Error Compensation of Closed Loop Hall Effect Current Sensors

Ji-Gou Liu (IEEE), Abdulkadir Sanli, Yixiao Wang and Cheng Liu

ChenYang Technologies GmbH & Co. KG.
Markt Schwabener Str.8, 85464 Finsing, Germany
http://www.chenyang.de, Tel. +49-8121-2574100, Fax: +49-8121-2574101
Email: jigou.liu@chenyang-ism.com

***Abstract* — In this paper an error compensation method is proposed for improving the measuring accuracy of closed loop Hall Effect current sensors, especially in low current measuring range. The measuring range is divided into *n* sub-ranges. The measuring resistance at the sensor output is optimized for each sub-range in order to obtain a minimum error variation of the output voltage. The deviation of the sensor can be then compensated by offset and gain adjustment circuit during the sensor calibration procedure. The proposed methods can be used in all current sensors based on closed loop measuring principle.**

Keywords - Error compensation; accuracy improvement; Hall Effect current sensor; measuring resistance optimization

I. INTRODUCTION

Hall Effect current sensors find increasing applications to power systems, inverters, rectifiers, motor drives, electric powered locomotives, telecommunications, transformer sub-stations, wind generators and photovoltaic equipment etc. Compared with shunt resistor and current transformer, a Hall Effect current sensor has much more benefits in wide measuring range, good linearity, relative high accuracy, high isolation between input and output, diverse sensor configurations and applications etc. [1,5].

However, the measuring accuracy of both open loop and closed loop Hall Effect current sensors cannot be satisfied with some applications, especially in low current measuring range. The accuracy of most open loop current sensors can be controlled only within ±1.0% of Full Scale (FS) even if its deviations are compensated by offset and gain adjustment during sensor calibration. The accuracy of closed loop current sensors can reach within ±0.5% FS. But for conventional closed loop current sensors it is not easy to eliminate the error by sensor calibration. One of methods for error reduction is the adjustment of the turn ratio of the sensor [5]. The deviation of measuring low current range will be strongly increased when the current is measured with sensor calibrated in high current range.

There are many error compensation and correction methods for measurement of current [2-4] and electrical quantities [5-9]. The most of them are based on the error analysis, mathematical models and self-calibration etc. without considering the optimization of relevant system parameters. By using these methods it is not possible to compensate the measuring errors of measuring low current ranges of Hall Effect current sensors.

Therefore it is necessary to divide the measuring range of a closed loop Hall Effect current sensor into *n* sub-ranges and to optimize the measuring resistance in each sub-range according to power supply firstly, and then to integrate an offset and gain adjustment circuit into the current sensor in order to compensate the offset and linear deviation in each sub-range by sensor calibration. The accuracy of closed loop current sensors can be improved in this way.

II. CLOSED LOOP HALL EFFECT CURRENT SENSOR

In a conventional closed loop Hall Effect current sensor (see Fig. 1) a primary conductor of current under test passes through a magnetic core. The magnetic flux generated by the primary current is concentrated in the core, which is proportionate to the current. A secondary coil is wound around the magnetic core. The magnetic field is sensed with the Hall sensor. The Hall voltage is connected to an integrating amplifier to generate a current for driving the coil. The current through the coil produces an opposite field. Thus the magnetic flux in the core is constantly driven to zero. The coil connects the sensor output. Therefore the sensor has an output current I_s, which is equal to the primary current I_p divided by the number of turns N on the coil:

$$I_s = I_p / N \tag{1}$$

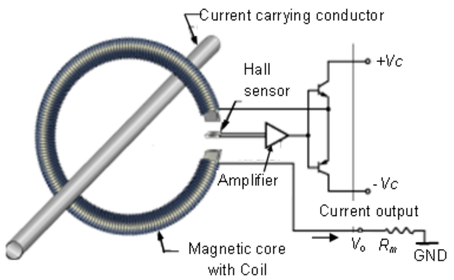

Fig.1. Conventional closed loop Hall Effect Current Sensor [5]

