Performance evaluation of an energy meter for low-voltage system monitoring

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Abstract. The paper presents the design, realization and performance evaluation of an energy meter to be installed in LV power networks with specific features to be live-installable, with high accuracy and with high immunity vs. external electric and magnetic fields. The device can be controlled both through Bluetooth and Power Line Communications (PLC) protocols. Such an instrument has been commissioned by some main European utilities for online periodic comparison of energies and powers measured by smart energy meters installed in houses for billing purposes.

1. Introduction
In recent years the evolution and implementation of Smart Grids in LV networks has led also to the mass deployment of Smart Energy Meters in houses for billing purposes. Such devices feature many advantages with respect to traditional “inductive” ones, like higher accuracy, possibility to be remotely controlled, the possibility to apply different hourly tariffs, etc. A further advantage of such a technology is that it allows to implement periodic on-site metrological verification procedures and comparisons. In this paper authors present the design, realization and metrological verification of an energy meter to be used as a monitoring system for on-line comparison with energy meters installed in houses. This development of such a system has been requested by some major utilities in Europe to detect one of the biggest energy losses component: the illegal energy consumption. The most important specifications and constraints have been to be live-installable, to feature high accuracy (better than the deployed energy meters) and to be also insensitive to external magnetic and electric fields given that it will be typically installed in small and tight electrical cabinets positioned at the side of the roads. The paper presents the internal architecture of the energy meter developed along with the set-up and the experimental results of the measurement campaign carried out for its performance verification. A large and complete set of tests have been performed for the verification of both its accuracy and metrological characteristics. Results confirm the good behaviour of the device and the fulfillment of the accuracy specifications.

2. The energy meter
The energy meter has been designed for being installed in low voltage power networks. Figure 1a shows a picture of the system. In particular, it is aimed at measuring energy and relevant parameters along the main feeder that, starting from the medium/low voltage transformer, supplies a group of household and small commercial customers. It will be mainly placed inside electrical cabinets positioned at the side of the streets. The designed energy meter is a three-phase device featuring \( U_e = 230 \text{ V} \) and \( I_e = 200 \text{ A} \) as rated line-to-neutral voltage and current, respectively. As schematically shown in figure 1b, it is made by:
• Three Rogowski coils featuring: nominal ratio 1000 A/100 mV @ 50 Hz, accuracy 1 %, non-linearity 0.2 %, frequency range 20 Hz – 5 kHz.
• Three resistive voltage dividers having nominal ratio 230 V/ 115 mV and made by resistors with 0.1 % tolerance.
• A conditioning circuit which, among other things, implements a second order antialiasing filter (cut-off frequency set at 4 kHz) for each of the six input channels. The bandwidth of the system is then limited to 4 kHz, sufficient by considering that the power quality frequency range is up to 2.5 kHz.
• A commercial high-accuracy multifunctional energy metering IC. Such a device can operate simultaneous sampling at 8 kSa/s on its six input channels and measure several electrical parameters (for example voltage and current RMS, active and reactive energy and power, harmonics, etc.) with an accuracy up to 0.1 %.
• A 32-bit microcontroller which communicates with the energy metering IC via PC, stores the measurements in its internal flash memory and makes them available via Bluetooth or USB port.

3. Measurement setup
In order to evaluate the performance of the above-described energy meter, the measurement setup reported in figure 2 has been implemented. It consists of:

• The energy meter under test (EUT).
• A Fluke 6105A Electrical Calibrator with the Fluke 52120A Transconductance Amplifier.
• A personal computer (PC) running a proper software developed under NI Labview environment and connected to the calibrator via IEEE 488 and to the EUT via USB port.

The calibrator can provide sinusoidal voltage and current up to 1008 V and 21 A RMS, respectively, in the frequency range 16 Hz ÷ 850 Hz [1]. The use of the external transconductance amplifier allows to extend the current range up to 120 A [2]. Moreover, it is also possible to set the phase shift between voltage and current with a resolution of 0.001 °. The uncertainty on this angle is 0.003 ° (96 %-confidence level) at 50 Hz. Additional 0.006 ° must be considered, as in this case, when the external transconductance amplifier is used. As for the uncertainty affecting voltage and current, the manufacturer states that it is no more than 60 ppm of output plus 3.2 mV for voltage (96 %-confidence level) and no more than 0.015 % of output plus 0.006 % of range (99 %-confidence) for the current provided by the transconductance. All the above specifications refer to the case of sinusoidal, 50 Hz waveform. The software running on the PC first controls the calibrator by setting the desired values of voltage, current, frequency and angle. Then, it waits a few seconds to allow all the transients to be ended and starts to read via USB port the measurements performed by the EUT.
4. Results and discussion

Aim of the experimental activity is to verify the performances of the energy meter depending on the actual network operating conditions, besides to evaluate the uncertainty affecting each measurement of a given quantity. In this connection, all the parameters that can be set in the calibrator (voltage, current, frequency and phase angle) have been considered as influence quantities and their range of variation has been chosen according to what is defined by the international Standards [3-7]. In particular, the following values have been selected:

- Voltage RMS: 80%, 100% and 120% of the rated RMS voltage (230 V).
- Current RMS: 5%, 20%, 100% and 120% of the rated RMS current (200 A).
- Frequency: 47 Hz, 49.5 Hz, 50 Hz, 50.5 Hz, 52 Hz.
- Phase angle: 60°, 36.870°, 25.842°, 0°, which corresponds to power factors 0.5, 0.8, 0.9 and 1, respectively.

