QUASI-DIGITAL CONSTANT DC CURRENT SENSOR

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Abstract

This article describes a solution of the constant DC current sensor with quasi-digital output and continuous auto-calibration measurement procedure. This solution is designed to be connected with a PC and it is based on the universal transducer interface UTI-03, resistive shunt and a general purpose 8-bit microcontroller. The results, obtained in the reference laboratory show a good agreement with the theoretical assumptions.

Keywords: quasi-digital, UTI-03, resistive shunt, calibration, microcontroller, LabView.

INTRODUCTION

Current measurement or current monitoring within electronic circuits is a frequent need in many types of applications. The measurement range, costs and performances, and the accuracy, are critical parameters during a current sensor choice [3, 4, 6]. The response time may also or may not be critical, depending on the application. Current measurements based on the resistive shunt are mainly the most accurate and fastest but for relative low current and with loss insertion [8]. Other current measurement techniques are based on the magnetic field measurement and on the current transformer.

Owing to the high resolution A/D converters, current sensors based on the resistive shunt can achieve high accuracy. However, such A/D converters are typically expensive and mainly slow [7].

This article represents a new approach of the designing current sensor with quasi-digital output signal, compatible with analog and digital domains. The high accuracy is achieved by applying the three signals technique which eliminates the first order errors such as offset error and gain error. For the realization of the current sensor is used universal transducer interface UTI-03, produced by the *Smartec* [1] and a general purpose 8-bit microcontroller.

UTI-03 INTERFACE

As has been said, the heart of the proposed current sensor represents selected universal transducer interface UTI-03 [1]. This dedicated integrated circuit is designed for connection with more types of sensors as capacitive and resistive sensors, resistive bridges, potentiometers and their combinations. The output of the UTI-03 is a period modulated signal consisting of three phases. Figure 1 shows the functional block diagram of the UTI-03 interface. Selection of any of the sixteen operating modes of the UTI-03 takes place by setting four mode-bits SL1 to SL4. The low-frequency interference is removed by an advanced chopping technique.

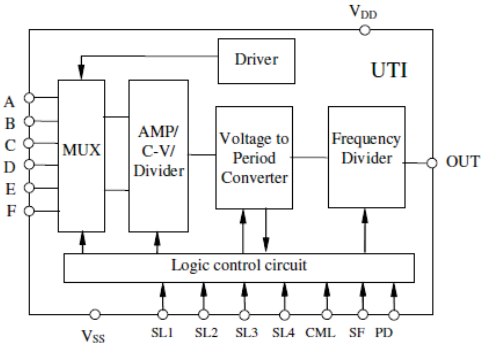

Fig. 1. *Functional block diagram of UTI-03 transducer interface.*

As can be seen in Fig. 1, main blocks of the interface are capacitance-to-voltage converter and voltage-to-period converter. Various analog sensing elements can be directly connected to the multiplexed nodes A to F, depending on selected operating mode. The UTI-03 outputs a microcontroller compatible period modulated signal and excitation signals to drive the sensing elements. The number of measurement phases in a complete output cycle depends on an operating mode of the UTI-03 and it varies between 3 and 5.

THREE-SIGNAL TECHNIQUE

This technique eliminates the unknown offset and the unknown gain of a linear system owing to the cognition of two reference signals. The UTI-03 interface outputs independent and consequent three up to five phases which make one measurement cycle [1], Figure 2,

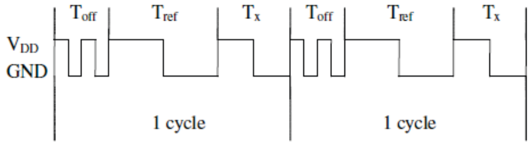

Fig. 2. *The output signal of the UTI-03 for a three-phase mode.*

where T_x is the period duration proportional to the unknown sensor parameter as resistivity for example, T_{ref} the period proportional to the known reference parameter and T_{off} double period proportional to the offset of the measurement system. The reference and unknown parameters should be the same nature, as for example voltage, capacitance, or resistivity.

