Energy meter behaviour under non-sinusoidal conditions

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Abstract. Currently, there are two energy meters types installed: electromechanicals and electronics. The first ones are still the most frequent. However, new facilities tend to use electronics energy meters based on solid-state technology. Electromechanicals devices present characteristics already well known that allows us to measure only energy consumption. However, now the rules that manage the energy supply are totally new, there is a competitive electricity market. This way, detailed information on the energy consumption of each client is needed. In this point, electronic meters seem to be the best option to face the new challenges. This study will review the operating principles of solid-state energy meters. The behavior of some three phases models under nonsinusoidal conditions is studied. Experimental setup and test methodology are discussed as well.

Key words

Energy measurement, power quality, power system harmonics, unbalance.

1. Introduction

The interest of the authors in the influence of power quality on energy meters began when a utility asked us to evaluate an active filter in order to decrease the harmonic distortion and obtain an almost sinusoidal waveform. The result was satisfactory since power quality levels were improved at this common coupling point (CCP). However, active filters inject harmonic power converted from the fundamental component, which increases the energy bill, [1]. Thus, the study of the effect of common disturbances on meters was considered.

Both classical electromechanical Ferraris and electronic meters have demonstrated that are accurate enough in common sinusoidal conditions so the continuity of electromechanical meters in the market is mainly based on:

- Long working life.
- Low price.
- High reliability.

From the point of view of cost, electronic energy meters are cheaper than electromechanical ones. However, it isn't clear how accurate they are under typical disturbances and non-sinusoidal conditions. It is also well known that these devices are rather sensitive to external conditions so there are many factors that can lead to their miscalibration.

This research work is focused on the analysis of electronic energy meters errors under the next non-ideal conditions:

- Harmonics.
- Unbalance.
- Frequency variations.

The advantages of these meters include greater stability and accuracy in comparison with the conventional ones (electromechanical). In addition, they generally have multiple functions. It is possible to check many others parameters related with the state of the net as, powers, voltages and currents of every phase. And what can be more interesting, they let to know the distortion level that exists in the system at this moment.

The paper includes a theoretical review of different technologies widely used in electronic meters: i) Time division; ii) Hall Sensor and iii) Digital sampling. After that, the paper introduces a test system and a methodology.

The hardware of the test system consists of a device able to generate the typical disturbances present in electrical systems, and a resistive load (wye connection). The energy meter under test is supplied by the arbitrary waveform generator in order to obtain their behaviour under non-ideal supply conditions.

Both the equipment and the methodology are put to the test with three commercial solid state energy meters based on different technologies. Among others, the most important results included in the paper are:

- Measurement error of solid state energy meters under active harmonic energy.
- Measurement error of solid state energy meters under unbalanced energy.
- Measurement error of solid state energy meters under variations of the nominal frequency.

2. Previous Works

There are some research works related with this field but it seems that there is only one previous reference dealing with unbalance, focusing on two real cases: an office building and a pumping station, [2]. This paper considers the error evolution in energy meters under a situation of unbalance over a wider range, from total balance to phase fault.

In [3], the effect of harmonic distortion on single-phase energy meters is studied. The responses of both electromechanical and digital meters are compared. Voltage and current harmonics in quadrature were applied and unexpected nonexistent energy was registered by the electromechanical devices.

Other works showed that the effects of harmonics on kVA demand meters are far greater than on watt-hour meters. kVA meters can exhibit very high errors. Problems with measuring apparent power under nonsinusoidal conditions originated quite often in the definition of the three-phase apparent power, [4].

A few more related studies have been published in this field, [5,6,7], but will not be commented here.

3. Related Equations

The main task of any electronic energy meter is the calculation of power. The definition of the active power P, considering periodic waves, in the temporal domain is:

$$P = \frac{1}{T}\int_T u(t)\, i(t) dt \qquad (1)$$

where u(t) is the instantaneous voltage, and i(t) the instantaneous current. The most general form, considering a frequency domain formulation, is [8]:

$$P = \sum_{n=0}^{N} U_n \;\; I_n \;\; \cos\phi_n = P_0 + P_1 + P_H \quad (2)$$

where U_n and I_n are the harmonic voltage and current respectively, and ϕ_n the phase shift between the previous magnitudes.

