Giant magnetoresistive based galvanically isolated voltage measurement

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Abstract—**Nowadays, direct current (DC) is much more widely used than a decade ago. Not only in the well-known high voltage direct current (HVDC) transmission but also as DC powered marine system, DC data center and DC fast charging system for electric vehicles. DC is now challenging the alternative current (AC) in a large variety of fast growing markets. However a galvanically isolated DC voltage measurement for low and medium voltage is, from the technical and scientific point of view, still far behind the AC voltage measurement methods. In this paper a new giant magnetoresistive (GMR) based sensor system for galvanic isolated DC voltage measurement is introduced. The measurement system consists mainly of a special coil arrangement with low inductance, a GMR sensor, AD converters and a low-cost FPGA. The voltage sensor system showed an outstanding measurement accuracy of 0.3% for voltage values up to ±550V in a temperature range from -30°C to 90°C. This completely new approach for the galvanic isolated measurement of electric voltages avoids the use of bulky magnetic components and expensive power consuming analog electronics.**

Keywords—Giant magnetoresistive (GMR); voltage sensor; voltage measurement; signal conditioning; B-spline interpolation.

I. INTRODUCTION

Galvanically isolated voltage measurement is usually based on current measurement. With a suitable resistive pre-resistor, the voltage signal is converted to a small current signal. The weak magnetism of the small current is handled by using a high magnetic flux concentrator and a huge number of windings, leading to a high inductance and a weak frequency response. Nevertheless, due to the modest sensitivity of commonly used Hall Effect sensors, a voltage measurement can hardly reach an accuracy level below 1% at room temperature, and this accuracy would be much worse over a wide temperature range [1]. If, instead of the Hall Effect sensor, a fluxgate sensor or isolation amplifier based sensor is used, a better accuracy over temperature (0.6% or 1%) can be achieved [2][3]. However due to the more complex analog techniques needed, this alternative is very expensive. We present here a development of a low cost, high accuracy, GMR based open-loop voltage sensor system combining accuracy with a compact and cost efficient system design.

After the discovery of GMR effect by Albert Fert [4] and Peter Gruenberg [5], GMR effect was implemented widely in disk drive head in a short time[6][7]. Subsequently GMR based sensors have showed their widespread applications in current, field, position, angle, velocity and rotational speed measurement [8]-[14]. Through hysteresis modeling an increase in the measurement accuracy of GMR current sensor is introduced [15][16]. Similar to the current measurement, the voltage measurement can also be performed with the help of a pre-resistor, however in contrast to current sensing, the magnetoresistive measurement can only use small currents in mA range, otherwise the power dissipation would be too much and make the sensor inefficient. Here a different procedure is necessary to increase the magnetic field amplitude at the position of the sensor. This can be solved by guiding the current line several times along the sensors position and superpose the field. A magnet intensifier based on a flat coil system is developed so that currents in the mA range can be detected, which makes it possible to implement the GMR sensor based voltage measurement. The nonlinearity and temperature influence of the GMR sensors can be corrected through [17] introduced B-Spline modeling.

For the experiments shown here, sophisticated GMR spin valve sensors were used. The same type of GMR sensor showed excellent accuracy of 0.25% for current values up to ± 100A in a temperature range from -20°C to 80°C in a current sensor set up [17]. Here the sensor is demonstrated for voltage (small current) measurements with a range of -550V to 550V, which is suitable for isolated voltage monitoring, for example, in commercial buildings with direct current electric distribution system [18][19] or in solar power systems. The proposed sensor has the potential to be applied in higher voltage sensing applications up to 1500V. The sensor system structure is described in Section II. Section III describes the experimental setup. The absolute error and relative error are measured and shown in Section IV. Section V concludes the paper and gives an outlook.

II. SENSOR SYSTEM STRUCTURE

A. Coil and sensor arrangement

As mentioned the voltage measurement is in fact a current measurement with the help of a pre-resistor, in this paper a 20 kΩ pre-resistor is used (Fig. 1a). The current flows through the pre-resistor and then goes in the multi-layer flat coil system. The coil structure configuration leads the current to

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flow in opposite directions on each side of the sensor and therefore generate opposite fields there (Fig. 1b). The four GMR elements of the sensor are composed in a full-Wheatstone bridge configuration (Fig. 1c).

