# The Registration of Harmonic Power by Analog and Digital Power Meters

Johan Driesen, *Member, IEEE*, Thierry Van Craenenbroeck, *Member, IEEE*,
and Daniel Van Dommelen, *Senior Member, IEEE*

***Abstract*— This paper discusses the measurement error of energy meters operating under harmonic distortion. A system to determine the magnitude of the error caused by an individual harmonic is used to generate curves on which the error introduced by different frequency components is displayed. An algorithm using these data to predict the resulting measurement error of a linearly operating energy meter registering under circumstances of any known harmonics in the voltage and the current is presented.**

***Index Terms*— Energy measurement, power measurement, power quality, power system harmonics, reactive energy.**

## I. INTRODUCTION

DURING recent years, there has been a growing interest in electric power quality. This can be explained partly by the widespread use of nonlinear (power) electronic equipment in the industrial environment and office buildings. The occurring power quality problems are harmonics, transients, sags, and many others. They cause unwanted effects like transformer overheating, overcurrents on neutral conductors and communications failures [1].

This paper focuses on a special effect caused by harmonic distortion in the current and in the supply voltage, namely registration errors in energy measurement devices in widespread use. This is an effect with a substantial economic impact especially when large quantities are interchanged.

## II. ENERGY METERS

The energy meters that are being used by electricity suppliers in Europe, can be divided into several types.

1) *Analog electromechanical meters:* The operation of these meters is based on the induction principle of Ferraris. Several millions of these devices are installed in Europe.
2) *Purely digital meters:* This type of meter samples the voltage and current signals and then calculates the energy quantity in a microprocessor.
3) *Mixed analog–digital meters*.

## III. REFERENCE QUANTITIES

Nowadays there is a lively discussion going on in the engineering world concerning power definitions in nonsinusoidal situations [2]. Currently, no general standard has been adopted regarding which power terms have to be integrated by energy meters.

Due to lack of space it is not possible to give an overview nor a discussion of all the proposals up to now.

### A. Active Power and Energy

Active power and active energy, have a clear physical meaning: they reflect the net power flow or energy transfer over the integration period

$$w(t) = \int_0^t p(t)\,dt = \int_0^t u(t)\cdot i(t)\,dt. \tag{1}$$

If the power flow is stationary and if only integer harmonics are involved, the power integral can be written as

$$P = P_1 + P_H = U_1 I_1 \cos\varphi_1 + \sum_{h>1}^{N} U_h I_h \cos\varphi_n. \tag{2}$$

This quantity, the total active power $P$, is measured in many energy meters.

The first term of (2), the fundamental active power $P_1$ is sometimes used too. The difference, the harmonic active power $P_H$ can be positive or negative and can amount up to a few percent of $P_1$ in the presence of severe harmonic loads on existing power grids.

### B. Reactive Power and Energy

The definition of reactive power in nonsinusoidal situations is still heavily debated. Even the physical meaning and the name of such a quantity in the presence of harmonics is at question [3].

Its is not the intention of the authors to interfere or to choose a side in this debate. Therefore no fixed choice is made for the definition of the reactive power and its integrated counterpart, the reactive energy.

It is appropriate to mention here that most meters have the following definitions implemented:

$$Q_1 = U_1 I_1 \sin\varphi_1 \tag{3}$$

$$Q_F = \sqrt{U_{\mathrm{rms}}^2 - I_{\mathrm{rms}}^2 - P^2}. \tag{4}$$

Manuscript received June 1, 1997; revised April 1, 1998.

The authors are with the Research Group ESAT/ELEN, Department of Electrical Engineering, Katholieke Universiteit Leuven (K.U. Leuven), Faculty of Applied Sciences, B-3001 Heverlee, Belgium (e-mail: johan.driesen@esat.kuleuven.ac.be).

Publisher Item Identifier S 0018-9456(98)05459-X.

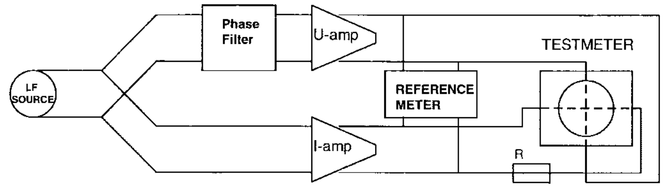

Fig. 1. Laboratory setup for testing single phase watt-hour meters.

