software filters and the integrating measurement method is a necessary effort in working with sigma-delta converters.

Temperature stability of the shunt along with scalability of the measurement setup and simple layout routing are the noteworthy benefits of this highly-integrated, EMI insensitive setup.

2.3. Measurement Interface and Hardware environment

Within the MIPAQ™ sense Infineon included shunts and sigma-delta converter units. The module provides galvanically isolated, digital information about the application currents.

In order to transform the single-bit Σ/Δ data stream into a multibit signal a digital filter is necessary. The filter extracts the instantaneous current value from the sigma-delta data stream. The value is transferred to the microcontroller using a standardized protocol like SPI or parallel bus. The filter's parameter can be chosen and adapted by the user. This allows to fine tune the conversion time to the application's demand.

Typical filters IC contain more than 3 independent SINC filter units. These filters can be triggered externally and are then read out serially.

Fig. 5 a typical block diagram showing the interconnections between power module, digital filter unit and microcontroller is depicted.

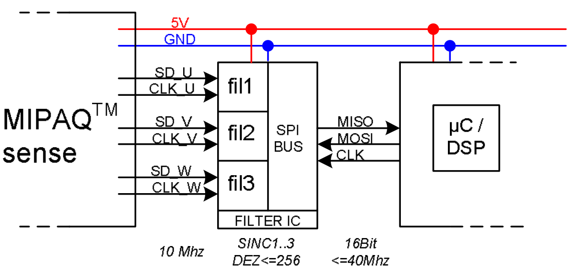

Fig. 5. Connecting a MIPAQ™ sense to µC/DSP by using a digital filter IC

The resolution and sampling time can be adjusted individually for each sigma-delta bit stream by adjusting the kind of filter and the factor of decimation. It is possible to measure the phase currents with an accuracy exceeding 12 bit at a sample frequency equal to the IGBT switching frequency.

3. Measured Results

To compare the different current measuring methods, a frequency converter with a 75A MI-PAQ™ sense IGBT modul was connected to a three-phase inductive load as a laboratory setup.

3.1. Converter Output Current Measurement

The phase current was measured by a standard 100A closed loop Hall effect current transducer, a 60A, 20kHz oscilloscope AC/DC current probe and a digitally filtered Σ/Δ data stream that was converted into SPI-BUS signals.

To visualize the SPI data using an oscilloscope a SPI/A DAC was utilized as displayed in Fig. 6.

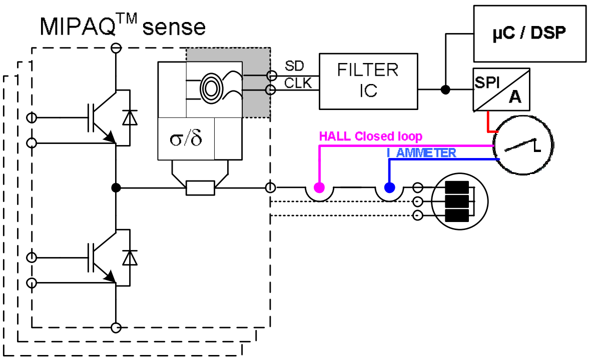

Fig. 6. Block diagram of current measurement setup

The digital filter was parameterized by the SPI-BUS of an Infineon 8-Bit microcontroller. The settings used were:

- Type of Filter: SINC3
- Decimation Ratio: DEZ128
- Current sample frequency: 13kHz
- Switching frequency: 16kHz
- Measured Phase Currents: $20A_{rms}$
- SPI Frequency: 13MHz

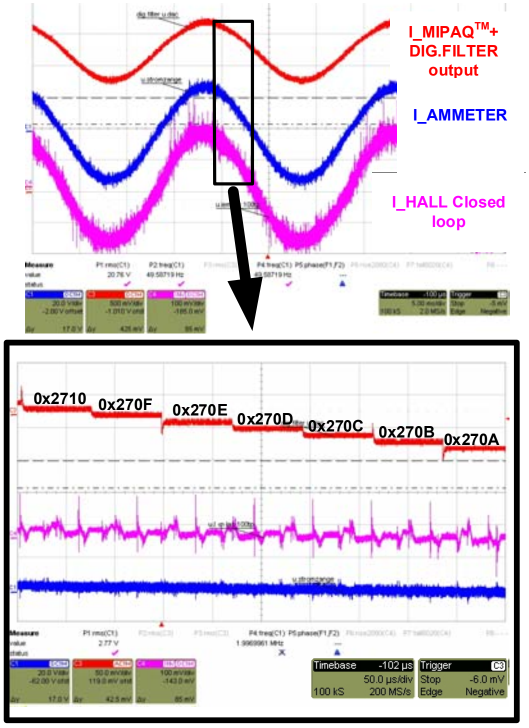

Fig. 7. Comparing results from MIPAQ™ , AM-METER and closed loop Hall

The measurement data coming from the digitally filtered sigma-delta data show lower levels of noise and eliminated spikes as can be seen in the detailed view in Fig. 7.