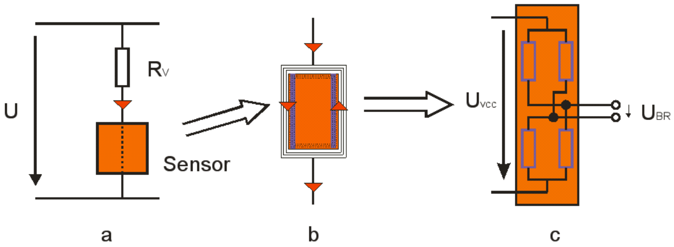

Fig. 1. The galvanic isolated voltage measurement over a pre-resistor. a) Schematic with a pre-resistor. b) Coil in rectangle shaped section. c) MR sensor in a full Wheatstone bridge configuration.

The two flat coils are designed with 16 layers and are connected in a series-opposing connection (Fig. 2). This configuration is enhancing the magnet field along the sensitive axis (x axis) of the GMR sensor, which allows very small current to generate strong gradient field at the sensor position. When current flows in the coil system, the resistors at one side decrease their resistance value, whereas the resistors at the other side increase it. Thereby an electric voltage U_{BR} (output voltage of the Wheatstone bridge) gives a measure for the electrical voltage by remaining galvanically isolated.

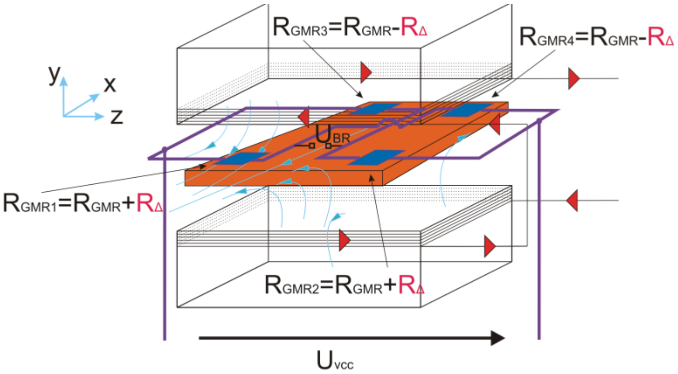

Fig. 2. Measuring principle with two coils.

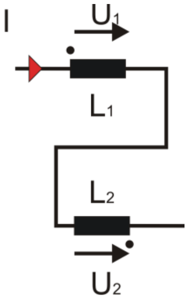

Fig. 3. Schematic two coils in a series-opposing connection.

Fig. 3 shows the schematic of the two coils in a series-opposing connection in detail. The voltage drop from the two coils can be calculated as follow:

$$U_1 = \omega L_1 I - \omega M I$$
$$U_2 = \omega L_2 I - \omega M I$$

Since the coils are designed identically:

$$L_1 = L_2 = L_0 = \frac{1}{k} M \,; \quad (k < 1)$$

Then the total voltage could be calculated:

$$U = 2\omega I L_0 (1 - k)$$

Thus the total inductance is:

$$L = 2L_0 (1 - k)$$

For a coupling factor k smaller than 0.5 the total inductivity is lower than the inductance of a single coil, but generation twice as much magnet field for the measurement resulting in a better accuracy and an improved frequency response. A large bandwidth and a high slew rate are necessary for applying the GMR voltage sensor in protection devices and in control systems.

The FEM simulation in Fig. 4 represents a double-sided coil system indicating the enhanced magnetic field at the position of the GMR-Sensor. Each coil consists of multiple layers with 30 windings. Magnetic fields up to 4000A/m are available in the central sensor region with 100 mA current flow.

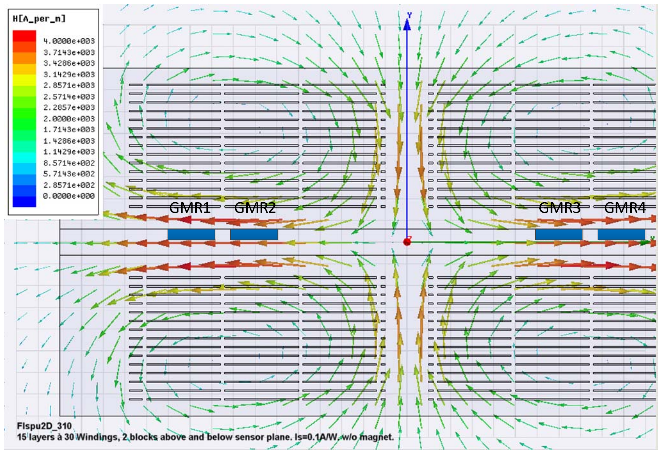

Fig. 4. FEM 2D simulation of a two-sided coil model with 15 layers/30 windings each; and magnetic field, arising from a 0.1A current per winding flowing through both legs of the coil system.