In a three-phase system, the energy meter should respond to the algebraic sum of active power of all the phases.

$$P = \sum_k P_k \qquad k = a,b,c \quad (3)$$

After the power calculation, it is necessary to integrate it to obtain the correspondent energy, w, consumed in period T.

$$w(t) = \int_0^t p(t)\, dt \qquad (4)$$

The components in equation (2) correspond to the active power due to the continuous component, P_0, the active power due to the fundamental frequency, P_1, and the sum of active powers of the rest of the harmonic frequencies, P_H, respectively. Harmonic signals can cause additional errors in the measurement of active power if the frequency response of the measurers is not good, especially in the case of old meters. The results of the tests performed will verify a quite reasonable behaviour of the solid-state meters, depending on their level of accuracy. Nevertheless, it is well known that electromechanical meters suffer great errors measuring active harmonic power.

On the other hand, on the residential level, P_H is often negligible because of its relatively low value. It is not practical to consider the harmonic error for this category of consumers. In other facilities, such as office buildings or industries, harmonic power may reach important values, even though the power components correspond to harmonics of low order which can be registered with meters with a low frequency response [8]. The additional error that can be attributed normally to harmonics is lower than 1%. At higher voltage levels, the magnitude of the harmonics is smaller due to the cancellation between harmonics with different angles from phase. In the case of near high power nonlinear loads, it is not possible to disregard the error.

It is debatable whether the active power should be measured according to its definition or not. Some authors argue that it would be interesting for energy distributors not to measure harmonic active power [9].

4. Measurement Principles

A. Time Division

Several electronic principles have been developed in order to multiply two signals. The multiplier with double modulation (TDM for time division multiplier) is classified as the most accurate and is widely used in precision wattmeters. The impulse signal is modulated in width according to the voltage and in amplitude according to the current, in such a way that the mean value of the impulse signal is proportional to the product of v and i. Also due to the rapid development of integrated electronic circuits, digital electronic circuits are challenging the known analog principles.

B. *Hall Sensor*

The Hall sensor is based on the physical principle of the Hall effect. This means that a voltage is generated transversely to the current flow direction in an electric conductor (the Hall voltage), if a magnetic field is applied perpendicularly to the conductor. The current flow will be proportional to the line voltage and the magnetic field will be proportional to the line current. As the Hall effect is most pronounced in semiconductors, the most suitable Hall element is a small platelet made of a semiconductor material.

Although the first meters based on this technology presented problems of linearity and stability, an important manufacturer developed a new model eliminating these disadvantages. The main feature of the new version is that the sensor is now sensitive to a magnetic field parallel to its surface, rather than perpendicular to it. A complete system with Hall element and associated electronics is included in an integrated circuit, delivering output pulses for the frequency, which is proportional to the power.

C. *Digital Sampling*

A solid state meter that incorporates a sampled data system obtains energy with a discrete summation instead of an integral:

$$W = \frac{\Delta t}{3.6x10^6} \sum_{i=1}^{N} P_i \qquad (5)$$

in kilowatt-hours (kWh), where Δt is the interval of time (seconds) and P_i the power in watts. The power is obtained from the multiplication of pairs of synchronous voltage-current samples taken at regular intervals. The summation of these products multiplied by the sampling interval gives a representation of the instantaneous energy. Common devices in this sort of implementation are analog-to-digital converters for each signal (voltage or current) and generally a microprocessor or DSP, to make calculations. After that, a display will show the result, fig 1.