The reasons are the high oversampling frequency and the integrating nature of the sigma delta conversion method. At the chosen filter settings the input current is reconstructed from 200 single bit informations gathered in about 20µs.

High-frequency components e.g. caused by the IGBT switching procedure are removed by the filter's noise shaping function.

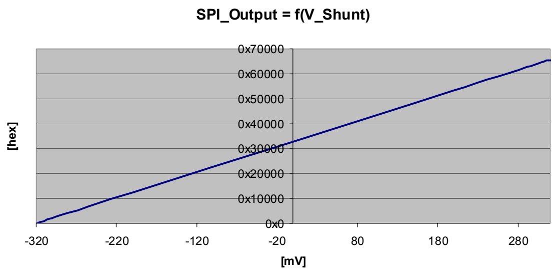

Fig. 8. SPI output=f(shunt voltage)

The relation between the voltage across the shunt and the numerical value coming from the SPI-bus is given in Fig. 8.

3.2. Short Circuit Detection

Protecting the sensitive semiconductors is one of the central tasks in any inverter and several techniques are known to achieve a proper turn-off time. For the actual IGBT4 the short circuit needs to be turned off in 10µs or less. In an analogue system as a Hall sensor, basic comparators can be used, generating a signal when a given threshold is exceeded. This however adds further hardware components to the design

In Σ/Δ-based measurements overcurrent detection can be achieved utilizing a simple counting procedure. Every "0" in the datastream denotes a current with a negative slope. Likewise a "1" represents a positively growing current. If the current constantly grows in one direction it has to exceed the limit sooner or later.

Counting CLK-pulses and restart the counter with every edge in the Σ/Δ-datastream is a common method to recognize that the limit is exceeded. If a string of data with a predetermined length exclusively containing either "1" or "0" is found, positive respectively negative overcurrent is detected. 25 pulses were chosen in a demonstrator and an overcurrent of three times the rated current was triggered.

Fig. 9 below depicts, that after 2.8µs a short circuit or overcurrent situation is recognized. The remaining 7µs are a comfortable time to turn off the semiconductor.

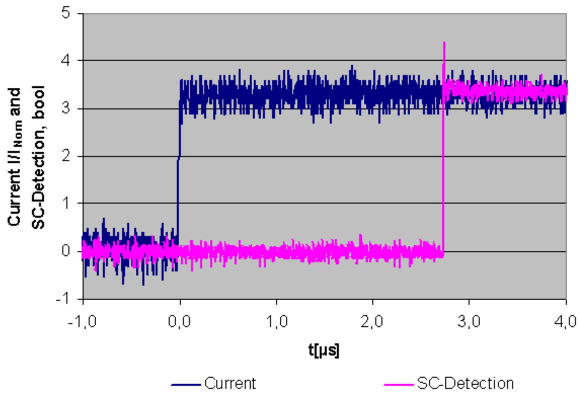

Fig. 9. Fast and accurate overcurrent detection using basic and reliable algorithms

A further method to detect an overcurrent can be implemented using the digital filter. For Example, the AMC1210 [6], a digital filter IC build by Texas Instruments, features additional filter units with programmable thresholds. These can be chosen independently by the user to trigger an overcurrent signal.

4. Conclusion

In this paper, an alternative current measurement system in addition to the conventional Hall sensor based systems was shown. Here, the essential measurement components like current probe / shunt, sigma-delta converter unit and also the electrical isolation unit are fully integrated into an IGBT sixpack module with standard size and terminals. Measurement results are showing that the integrated sigma-delta measurement unit fulfills the control demands of today's drive systems. The integration into high power semiconductor modules allows for a reduction of the number of external parts and therefore the required converter space. Along with reduced number of parts the design benefits from lower demand towards space and improved EMI immunity.

5. Literature

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