B. *Sensor electronic*

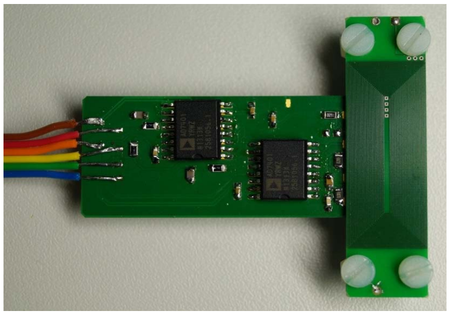

Fig. 5. View of printed circuit board with coil system. The GMR sensor is under the middle of the upper coil.

A printed circuit board (PCB) is designed to position the GMR sensor between the middle of the two flat coils and to convert the analog sensor signal and temperature signal into digital form. The 16 bit, up to 20 MHz, isolated signal-delta modulator AD7401 from analog devices is used for the analog digital converting. The coils are stacked on the both sides of the sensor board and they are fixed by four plastic gearheads. The converted digital signals are transferred over the cables on the left side to a FPGA for further processing (Fig. 5).

The output amplitude of the GMR full bridge UBR is slightly dependent on the temperature. Furthermore the resistance of the coil system is due to its fine structure and huge number of windings, nearly 800Ω at room temperature. In a large Temperature range from -30°C to 90°C, the resistance value of the coil system can vary up to 50%, which equate to 2% of the total resistance. Since the current is inversely proportional to the resistance, the measuring error of this small current and later the voltage can be strongly affected. In conclusion, it is necessary to measure the temperature of the GMR sensor system as well as the output voltage of the Wheatstone bridge (UBR) in order to correct the influence of the ambient temperature on the obtained voltage value. This can be achieved without using an extra temperature sensor. The changes of the GMR resistors are used to sense the Temperature (Fig. 6). Due to the small variation of the GMR resistor value dependent on temperature, a suitable SMD shunt is used to detect the current change, which is inversely proportional to the RGMR. The shunt value is very small by comparison to the resistance of the Wheatstone bridge; therefore it doesn't affect the whole system. The temperature changes along with UBR are parallel with synchronized clock signal from the FPGA sampled by the analog digital converters.

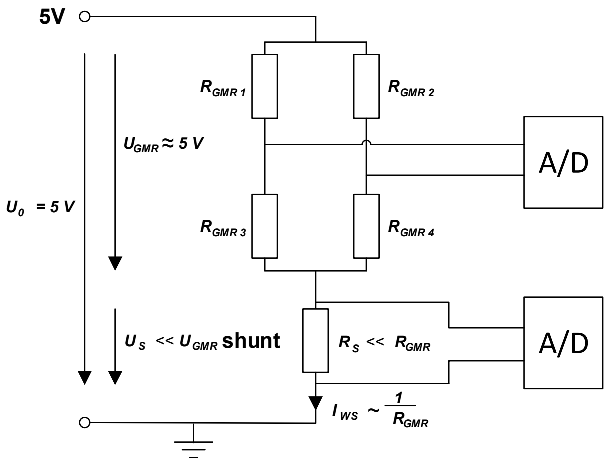

Fig. 6. Block diagram sensor and PCB.

III. EXPERIMENTAL SETUP

A measurement station has been built for calibrating the sensor system and receiving the output characteristic (Fig 7). For taking the measurement at a well defined temperature (-40°C – 100°C), the PCB with the coil system in Fig. 5 has been mounted in a Voetsch VT7004 convection oven.

The voltage signal is generated by an Agilent N5772A computer controlled voltage source. The maximum voltage output of this device is 600V, which is enough for the calibration of a low voltage sensor up to 580V. A DE0-Nano board based with an Altera Cyclone IV EP4CE22F17C6N FPGA is used for the digital signal processing. Two 40-pin Headers (GPIOs) on the Board provide 72 I/O pins, 5V power pins, two 3.3V power pins and four ground pins [20], which allow a multi channel measurement of voltage and current.

The measuring system is controlled by a LabVIEW program. A pulse signal loop in 5V steps from -580V to 580V and then back to -580V is generated by Agilent N5772A. As the Agilent N5772A here is controlled by analog signal, a Data Acquisition (DAQ) card from National Instruments (DAQ NI PCI-6052E) has been used as an interface between the LabVIEW Program and the measuring equipment. Parallel to the analog signal, the DAQ triggers the FPGA with a digital signal to start the measurement. The measured data from the sensor is sent to the FPGA and then to the PC at last. A Keithley 2000 (with 0.002% accuracy) is used to measure the voltage output from Agilent N5772A. This referent measurement is sent to PC as well. After a complete loop, the oven is instructed by the LabVIEW program to go to the next measure temperature.