The current output can be converted into a voltage output by connecting a measuring resistor R_m between the output and ground. The voltage output V_o is scaled by selecting the resistor value and can be determined by:

$$V_o = R_m \times I_s \tag{2}$$

The relative measuring deviation E_s in the measuring range $[0, I_p]$ is defined as:

$$E_s = \Delta I_s / I_s \times 100\% = \Delta V_o / V_o \times 100\% \tag{3}$$

with ΔI_s as the maximum absolute current deviation and ΔV_o as the maximum absolute voltage deviation. The relative measuring error will increase if a current sensor calibrated in high measuring range is used to measure a low current range without optimizing the measuring resistance R_m. In this case the maximum absolute deviation is considered as the same. The maximum measuring error E_m can be estimated by

$$E_m = I_s / I_{sm} \times E_s \tag{4}$$

where I_{sm} is output current of the rated low input current I_{pm} to be measured. Taking the sensor CYHCS-SH1000A (see Table I.) as example, the relative error of this sensor is 0.2% in the measuring range of [0,1000A], i.e. I_p=1000A and I_s=200mA. The maximum relative error can be 20% if the sensor is used for measuring a low current range of [0, 10A], i.e., I_{pm} =10A and I_{sm}=2mA.

III. Error Compensation Method

A. Optimization of Measuring Resistance

In order to reduce the measuring errors before error compensation, the measuring resistance R_m must be optimized for the corresponding measuring range. Two criterions can be used for the optimization of measuring resistance. The first criterion is a conventional method that optimizes the resistance to get a minimum deviation without considering error compensation. The second criterion is to optimize the resistance in order to obtain minimum error variation in the measuring range. In this case the constant and linear errors can be then compensated with an offset and gain adjustment circuit in order to improve the measuring accuracy.

The rated measuring current range $[0, I_{np}]$ of a closed loop current sensor can be divided into n measuring current sub-ranges $[0, I_{kp}]$, k=1,2,…,n. The corresponding output current sub-ranges are presented by $[0, I_{ks}]$ with k=1,2,…,n. The output currents are calculated by

$$I_{ks} = I_{kp} / N, \quad k = 1, 2, ..., n \tag{5}$$

The measuring resistance R_{km} (k=1,2,…,n) in the k-th sub-range $[0, I_{kp}]$ is limited by the power supply V_c of the sensor :

$$R_{km} = V_o / I_{ks} < V_c / I_{ks}, \quad k = 1, 2, ..., n \tag{6}$$

The maximum measuring resistance R_{kmm} can be determined by V_o=0.9V_c. The measuring resistance R_{km} of each current sub-range is optimized by experiments. Here is the optimization procedure (see Fig. 2):

- Calculate the maximum resistance R_{kmm} according to (6) and assign it as initial measuring resistance R_{km0}, and connect it between the sensor output and ground.
- Measure offset ΔV_{os} (i.e. V_{o0}) and output voltage V_{oi} under input current $I_{pi} = i\, I_{kp}/10$, i=1,2,…,10, in the current sub-range $[0, I_{kp}]$.
- Determine the minimum error E_{min} and maximum error E_{max} from the measuring data.
- Calculate the error variation $\Delta E=E_{max} - E_{min}$ and check if ΔE is minimized.
- The measuring resistance is optimized if ΔE is minimized. Otherwise reduce the measuring resistance and repeat the optimization procedure mentioned above.

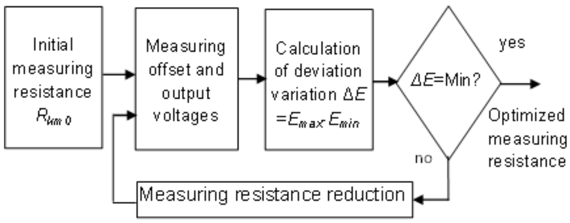

Fig. 2. Optimization algorithm of measuring resistance

Instead of the error variation ΔE, the standard deviation of measuring data can also be used as valuation quantity for the resistance optimization. The result of this method is near the same as by using error variation. The calculation of error variation is, however, simpler than that of standard deviation.

B. Error Compensation

The error compensation is carried out by digital and analog signal processing methods. The digital signal processing is useful for sensors with microprocessor and measuring systems [6-10]. The analog signal processing is suitable for current sensors without using microprocessor.

