Calibrations of phase and ratio errors of current and voltage channels of energy meter

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Abstract. This paper deals with measurement of phase and ratio errors of current and voltage channels of a new produced energy meter. This fully digitally controlled energy meter combines the classical static energy meter with power quality analyzer. The calibration of phase and ratio errors in wide frequency range is then necessary. Paper shows the results of error measurement, introduces the mathematical approximations and describes the calibration constants. It allows error compensation and power calculation of particular harmonics. The electric power of the higher harmonics can be interesting information of distributed electric energy quality.

1. Introduction

Nowadays electric energy is distributed to most of households, offices and industrial buildings around the globe. Precise measurement of consumed energy is very important for consumers and distributors. Electromechanical induction watt-hour meters with rotating disc are now replaced by static energy meters. Static energy meters are mostly based on digital processing of sampled instantaneous voltage and current waveforms.

The heart of the static energy meter is a microcontroller (MCU) that provides timing, sampling, calculations and communication with superior systems. Voltage channel is usually very simple because there are not so high dynamic range requirements. Most of energy meters assume to be connected to distribution network with constant voltage level (e.g. 230V) with tolerances in order of ten percent (e.g. ±15%) or the energy meters are connected to voltage transformer with standard ratio. Therefore voltage channels mostly contain only voltage divider, buffer and low pass filter (LPF). Following analog-digital converter (ADC) is the last part of the measurement chain that provides digital data.

On the other hand current channel is rather complicated. It is due to the high dynamic range of measured signal, needs galvanic insulation and DC immunity and limited power dissipation. Mostly the range is from ones of milliamperes (e.g. 10 mA) up to tens of amperes (e.g. 100 A). All these requirements fulfils only sensors that are based on measurement of the induced magnetic field like Hall probe, current transformer (CT) and Rogowski coils. More details about sensors in energy meters can be found in our previous work [1]. Current sensor is, like in voltage channel, followed by a buffer, amplifier, LPF and ADC.
2. Current transformers in energy meter
In this work we focus only on current transformers used for sensing the current in energy meters. There are special requirements defined in International and European Standards (e.g. EN 62053-21 or EN 50470-3). Except the others the immunity to dc current is also defined there. It is defined as a magnitude of half wave rectified current that causes power measurement error greater than predefined limit (according to class of the energy meter). The reason of the requirement is that some loads can be supplied through a diode to reduce power or saturate current sensors, cheat the electricity meter and steal energy.

Special type so-called DC tolerant CTs have to be used in this application. These CTs use low permeability core with large saturating intensity of magnetic field. So they can work even with large dc magnetic field induced by dc current without saturating the core. Two types of the transformers matching these demands: linear CTs and dual core CTs. Dual core CTs are cheaper than the linear ones but there are problems due the different phase errors with and without presence of dc current [2].

![Figure 1. Example of BH loop of linear CT](image)

In our work we deal only with linear CT (see figure 1) with almost constant permeability and phase error $\varphi_I$ - about 4 deg in wide range of measured current. We use VAC 4626-X101 current transformers with amorphous core that can work even with 100 A peak value [3].

$$\varphi_I = \varphi_{secondary} - \varphi_{primary} \text{ (deg)} \quad (1)$$

3. Concept of modern energy meter with power quality analyzer
The basic concept of energy meter has been presented in section 1. As stated above voltage and current are sampled by ADCs with frequency $f_S$ and discrete samples are processed by MCU. The electric power $P$ is defined as a product of corresponding samples of voltage $u_i$ and current $i_i$ ($N$ samples per period) and consumed energy $E$ is sum of the power in time.

$$P = \frac{1}{N} \sum_{i=1}^{N} u_i i_i \text{ (W; V, A)} \quad (2)$$

$$E = \frac{1}{3600 \cdot f_S} \sum_{t=0}^{T} P \text{ (Wh; W)} \quad (3)$$

This calculation assumes that there is no phase shift between voltage and current caused by the sensors. But as was stated above linear CT has constant phase error about 4 deg but only at frequency 50 Hz. Therefore the current samples have to be shifted by this phase.

In present time there are many appliances that consume no harmonic current moreover some power plant (e.g. solar) produce dc current and use DC/AC converter that can be source of higher harmonics. These facts lead to the necessity of measurement of particular harmonics component and analyses the electric power of higher harmonics.
Due to large performance of modern MCUs complicated calculation can be done. It is no problem to use FFT to compute spectrum in real time, get the amplitudes and phases of particular harmonics and use this information to analyze the power quality (PQ) of electric energy. Moreover it allows power calculation of higher harmonics.

Previously described functionality along with communication ability allows using these electricity meters in Smart Grids that is required by Directive of the European Parliament and Council Directive 2009/72/EC.

4. Frequency dependence of sensors

Previously described method for electric power calculation needs constant phase error in wide frequency range. In fact phase shift of CT as well as following electronic circuits (amplifier, LPF ...) are frequency dependent. It is necessary to calibrate whole measurement channel. Similar calibrations have to be done in voltage channel. Moreover the amplitude errors of both channels also have to be calibrated.