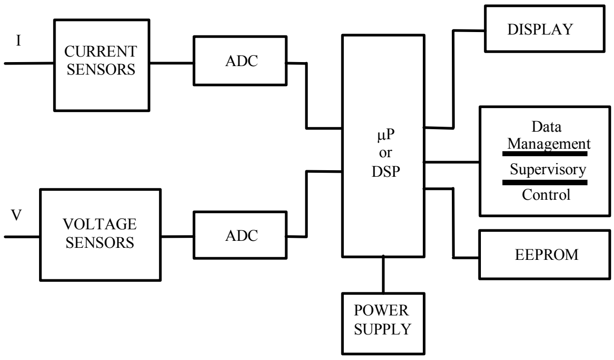

Fig. 1. Basic scheme of a digital sampling based energy meter.

5. Laboratory Setup

As can be seen in Fig. 2, the set-up consists of a device capable of generating the typical disturbances present in electrical systems, and a resistive load (wye connection). The energy meters to be tested will be inserted in this simple system. Their readings will be compared with the reference, thus obtaining the measurement error. The methodology used to test the energy meters is described below:

1) Program the AC Power Source to generate a particular waveform.
2) Configure the Reference Meter.
3) Set the Pulse Counter to zero.
4) Turn on/off the switch (I), at the beginning/end of the test, respectively.
5) Record results and make the corresponding error calculations.

Since our interest focuses on observing the behavior of modern energy meters under different disturbances, we will use a resistance as a load that translates the distorted voltage directly provided by the waveform generator to a proportional current with the same characteristics.

A. *Set-up Components*

Reference Meter: Accuracy <1% from 0 to 2.5 kHz. Sampling rate 6.4 kHZ at 50 Hz. 45-65 Hz (error<10ppm). It can measure 4 currents and 4 voltages or 8 voltages alternatively. Voltage probe 830 V, CAT III. Current probe 100 A/10A, CAT III.
Single phase Power Quality Analyser: Used in order to check parameters related to every phase.
Programmable AC Power source.(5 kVA per phase): Generates distorted waveforms.
Pulses counter: Registers the number of pulses from S0 outputs of static meters, [10].
Load: Three phase Resistor. 75 Ohms per phase. Wye connection.
Computers: Control Reference Meter. Control waveform generator.

B. *Features of the Meters used in the test*

Meter S1: Direct connected 2 tariff meter with integrated ripple control receiver. 3x230/400v. 5(80)A. cl.2. 50Hz. 2002. SO=100 imp/kWh. Operation principle: Hall effect.

Meter S2: Direct connected single tariff kWh meter. 3x230/400 V. 5(100)A. cl.2. 50Hz. 2002. SO=100 imp/kWh. Operation principle: Hall effect.

Meter S3: 3x230/400 V. 5(85) A. cl. 2. 50 Hz. 2003. SO=500 imp/kWh. Operation principle: Time Division Principle.