The output voltage V_o of a current sensor consists of true output voltage V_t and deviation voltage ΔV, which comes from offset voltage ΔV_{os}, linear deviation ΔV_l, non-linear deviation ΔV_{nl} and random error ΔV_r, i.e.:

$$V_o = V_t + \Delta V = V_t + \Delta V_{os} + \Delta V_l + \Delta V_{nl} + \Delta V_r \tag{7}$$

In the digital signal processing the offset voltage ΔV_{os} can be corrected by adding a correction $-V_{o0}$. The linear deviation ΔV_l is caused by the gain deviation of the sensor and can be determined by regressive line under using the measuring data. After the correction of ΔV_{os} and ΔV_l the output voltage U_o is described as follows:

$$U_o \; = \; V_t + \Delta V_{nl} + \Delta V_r \qquad (8)$$

For sensor without microprocessor an offset and gain adjustment circuit must be integrated in the sensor. Fig. 3 shows the sensor structure. In this system the closed loop Hall Effect current sensor is a conventional sensor. The current output I_s of the sensor is converted into output voltage V_o by connecting the optimized measuring resistance R_{km} between the sensor output and ground. The output voltage V_o is connected to a voltage follower, i.e., impedance converter, which has a high input resistance and a low output resistance. Therefore the output voltage V_o of the voltage follower is the same as that of the sensor. In this case there is no interaction between the sensor output and the offset and gain adjustment circuit. The offset and linear errors of voltage output V_o are compensated with offset & gain adjustment circuit during the sensor calibration. The output voltage U_o after analog error compensation is more accurate than the output voltage V_o.

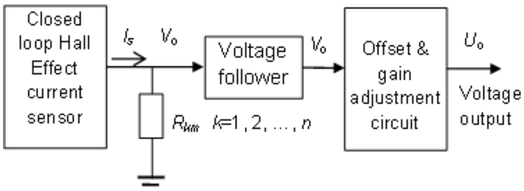

Fig. 3. Analog error compensation of closed loop current sensor

IV. EXPERIMENT RESULTS

The Hall Effect current sensor CYHCS-SH1000A is used for experiments of low measuring current ranges [0,10A] and [0,50A]. Table I indicates the specifications of this sensor.

TABLE I. SPECIFICATIONS OF HALL EFFECT SENSOR CYHCS-SH1000A

Rated input current	*Turns ratio*	*Rated output current*	*Power supply*	*Measuring accuracy*
1000A	1:5000	200mA	±15-24VDC	±0.2% FS

A. *Measuring range [0,10A]*

Fig. 4 shows relative deviation as function of input current under using different measuring resistances. The deviation depends on the measuring resistance. Fig.5 gives the error variation as function of measuring resistance. The minimum error variation locates at measuring resistance of 4.66kΩ, which can be considered as the optimized resistance for the measuring range [0,10A]. The maximum relative deviation by using the optimized measuring resistance is 2.41%, which is lower than those of using other measuring resistances.

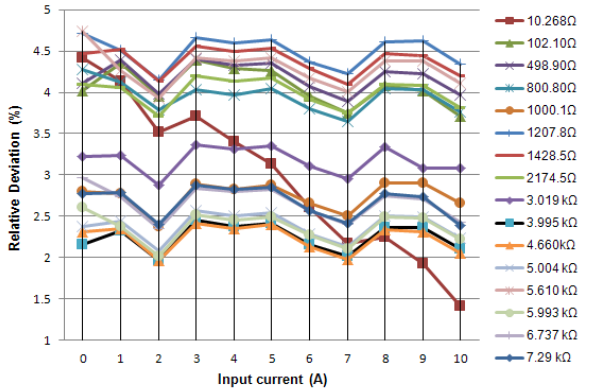

Fig. 4. Relative deviation as function of input current under using different measuring resistances and power supply of ±15VDC

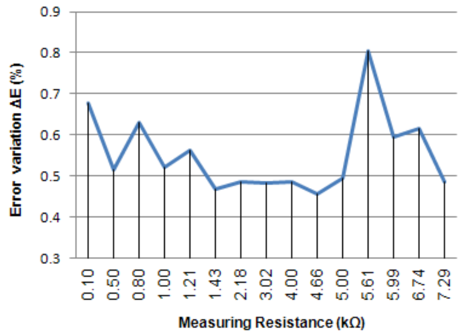

Fig.5. Error variation as function of measuring resistance

Fig. 6 indicates the relative deviation under using the optimized measuring resistances after digital offset correction. The error is controlled within ±0.40% for measuring current range [0,10A]. Fig. 7 and 8 show the deviation after analog error compensation (see Fig. 3) of three current sensors in comparison with deviation before compensation. The error after compensation is controlled within ±0.25%.