$Q_1$ is the so-called fundamental reactive power, while $Q_F$ is known as the Fryze reactive power [2]. The numerical implementation of these formulae can differ.

## IV. LABORATORY TESTS

### A. Previously Published Tests

In the literature some tests have been published that discuss the performance of analog and digital metering equipment for the registration of active and reactive energy [4]–[8].

The results of [4] show that there can be a great difference between the performance of watt-hour meters based on different operating principles. In these tests, the actual waveforms recorded were used to determine the magnitude of the measurement error. Single-phase and three-phase meters were subjected to unbalances and harmonics. Errors up to $-10\%$ were registered.

In [5], the research was focused on reactive power meters. The major conclusion was that the definition selected to be the reference was the major source of the size of the calculated error. Relative errors ranging from $-41\%$ to $+68\%$ occurred when real-world waveforms were applied.

### B. Testing Method

In our research, other kinds of tests are performed: the devices are subject to signals consisting of a single controlled harmonic in voltage and current, sometimes mixed with a fundamental wave to investigate the linear operation of the device (Fig. 1).

In the first series of tests, an individual voltage and an individual current harmonic of the same order and in phase with each other are sent to the meter. These are supposed to make the active energy meters count, if the power definition of the total power is implemented, since they simulate the transfer of net active power at harmonic frequencies. The reactive energy meters should stand still.

In the second series of tests the same single voltage harmonic and single current harmonic are applied, but now their phases are in quadrature (phase difference of 90°). In this case, there may not be a registration action by the active energy meters since there is no net energy transfer remaining after an integration over at least one period of the signal.

## V. TEST RESULTS

### A. Active Power Meters

*1) The Registration of Active Harmonic Energy by Active Energy Meters:* At first, classical analog electromechanical meters, working according to the Ferraris principle (induction meters), are tested along with digital meters.

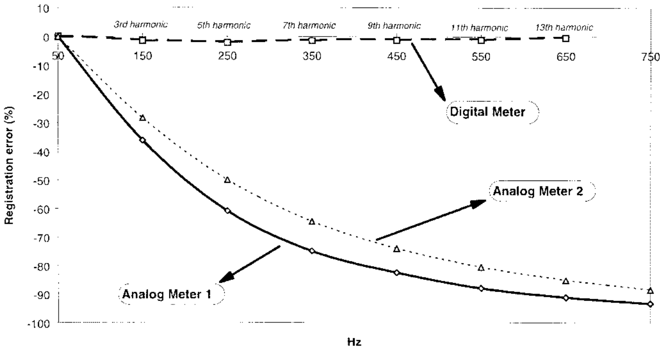

Fig. 2. Relative measurement error of active energy meters when supplied with active harmonic energy.

As expected, they both register the energy-transfer at 50 Hz correctly, but for the Ferraris based analog meter, the energy contained in the harmonics is taken into account with a rather huge error which increases with the order of the harmonic. The relative value of this error rises quickly (Fig. 2): for instance, for meter #1 at the third harmonic (= 150 Hz) the registered value is almost 40% less than the true value, whereas at the seventh harmonic (= 350 Hz) the error is already 80%.

This effect can be explained as follows: the magnetic flux driving the rotating disk inside the meter decreases in magnitude proportionally with the order of the harmonic, and hence the meter slows down at higher frequencies when constant power is drawn.

Meanwhile, the digital meters continue recording the active energy correctly at every frequency within their bandwidth which depends on their sampling rate.

This means that the energy registered by a lot of analog meters is neither the integration of $P$, harmonics included, nor the fundamental energy, the integration of $P_1$.

The digital meters usually integrate $P$ within their bandwidth.

*2) The Response of Active Energy Meters to Voltage and Current Harmonics in Quadrature:* The result of a second test can be called rather unexpected: an induction meter for active energy measurement sometimes registers active energy which is nonexistent.

This is shown in Fig. 3: to perform this measurement, a harmonic current and a harmonic voltage of the same order and a phase which differs 90° with the phase of the current was sent to the meter under test, both lagging and leading. According to the electrical laws, the meter should stand still since there is only "reactive" oscillating energy transfer and thus no net energy transfer, but the disc rotates and hence registers a "phantom energy."

This nonexistent quantity can amount up to a few percent of the product of the voltage harmonic with the current harmonic. The error created can be positive or negative, depending on the capacitive or inductive nature of the harmonic load.