If a system has linear transfer function in the form of:

$$M_i = kE_i + M_{off}$$

then for three different input values $E_1 = 0$, $E_2 = E_{ref}$ and $E_3 = E_x$

the three measured output values are

$$M_1 = M_{off}$$
$$M_2 = M_{ref} = kE_{ref} + M_{off}$$
$$M_3 = M_x = kE_x + M_{off}$$

The calculated ratio

$$M = \frac{M_3 - M_1}{M_2 - M_1} = \frac{M_x - M_{off}}{M_{ref} - M_{off}} = \frac{E_x}{E_{ref}}$$

eliminates the influence of unknown offset M_{off} and unknown gain k of the measurement system. In such a way the calculated value of M represents the ratio between the values of the unknown sensor element and the known reference element. The values of offset and gain can vary over the time but measuring system based on the UTI-03 is self calibrating. The duration of one complete cycle of the UTI-03 output signal is about 10 ms when the UTI-03 working in the fast mode and about 100 ms in the slow mode. The better resolution and linearity are achieved in the slow mode.

The implementation of the three-signal technique requires a microcontroller, which is used to digitize the period-modulated UTI-03 output signals and perform the data storage and calculations.

DC VOLTAGE MEASUREMENT WITH THE UTI-03 IN THE OPERATING MODE 11 (IB2)

Despite the fact that the interface is designed as a transducer, by selecting the appropriate operating mode the UTI-03 can be efficiently used for accurate measurements of low voltages such as a voltage drop on the resistive shunt [1].

The operating mode 11 (ib2) of the UTI-03 interface has the goal of the voltage signal measurement from resistive bridge or platinum resistor [1], but the same mode can be slightly modified for the DC voltage measurement. This mode is similar with mode 5 (Pt) of the UTI-03 but instead four only three phases have to be measured, as in Figure 2. Figure 3 shows the way of connection the UTI-03 interface with the reference and unknown DC generator.

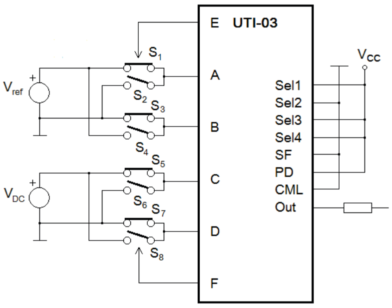

Fig. 3. *Simplified scheme of the UTI-03 interface in the mode 11 for DC voltage measurement.*

The switches S_1 to S_8 form a chopping for the measured voltage signals and they are controlled by the driving signals from pins *E* and *F*. The voltage V_{EF} is bipolar square wave with amplitude V_{DD} at ¼ of the internal oscillator frequency. In practice, only one signal from node E or F should be used. The resolution and accuracy for the voltage signal measurement could be 13 bits and 11 bits, respectively. The DC voltage signal is obtained from equation

$$V_{DC} = \frac{T_{CD} - T_{off}}{T_{AB} - T_{off}} V_{ref} = \frac{T_x - T_{off}}{T_{ref} - T_{off}} V_{ref} \tag{1}$$

In according with the producer specifications, the reference voltage should be up to 200 mV as well as the unknown DC voltage.

As shown in (1) V_{ref} must have a good long term stability due to the fact V_{DC} is given as a fraction of V_{ref}. This low V_{ref} can easely be made by a normal bandgap reference and a resistor divider.

CURRENT SENSOR ARCHITECTURE

The proposed current sensor is intended for the constant DC current measurement up to 100A. It consists of the three parts: DC resistive shunt of 1mΩ [2], measuring module and microcontroller. The task of the measuring module is the generation of the measuring phases using the UTI-03 interface and additional electronics to configure the interface in Ib2 mode (mode 11). A voltage drop on the resistive shunt, converted into the quasi-digital signal, is processed using the microcontroller and the result is delivered to the PC. The detailed scheme of the measuring module is shown in Figure 4.