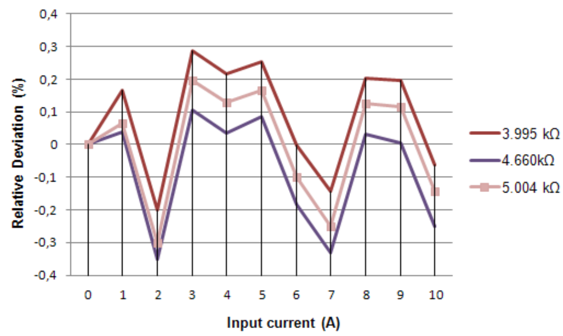

Fig. 6. Relative deviation under using optimized measuring resistances after digital offset correction

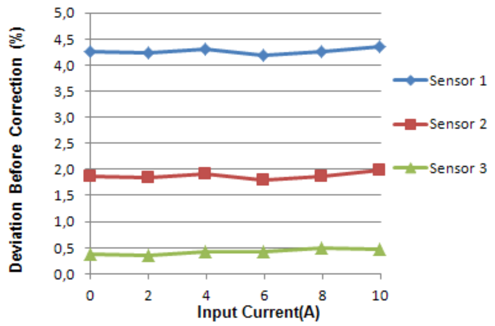

Fig. 7. Relative deviation of 3 sensors before error compensation

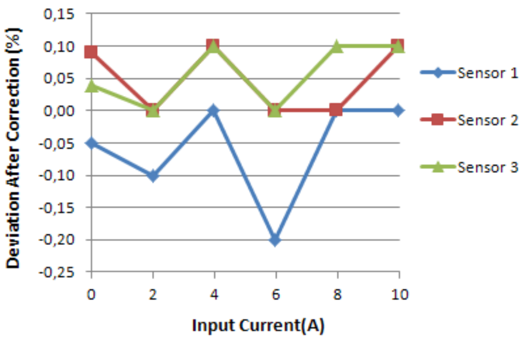

Fig. 8. Relative deviation of 3 sensors after analog error compensation

Comparing with the original errors of the sensor in the measuring range, see Fig. 4, the errors after offset correction and compensation are remarkably reduced. It is realizable to get a relative error of ±0.4% for measuring range of [0,10A] by using a sensor with maximum measuring range of [0,1000A]. It is very useful for practical applications.

B. Measuring range [0,50A]

Fig. 9 and Fig. 10 give the optimization of measuring resistance for current range [0, 50A]. The minimum error variation locates at the measuring resistance of 1.4kΩ. In this case the output voltage is 14V. For most applications this output voltage is too high. The measuring resistance should be 1kΩ for output voltage of 0-10V according to (6).

Fig. 11 shows the relative deviation and its regressive line in measuring range [0,50A] under optimized resistance of 1kΩ. The results after correction are described in Fig. 12. The relative deviation after digital offset and gain correction is controlled within ±0.10%.

Fig. 13 and 14 indicate the deviation after analog error compensation of three current sensors in comparison with that before compensation. The measuring error after compensation is controlled within 0.15%.

In this measuring range the offset and linear error must be eliminated by offset and gain adjustment. In this case the errors after compensation are limited within 0.2%.

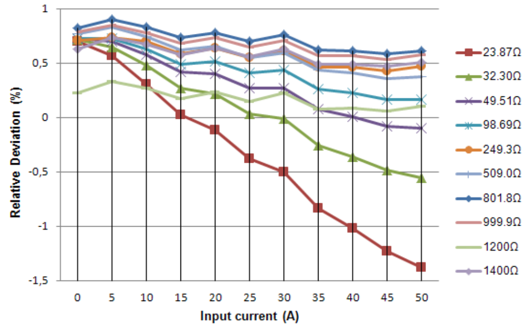

Fig. 9. Relative deviation as function of input current under using different measuring resistances