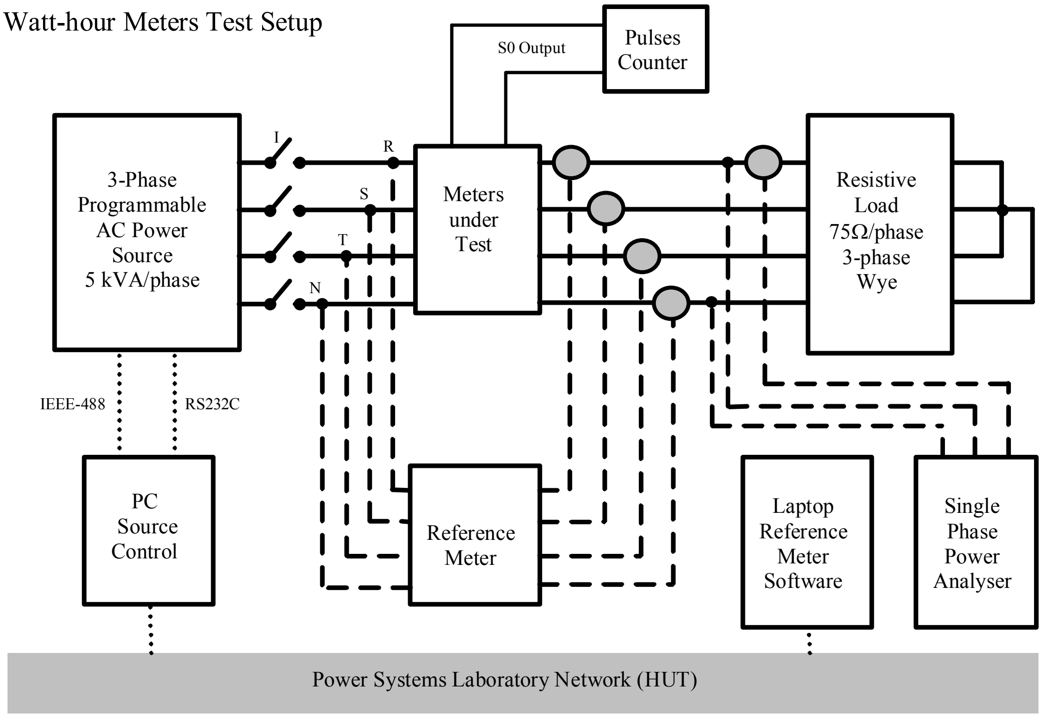

Fig. 2. Laboratory setup for testing three phases watt-hour meters.

6. Test Results

Some typical disturbances were injected into the load; harmonics, unbalance and variations of the nominal frequency. The tests lasted one hour in the case of solid state meters. The readings were obtained from S0 outputs using pulses counters, after which it was necessary to multiply the number of pulses by the corresponding constant of every meter.

A. Harmonics

The testing of the meters under harmonic energy was performed applying the fundamental frequency plus a single odd harmonic component. The meters were tested successively up to the 49th harmonic. The amplitude of these harmonic frequencies, with respect to the fundamental frequency, were as follows: 3(50%), 5(30%), 7(20%), 9(20%), 11(10%), 13(10%), 15(10%), 17(10%), 19(10%), 21(9%), 23(8%), 25(7%), 27(7%), 29(6%), 31(6%), 33(5%), 35(5%), 37(5%), 39(5%), 41(4%), 43(4%), 45(4%), 47(4%), 49(4%). In all cases the phase-shift was null.

Solid state meters offer a good performance in the conditions commented above (see Fig 3). It can be stated that their response is within a range of +0.5%. There are some exceptions, since during certain harmonics the three meters surpass this range, but considering that they are class 2, their operation is correct. Currently, commercial static energy meters have to be verified in an accuracy test under harmonics. The meter will have to register accurately, according to its class, electrical energy consisting of fundamental frequency and a fifth harmonic (10% in voltage and 40% in current), [11].

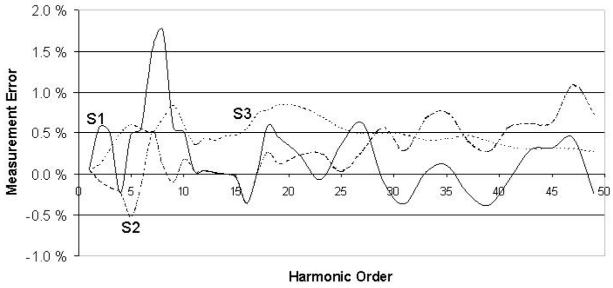

Fig. 3. Measurement error of solid state energy meters under active harmonic energy.

B. Unbalance

In this test, the reaction of energy meters under conditions of unbalance is explored. The test starts with perfect balance and then every step adds progressively a point of unbalance, until reaching V-/V+ = 100%, which corresponds to a single phase under voltage. The ratio of negative sequence voltage divided by positive sequence voltage is used to evaluate the degree of unbalance of the system.

Regarding solid state energy meters, their response is good enough under unbalance situations. Meters S1 and S2 show a maximum error around 0,5% for unbalance up to 14%, (see Fig. 4a). This maximum error increases up to approximately 1,6% when the degree of unbalance is greater, (see Fig 4b). Surprisingly, S3 is apparently insensitive to the unbalance, even in the extreme situation of 100%. According to the norm, [11], the error caused by voltage unbalance must be inferior to 4% for class 2 meters.