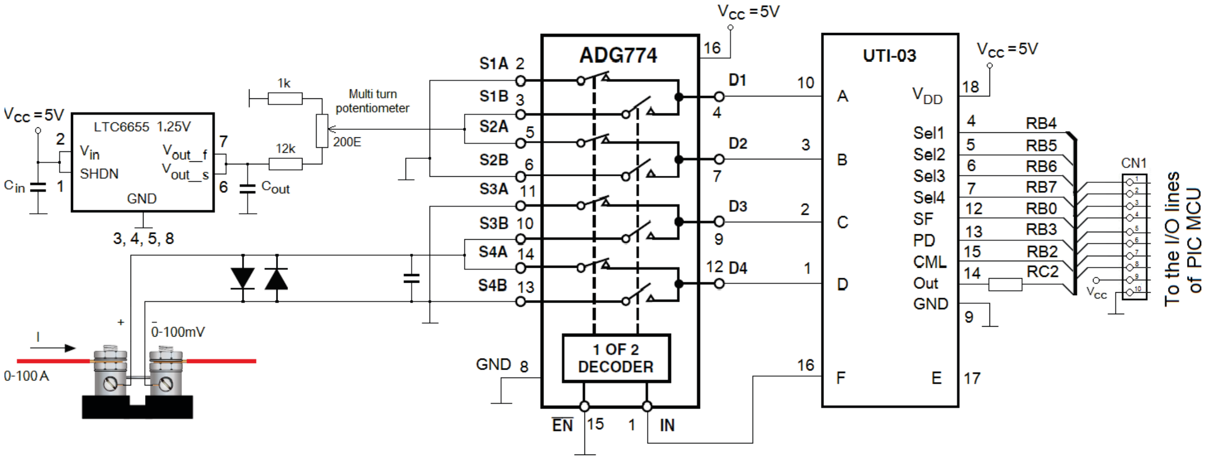

***Fig. 4**. Detailed scheme of the measuring module with the DC resistive shunt.*

As mentioned above, dominant influence on the accuracy and repeatability of the measurement has the accuracy and stability of the voltage reference, as can be seen from the expression of the relative measurement error of the DC voltage (2)

$$\frac{\partial V_{DC}}{V_{DC}} = \frac{\partial V_{ref}}{V_{ref}} + \frac{\partial\left(T_x - T_{off}\right)}{\left(T_x - T_{off}\right)} - \frac{\partial\left(T_{ref} - T_{off}\right)}{\left(T_{ref} - T_{off}\right)} \tag{2}$$

Because of that, the special care is dedicated to the proper selection of voltage reference.

As can be seen from Figure 4, the reference voltage is implemented by the careful selection of the low noise, low drift and precision bandgap voltage reference-LTC6655 and by the fine tuning voltage divider. This bandgap voltage reference has the temperature drift of the output voltage of 2 ppm/^{0}C or 2.5 µV/^{0}C, while the output voltage accuracy amounts ±0.025 % or ±312.5 µV. By the multi turn trimmer potentiometer, the voltage on its wiper is trimmed to 100.00 mV exactly.

In order to reduce the effect of the lead wire and the switch ON resistance, the analog switch with low leakage current should be used. The ADG774, comprising four 2/1 multiplexer/demultiplexers, with the very flat ON resistance profile over the full analog input range and with the bandwidth greater than 200MHz is selected in this solution. Such selection guarantees very fast chopping for the measured voltages using only one control signal from the node F of the UTI-03 as in the Figure 4. At the end, the heart of the measuring module - UTI-03 chip is used for the conversion of the small voltage drop on the resistive shunt into the quasi-digital, microcontroller compatible output signal. Moreover, the same chip together with microcontroller is used for the continuous auto-calibration of the measurement procedure.

The selected resistive shunt is a DC shunt with the nominal resistance of 1 mΩ at 25 ^{0}C and the tolerance of ±0.25 % or ±2.5 μΩ. A highly stable (±15ppm/^{0}C or ±15 nΩ/^{0}C) manganin sensing-element provides a wide – 40^{0}C to 60^{0}C operating temperature range [2, 8]. Because of their inherent added series inductance the frequency response of the device is limited. In order to provide protection of the device from high voltage transients, two opposite fast diodes are incorporated as in the Figure 4.

The main task of the microcontroller PIC18F2550 (Microchip) is the quantization of the measurement phases, i.e. digitizing the period-modulated UTI-03 output signals, the data storage and calculations. The ECCP module of the microcontroller in the capture mode is utilized for implementation of standard direct counting method of frequency-to-code conversion. The next task of the microcontroller is establishment of the serial communication with a IBM compatible PC. The integrated USB V2.0 periphery of the microcontroller using the appropriate driver is utilized for the conversion USB to UART. In that way the simple protocol is enabled between the current sensor and a PC. Figure 5 shows the microcontroller connected with the connectors CN1 and miniUSB. HSPLL quartz crystal oscillator with PLL enabled and with primary clock up to 48 MHz is selected.

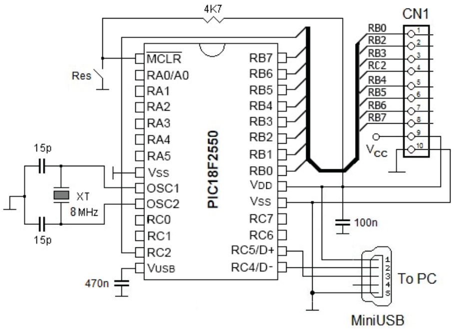

Fig. 5. The microcontroller PIC18F2550 as the part of the current sensor.