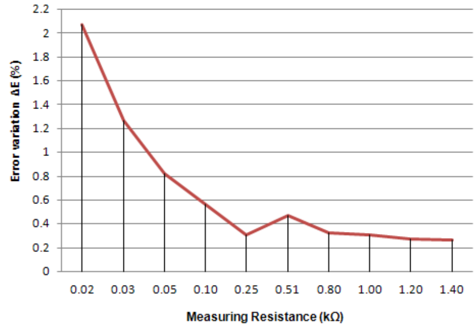

Fig. 10. Error variation as function of measuring resistance

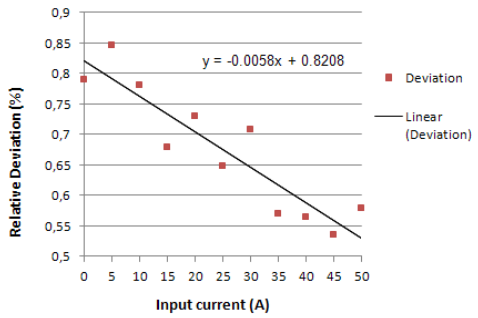

Fig. 11. Relative deviation under optimized resistance before correction

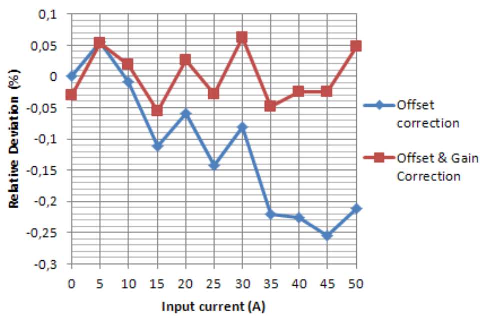

Fig. 12. Relative deviation under using optimized measuring resistances after digital offset and gain correction

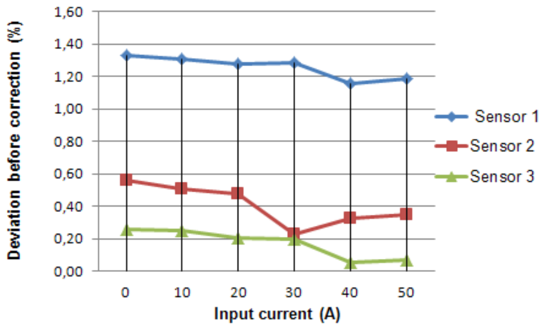

Fig. 13. Deviation of 3 sensors before error compensation

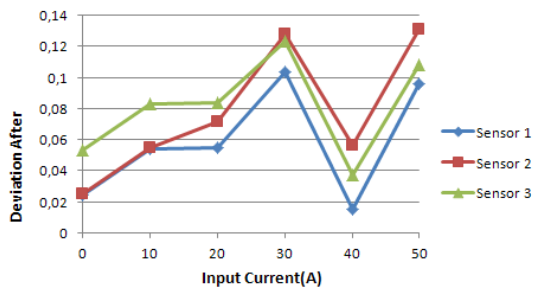

Fig. 14. Deviation of 3 sensors after analog error compensation

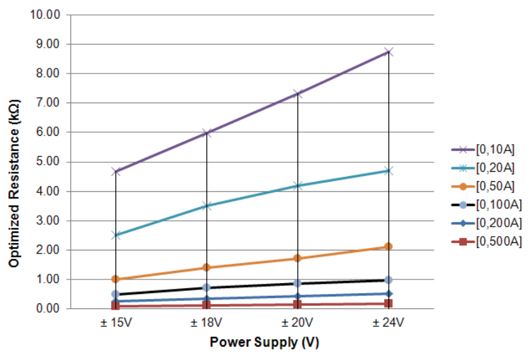

Fig. 15. Optimized resistance as function of power supply

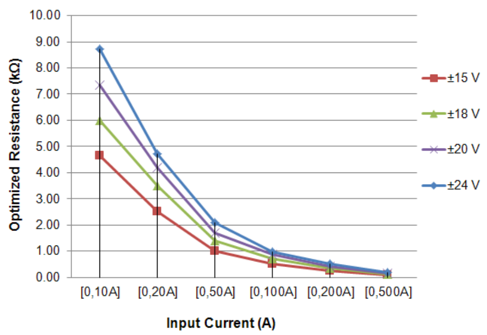

Fig. 16. Optimized resistance as function of input current sub-range

In the similar way one can do the measuring resistance optimization and error compensation for other measuring range. Fig. 15 and Fig. 16 give the optimized resistance as function of power supply and input current sub-range. The resistance increases with the power supply near proportionally and decreases with the input current sub-range nonlinearly. The error compensation, however, is the same under different power supplies and input current sub-ranges. Therefore the resistance optimization under application conditions is very important for implementation of error compensation method.

An example is given in the following figures. Fig. 17 shows original deviation of measuring range [0,10A] under using measuring resistance of 10Ω. In this case the error consists of offset and linear deviations. The error cannot be eliminated by offset correction, see Fig. 18. Under using the optimized resistance, see Fig. 6, the error can be corrected only by offset correction. Normally the error compensation is more convenient after optimization of the measuring resistance.