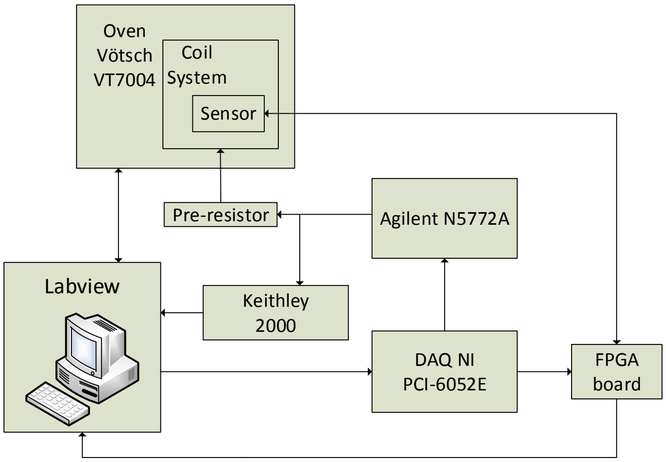

Fig. 7. Block diagram of the measurement station for the GMR sensor.

In the FPGA the converted sensor signal and temperature signal are filtered by a $sinc^3$ filter and a FIR filter in series. Then the filtered values are recalculated as within [17] introduced cubic spline interpolation method, which the grid data from calibration stored in a ROM in FPGA is used. After the interpolation the calculated voltages are stored shortly in a RAM and sent via RS232 to PC.

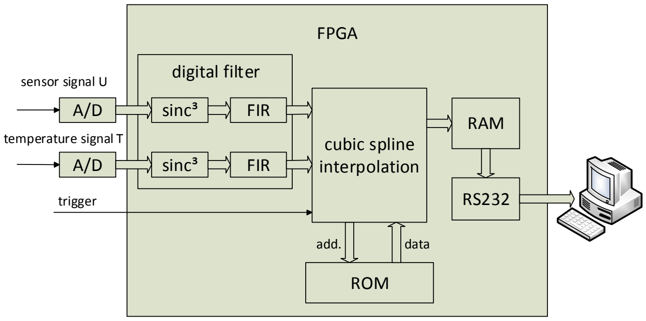

Fig. 8. Block diagram of the digital signal processing.

IV. RESULTS

The measurement is taken with an input voltage range of -580V to 580V in 5V step and an environmental temperature range of -40°C to 100°C. Fig. 9 shows the digitized sensor output before the B-spline interpolation for error correction. The temperature dependence and the non linearity of the output voltage of the simple GMR Wheatstone Bridge can clearly be seen in Fig. 9. For a voltage range from -580V to 580V the digital difference is about 3200, which correspond to 1160V/3200LSB ≈ 0.36V/LSB. The 16 bit ADC has a signal range from -320mV to 320mV; therefore the minimum difference between two different values is 640mV/216LSB ≈ 9.8μV/LSB. With the 5V supply voltage the sensitivity is (9.8μV/LSB) / (0.36V/LSB) / 5V ≈ 5.4μV / (V·V).

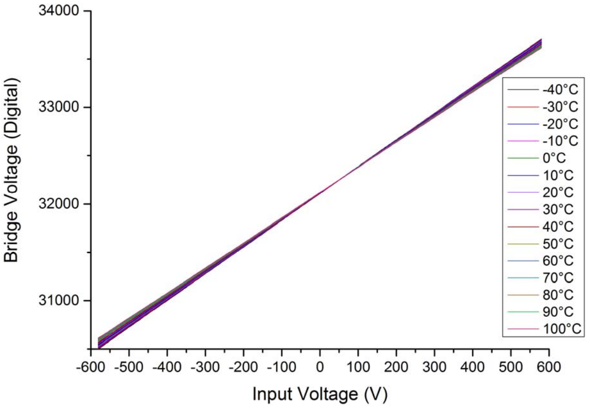

Fig. 9. Measurement without linearization (initial data).

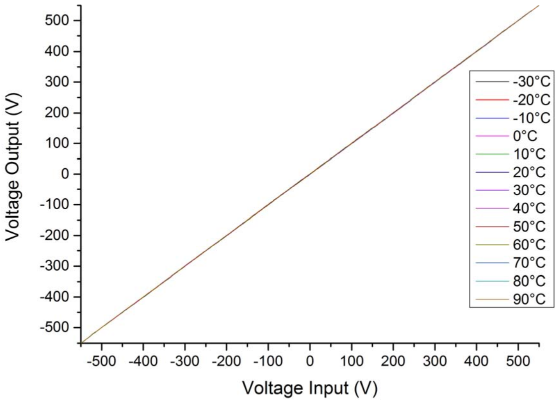

Fig. 10. Linearized measurement (with linear-cubical interpolation).