THE FIRMWARE AND PC APPLICATION

The firmware is written using the CCS (*Custom Computer Services*) C compiler IDE. The ECCP module of the microcontroller captures the 16-bit value of the timer 1 module every time when a rising edge occurs on the corresponding input of the ECCP module connected to the UTI-03 output. The timer 1 overflows are recorded as the content of the highest word of the 32-bit timer in the timer 1 interrupt routine. The second interrupt routine is the CCP1 routine which stores eight states of the 32-bit timer for eight rising edges of the input pulses. In that way, the seven periods measurements are made. Such approach guarantees the measurement of a full measurement cycle, consisting of three phases, regardless of the initial rising edge of the pulses which may be arbitrary.

The main function starts in the do-while loop when receives a character from the PC application. By enabling the interrupts, the counting of eight rising edges of the pulses begins. After calculation of the duration of seven periods, the identification of the starting period is performed. Then, by knowing the reference voltage and shunt resistance, the current intensity is calculated and sends to the PC application. After that, the main function disables the interrupts, restarts variables and returns on the top of the do-while loop where waits for a new character reception.

The PC application is implemented using the LabWindows CVI 9.0. It is the simple application for the current intensity presentment in the analog and digital form, as shown in Figure 6.

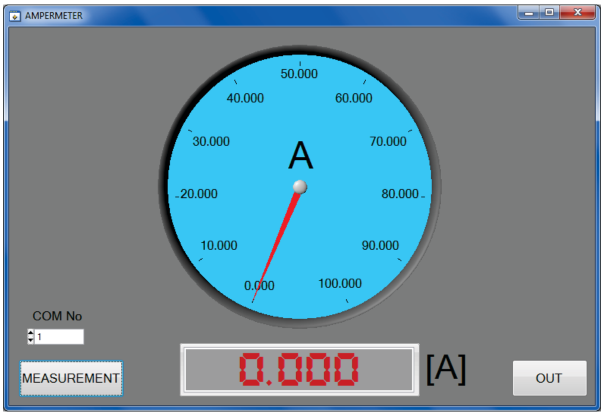

Fig. 6. The PC application.

After selection the serial port number, by pressing the button 'MEASUREMENT' the application sends a character to the current sensor and then gets the current intensity string which converts to the float number. Such number will be displayed to the analog and digital ampermeter. The application will be closed by pressing the button 'OUT'.

RESULTS

Checking the accuracy of the proposed current sensor is done in the reference laboratory of the Electrical Engineering Institute Nikola Tesla in Belgrade on two ways. A simple test procedure is based on the variable source of the DC voltage in the range from 0 mV to 100 mV which serves for emulation the voltage drop on the resistive shunt. The changes of this voltage are measured using precision digital voltmeter (4+4/5 digits) with resolutions of 1 μV in the range up to 50 mV and 10 μV in the range from 50 mV to 100 mV. By comparing the measured values with the readings from the PC application, the absolute and relative measurement error is obtained, Figure 7a and 7b.

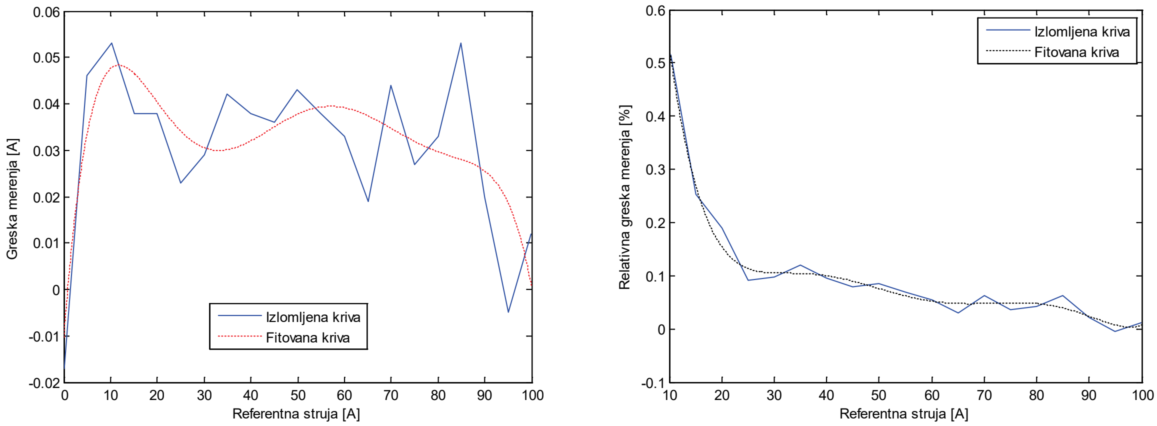

Fig. 7. *The experimental and fitted curves of the: a) absolute error b) relative error, obtained during simple test procedure.*