We prepare PCB with analog part of the energy meter consisting of the three voltage and current channels where all the errors can be measured and calibrated. Measurement system contains arbitrary generator HP 33120A for generating variable frequency voltage. Voltage is amplified by Krohn Hite 7500 amplifier and with the matching transformer MT-56R is converted to testing current. This current and voltage from amplifier are connected to current and voltage channel of the energy meter as well as to Multi-Channel Precision Power Analyzer LMG500. Outputs of analog parts of the energy meter are connected to sensor inputs of the second channel of the analyzer. Raw data from the analyzer are transferred to PC where the LabView program computes spectrum, phase shifts and ratio errors. Same program controls the generator. Multitone signal is used for testing current to speed up calibration procedure. Figure 2 shows the result of measurement of the errors for 30 frequencies in range 10 Hz – 10 kHz (points).

![Figure 2. Phase and ratio errors of voltage and current channel (points – real measured data, line – mathematical approximations)](image_url)

All the errors have to be digitally compensated. Compensating by lookup table is very easy solution and does not need high performance of MCU but it needs huge memory (with 10 Hz frequency bin and 16bit data number it needs $1000 \times 4 \times 2 = 8kB$ per channel of energy meter). Better solution is to describe the dependence by mathematical formulas with few parameters. Channels contain only LPFs and high pass filters (HPF) represented by CTs and errors can be described by following formulas.
\[ \phi_U = -\arctan(\omega K_U) \]  
\[ \phi_I = \arctan\left(\frac{1}{\omega K_I}\right) - \arctan(\omega K_I) \]  
\[ \varepsilon_U = \left(1 + (\omega K_{U})^2\right)^{\frac{1}{2}} + K_5 \]  
\[ \varepsilon_I = (\omega K_{I}) \cdot \left(1 + (\omega K_{I})^2\right)^{\frac{1}{2}} + \left(1 + (\omega K_{I})^2\right)^{\frac{1}{2}} + K_8 \]  

where \( \phi_U, \phi_I \) is phase error of voltage and current channel respectively  
\( \varepsilon_U, \varepsilon_I \) is ratio error of voltage and current channel respectively  
\( \omega \) is angular frequency = \( 2\pi f \)  
\( K_1 - K_8 \) are calibration constants given from calibration procedure

Calibration constants are obtained from curve fitting. Figure 2 (lines) shows the approximation curves for measured data. The calibration constants are stored in the table 1. Calibration process during energy meter production has to be as fast and easy as possible and thus it is impossible to measure in details all the errors. Most of calibrating generators are able to generate only base harmonic (50 Hz) and few (3 or 5) higher harmonic. Therefore the optimal calibrating frequencies have to be chosen. Figure 3 shows the approximation curves fitted from only 3 points 50, 500 and 5000 Hz (nominal frequency, 10th and 100th harmonics).

![Figure 2. Phase and ratio errors of voltage and current channel (line - curve fitting from 3 points – 50, 500 and 5000 Hz)](image)

Next figure shows the differences of real measured data and fitted curves. It can be seen that even only three points calibration provides satisfying results. Phase error is less than 0.5 degree and ratio error is less then 0.5% in frequency range from 30 Hz up to 5 kHz. If there is need to fit precisely at lower and higher frequencies the next two points should be included to calibration.
Figure 3. Differences of measured data and fitted curve (phase in degree, ratio in %)

Table 1. Calibration constants from 3 and 30 points calibration

| Const. | 3 points calibration | 30 points calibration | Error type       |
|--------|----------------------|-----------------------|------------------|
|        | (50, 500 and 5000 Hz) | (10 Hz – 10 kHz)      |                  |
| $K_1$  | 9.40E-6              | 9.70E-6               | Voltage phase    |
| $K_2$  | 3.96E-2              | 3.96E-2               | Current phase    |
| $K_3$  | 6.81E-6              | 6.90E-6               |                  |
| $K_4$  | 8.59E-6              | 8.30E-6               | Voltage ratio    |
| $K_5$  | 5.14E-3              | 6.09E-3               |                  |
| $K_6$  | 3.60E-2              | 3.94E-2               |                  |
| $K_7$  | 4.02E-6              | 3.94E-6               | Current ratio    |
| $K_8$  | -9.97E-1             | -9.97E-1              |                  |

5. Conclusion

Increasing number of alternative energy sources, inferential application of DC/AC converters and increasing number of nonlinear loads lead to necessity of power quality analysis and consider electric power of higher harmonics. All these tasks can be solved by new generation of fully digital energy meters. The phase and ratio error of voltage and current channels have to be corrected in whole frequency range. In this work we focus on calibration in range from 10 Hz up to 10 kHz. The dependencies can be approximated by mathematical formulas derived from LPF and HPF. It is necessary to know only 8 constant per channel of energy meter to make corrections. Only the three frequencies are enough to find a calibration constant that allows compensation of phase error under 0.5 degree and ratio error under 0.5% in frequency range from 30 Hz up to 5 kHz. Final conclusion can be done only with final PCB of real energy meter.

6. References

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