In Fig. 10 the digital output of whole voltage sensor system including B-spline interpolation for error correction is shown. By comparing Fig. 9 and Fig. 10 the outstanding improvement gained by the cubic spline interpolation for compensating the temperature influence as well as nonlinearity of the GMR Wheatstone Bridge sensor can be seen. The calculation for spline interpolation needs the neighboring points. The points at the edge which don't have enough neighboring points can't be calculated correctly; therefore after the interpolation voltage range (-550V to 550V) and temperature range (-30°C to 90°C) are a little bit smaller.

For quantitative evaluation, Fig. 11 gives the corresponding absolute measurement error and Fig. 12 the relative measurement error. All measurement operations were run from the minimum to the maximum voltage value and back. The absolute errors in the whole temperature range are relatively constant, due to a dominant hysteretic effect. Therefore the accuracy in low voltage range is limited, especially in the zero point. By using the B-spline based modeling technique, the nonlinearity of the GMR sensor and the influence of temperature are successfully calibrated, however this modeling is not able to compensate for the dynamic effects like hysteresis. Nevertheless an accuracy of about 0.3% for a nominal voltage of 400V in a temperature range exceeding the industrial standard by using galvanic isolation seems to be very promising for future use.

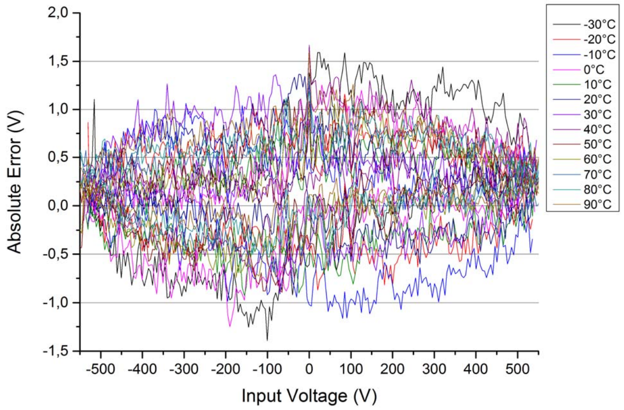

Fig. 11. Absolute error of the linearized measurement.

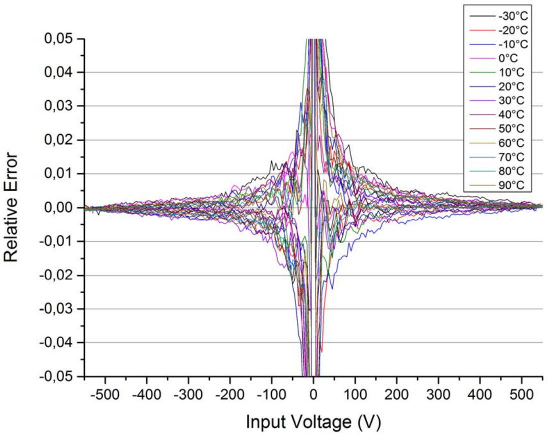

Fig. 12. Relative error of the linearized measurement.

V. CONCLUSION AND OUTLOOK

Using a flat coil system enables the voltage measurement in the form of small current measurement to implement. With the B-spline interpolation, which already showed successful excellent results in current measurement [17], a ±0.3%

accuracy by ±400V nominal voltage in a wide operational temperature range of -30°C to 90°C is reached. The digital signal processing based on the FPGA could also be implemented with the GMR sensor together into an ASIC chip. The digital signal output of the sensor system facilitates the further signal processing for the power monitoring system.

Furthermore, with a 20kΩ pre-resistor, the current at nominal voltage (400V) is about 20mA, which makes the sensor loss power about 8W. More sensitive magnetorsistive sensor is needed to reduce this loss. A newly developed tunnel magnetoresistive (TMR) based sensor has showed a much higher sensibility but also a much stronger hysteretic property. Further improvement of hysteretic compensation is under development.

The calibration method shows excellent results, however the mass production cannot afford to measure 15 temperatures and 361 points per temperature for each sensor. Nevertheless due to the similarity of the sensor characteristic curve a new calibration method for a later mass production is under development, which needs only one temperature and five measure points for every additional sensor.

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