The combination of the above values gives rise to 240 different working conditions. For each of them, 100 measurements of voltage and current RMS $U$ and $I$, active and apparent power $P$ and $S$ have been performed and stored for each of the three phases of the energy meter, which have been all connected to the same source. Moreover, two turns of cable around the Rogowski coils allow to get an equivalent current of 240 A, as requested. Mean values and standard deviations have been computed and, in order to simplify the comparisons, normalized to the values obtained under rated working conditions (230 V, 200 A, 50 Hz, unity power factor) which have been taken as reference and whose mean values $U$, $I$, $P$ and $S$ have been set to 1 p.u. (per unit). The first observation that can be drawn from the obtained results is that the contribution of random effects can be considered negligible. In fact, the standard deviations result lower (sometimes far lower) than $10^{-+}$ in all the 240 situations tested. This justify the above conclusions given that in the worst case (current equal to 5% of the rated one) the standard deviation is at least 1000 times lower than the corresponding mean value (1.6 $10^{-5}$ with respect to 0.05). This holds for the all the three phases of the energy meter. As for the performance under different working conditions, for the sake of brevity only the analysis of the variations of the active power versus voltage, current, frequency and power factor are reported in the paper. In each of these analysis, the quantities that aren’t varied are kept constant to their rated values. Figures 3a to 3d graphically shown the above relationships for phase #1 and can be considered as a sort of calibration curves. From such figures, it can be learned that the performances seem very good as far as the variation of voltage, current and frequency is concerned. As for the power factor, it appears as the active power is slightly overestimated and that such a behaviour is more marked for lower power factor. This can be easily explained if a constant phase error occurs in the measurement of voltage and current phasors. In fact, according to the cosine function, a given difference between actual and estimated phase leads to variation of the cosine that gets higher as the angle gets wider. To numerically quantify the performances, the calibration curves of figures 3a, b and d are then linearized by applying a regression technique, which provides a straight line crossing the axes origin; this way it is possible to define the deviation of the calibration curve from the ideal characteristic by means of the well-known following indexes:

$$k = \frac{g - g_m}{g_m}$$ (1)

Figure 3. Calibration curves of active power vs. voltage (a), current (b), frequency (c) and power factor (d)
\[
\delta = \frac{\max(|y_i-gx_i|)}{y_{FS}} \tag{2}
\]

In (1), \(g\) is the angular coefficient of the best fit line \(y = gx\), which linearizes the calibration curve, whereas \(g_n\) is the slope of the ideal characteristic. In (2), \(y_i\) is the generic measurement of the EUT, whereas \(x_i\) denotes the reference measurement. In the end, \(y_{FS}\) refers to the maximum of \(y_i\). Let us refer to \(k\) and \(\delta\) as gain error and the non-linearity error, respectively. As for data in figure 3c, given that it is expected that the ideal curve is horizontal (and hence \(g_n=0\)), two different indexes are used:

\[
\alpha = \frac{1}{N} \sum_{i=1}^{N} (y_i - x_i) \tag{3}
\]

\[
\beta = \frac{\max(|y_i-x_i|)}{y_{FS}} \tag{4}
\]

where \(N\) is the number of measurements. The higher is \(\alpha\), the more biased are the measurements provided by the energy meter with respect to reference ones. The lower is \(\beta\), the lower is the difference between actual and reference measurements. Table 1 shows the value of the above indexes for the case depicted in figures 3a-d. Such numbers confirm the previous considerations: the measured active power exhibits a very good linearity vs. voltage, current and frequency. On the contrary, when the power factor is considered, the effect of a constant phase error makes such relationship non-linear. Very similar results hold for the other two phases.

5. Conclusions

The paper has presented the design and the performance of an energy meter developed for some European utilities to compare its measurements with the ones provided by energy meter installed by the customers. This is the aim of detecting illegal energy consumption. The main characteristics of the system are its high accuracy, its capability to be installed during network operation, the possibility to be both remotely and locally controlled via PLC and Bluetooth, respectively. Experimental results, aiming at verifying the metrological performance of the system, confirm that the abovementioned specifications have been successfully met by the developed system.

6. References

[1] Fluke Calibration, “Electrical Power Quality Calibrator” 6105A datasheet, Sept. 2009.
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