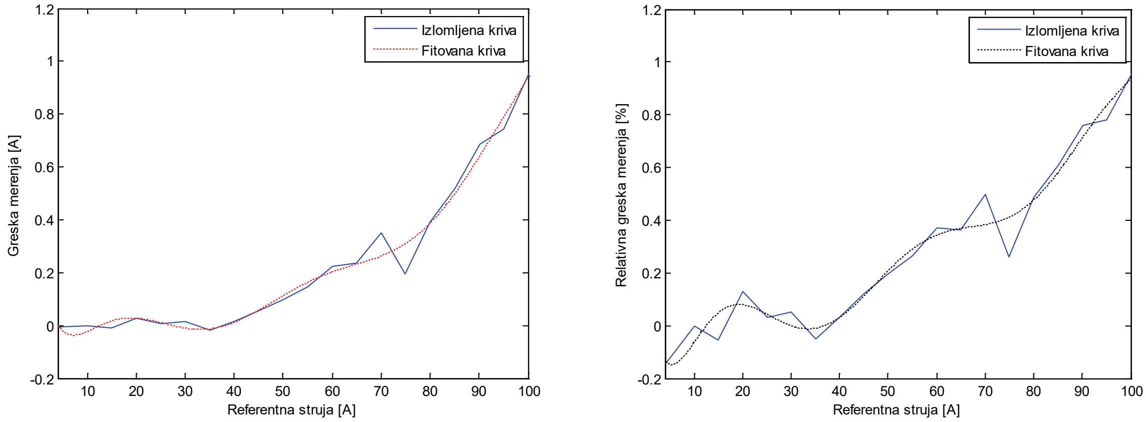

Fig. 8. *The experimental and fitted curves of the: a) absolute error b) relative error, obtained for continuous current excitation of the resistive shunt.*

The obtained absolute measurement error is in the range from 17 mA to 53 mA. It corresponds to the class of accuracy of 0.053%.

The second testing is executed under the real conditions when through the resistive shunt flows the continuous current. The stable DC current generator for the current range from 4 A to 100 A, manufactured by the Electrical Engineering Institute Nikola Tesla in Belgrade and traceable to the measurement standards of the Institute Nikola Tesla, is utilized in experiment. The secondary standard resistor of 1 mΩ, produced by the Otto Wolf and traceable to the national measurement standards of Serbia as well as the FLUKE multimeter, traceable to the measurement standards of the Institute Nikola Tesla are also used in experiment. The current intensity is tuning continuously with the approximate step of about 5A. The measurement errors are obtained by comparing the reference current readings from the digital voltmeter (the voltage drop on the standard resistor of 1 mΩ) as well as the readings from the PC application, Figure 8a and 8b.

As can be seen from Figures 8a and 8b, the measurement error increases at larger current intensities, approximate over 50A. Namely, because of the continuous current excitation, the increase of the measurement error in the upper half of the measuring range is the result of increase of self-heating of the resistive shunt due to increased dissipation, as well as relatively low upper limit of operating temperature of the shunt of just 60 ^{0}C.

The relative measurement error is less than 0.2% for the currents up to 50A, while over this margin it increases rapidly. At the end of the measuring range, the relative error reaches the value of about 0.95%. In accordance with the producer specification, if continuous current is required, a shunt must only be allowed to carry 2/3 of its maximum nameplate amperage. The 2/3 derating factor provides an adequate safety margin for convection cooled shunts operating in an ambient temperature of +25°C. At an elevated ambient temperature the allowed current is even less than 2/3 of nameplate amperage.

Better results may be expected in the case of intermittent current excitation of the shunt and therefore less self heating.

CONCLUSION

The new measurement concept for the current sensors based on the resistive shunt is analyzed in this paper. The realized sensor is based on the UTI-03 interface with quasi-digital output and microcontroller. Despite the fact that the interface is designed as a transducer, by selecting the appropriate operating mode the UTI-03 can be efficiently used for accurate measurements of low voltages such as a voltage drop on the resistive shunt.

Due to the continuous self calibration procedure, which uses three-phase technique for offset and gain error eliminating, greater measurement accuracy is achieved.

The described solution is suitable for intermittent constant DC current measurement or for continuous current less than or equal to 2/3 of maximum nameplate amperage of the shunt.

Further improvement of the accuracy and the measuring range increase may be expected by a fan installation near the shunt in order to decreasing its self heating.

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