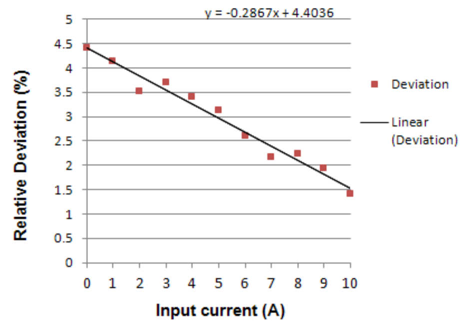

Fig. 17. Relative deviation under using resistance 10Ω before correction

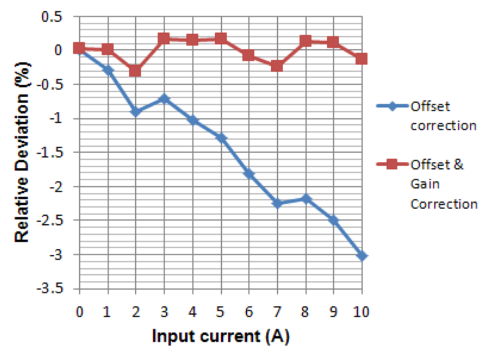

Fig. 18. Relative deviation under using measuring resistances 10Ω after digital offset and gain correction

V. CONCLUSIONS

From analysis and experimental results we can draw the following conclusions:

- The proposed error compensation method is based on the division of the measuring range into n sub-ranges and the optimization of the measuring resistance in each sub-range.

- The optimized resistance decreases with the input current and increases with the power supply. The resistors should have good sufficient current carrying capacity and temperature stability.

- The error compensation can be implemented by digital signal processing for microprocessor controlled sensors and systems and by offset and gain adjustment circuit for analogue sensors.

- The accuracy of all measuring ranges of any closed loop Hall Effect current sensors can be improved remarkably by using the proposed method. The relative accuracy of measuring current sub-ranges can be controlled within 0.5%.

- The method can be applied to accuracy improvement of all closed loop Hall Effect current sensors, especially for low current measuring range by using sensors with wide measuring range.

The further works are to investigate the long time stability of the error compensation method, to test the position influences of current conductor to the accuracy, and to design new microprocessor controlled closed loop current sensor under using the proposed error compensation method. The new sensors should have automatic localization of the measuring sub-ranges. For this purpose multiplexers must be used for selecting the corresponding optimized measuring resistance of each sub-range.

REFERENCES

[1] Edward Ramsden, "Hall-Effect Sensors, Theory and Applications", Amsterdam, London, New York etc., Elsevier 2006

[2] Dae-Woong Chung, "Analysis and compensation of current measurement error in vector-controlled AC motor drives", IEEE Transactions on Industry Applications, vol. 34, pp. 340-345, Mar/Apr 1998

[3] L.Cristaldi, A.Ferrero, M.Lazzaroni and R.T.Ottoboni, "A linearization method for commercial Hall-effect current transducers", IEEE Transactions on Instrumentation and Measurement, Vol. 50, pp.1149 - 1153, Oct 2001

[4] A. Cataliotti, D. Di Cara, A.E. Emanuel and S. Nuccio, "Improvement of Hall Effect Current Transducer Metrological Performances in the Presence of Harmonic Distortion", IEEE Transactions on Instrumentation and Measurement, Vol. 59, pp. 1091-1097, May 2010

[5] Y.X. Wang, J.-G. Liu, J. Zhao and Y.C. Yang, "Split Core Closed Loop Hall Effect Current Sensors and Applications", PCIM EUROPE International Exhibition and Conference for Power Electronics, Intelligent Motion, Power Quality, Nuremberg, Germany, pp. 1633-1638, 8-10 May 2012

[6] J.-G. Liu, U. Frühauf and A. Schönecker, "Accuracy Improvement of Impedance Measurements by Using the Self-Calibration", Measurement, Vol. 25, no. 3, pp. 213-225, April 1999

[7] J.-G. Liu and U. Früauf, "Self-calibration measuring methods and applications to measurements of electrical quantities", measurement, vol. 26, pp. 129-142, 1999

[8] J.-G. Liu, "Self-correction Algorithms and Applications to Digital Signal Processing", Measurement, vol. 31, no.2, pp. 107-116, March 2002

[9] J.-G. Liu, "Accuracy improvement in computer controlled measuring and test systems", Technisches Messen, in German, pp.390-398, tm 9/2002