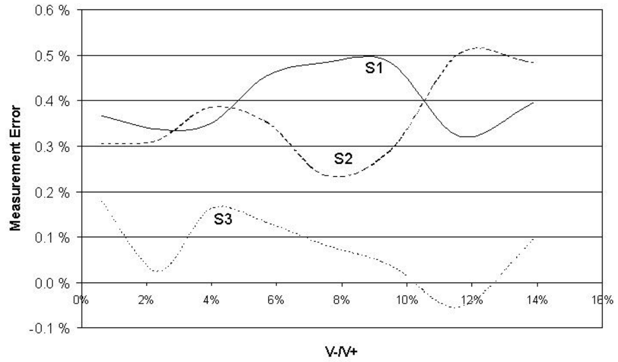

Fig. 4a. Measurement error of solid state energy meters under unbalanced energy.

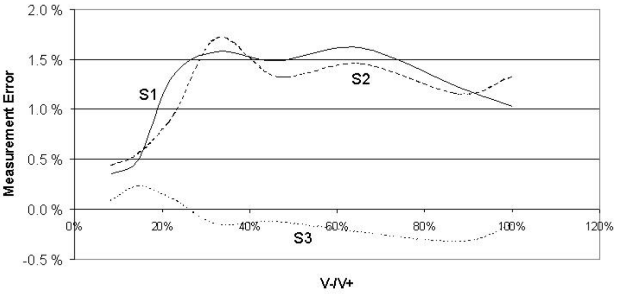

Fig. 4b. Measurement error of solid state energy meters under unbalanced energy.

C. Frequency

The sensitivity that energy meters show to variations in nominal frequency is studied in this test. The nominal frequency of all the tested meters is 50 Hz and the variation in the response of the meters ranges from 40 to 60 Hz.

It can be said, on observing the results of the tests on the electronic meters, (Fig 5), that the measurement error they exhibit under variations in the nominal frequency is minimal, and that their general performance is very good. The frequency response of these devices depends to a great extent on the frequency response of their filters. Poor tolerances of their components may induce phase errors that will become considerable measurement errors.

7. Conclusions

The energy calculation in the case of electronic meters is more stable since it is performed digitally. In contrast, due to all their mechanical and magnetic components, electromechanical meters are more prone to suffer errors due to the effects of the environment, usage and age.

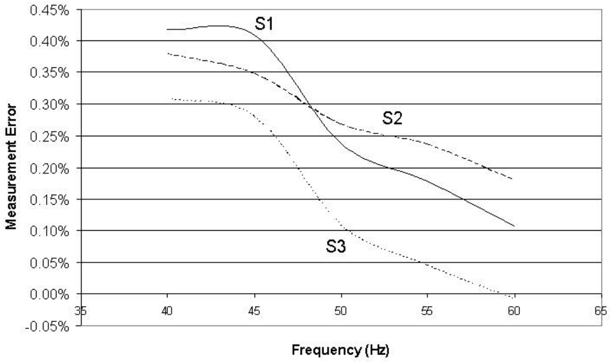

Fig. 5. Measurement error of solid state energy meters under variations in the nominal frequency.

Moreover, electronic meters offer greater flexibility of design and updating capacity. The reason for this is that the output is digital, which facilitates connection with communication devices. Allowing communication between the electronic meter and a base station makes remote reading possible, thus reducing costs. Load profiling, prepayment and multi-tariff billing are also made possible. Utilities will have more control over their capacity to provide energy to the network more efficiently. The power factor can be calculated, allowing generation companies to maintain a cleaner distributed energy in the network. At the same time, energy interruptions can be detected more quickly.

The advantages of solid state meters were confirmed by the above tests. However, one important point has yet to be discussed: the cost of substituting the widely used electromechanical meters with electronic ones. Our view is that it may be more expensive to remain faithful to a low accuracy technology with very limited possibilities. Under these conditions, a long life expectancy would seem to be of little value.

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