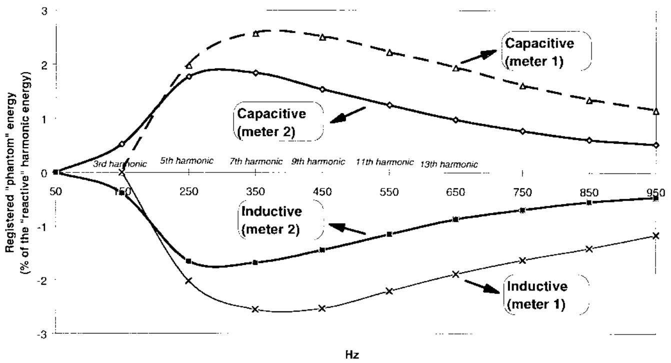

Fig. 3. Relative measurement error of Ferraris-based active energy meters when supplied with "reactive" harmonic energy.

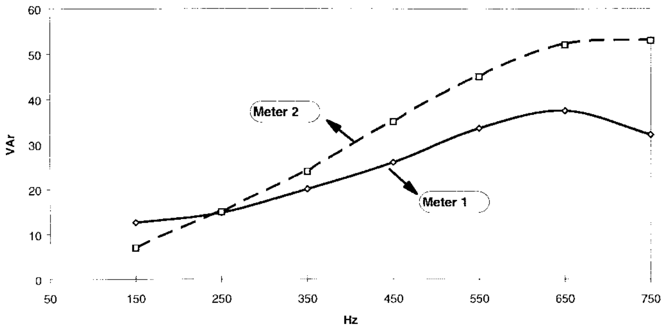

Fig. 4. Comparison of the registration of two (digital) reactive energy meters when supplied with harmonic "reactive" energy.

The explanation for this effect is more complicated: normally the Ferraris-based energy meters generate a torque on the rotating disk proportional to the active power. This is done by generating a flux proportional to the voltage which interacts with a flux proportional to the current. These fluxes have the same frequency as the applied voltage and current.

To generate a maximum electromagnetic torque when the voltage and the current are in phase, a mechanism is built-in which causes a phase difference of 90° between the fluxes. Hence, there is no torque when the signals are purely reactive.

This mechanism causes the measurement error: it is designed and calibrated to operate correctly at fundamental frequency. Therefore it may no longer be performing correctly at the harmonic frequencies. Thus a kind of nonexistent "phantom" active energy is registered.

Also in this situation, the digital meters keep on registering the harmonic energy correctly.

It may be clear that all these effects surely will have an influence on the electricity bill, which will show an amount that will become more uncertain as the distortion increases, depending on the type of meter used.

### B. Reactive Power Meters

It is not yet possible to perform similar tests for reactive energy meters as for active energy meters, since there is still no agreement on the definition of reactive energy in the presence of harmonics and therefore the reference base needed to determine the error is not present.

The only kind of tests that could show useful information are comparative tests. As an illustration, a result of one of those tests is shown in Fig. 4. In this particular test two digital meters which registered the energy by integration of $Q_F$ were compared. They were fed with the same single harmonic signals in quadrature, thus purely "reactive." As can be seen their registration differed.

Hence, it can be expected that extra measurement errors are also present in the results given by reactive energy meters working under harmonic distortion.

The reason for this kind of errors can be found in the numerical implementation of (4). For instance, different approximations are possible for a fast calculation of the square root.

## VI. PREDICTION OF MEASUREMENT ERRORS

### A. Principle

The above described measurements can be used to predict the measurement error for every set of current and voltage signals of which the spectrum is known, on the condition that the energy meters can be assumed to perform linearly at all harmonic frequencies of interest.

This is true since the (spectral) error characteristics for current and voltage components in phase and in quadrature are known for different harmonic frequencies. Theoretically, this is enough information to calculate a total error.

Using the spectral information of the voltage and the current (both amplitude and phase angle), the signals can be split into two sets of pairs of harmonics by performing a projection of the harmonic current phasors onto their voltage counterparts. The set hence obtained gives the magnitudes of the in-phase parts of the occurring voltage and current harmonics. The other set, consisting of the complements of the projection, gives the magnitudes of the parts in quadrature (see Fig. 5). The relative errors produced by the meter for every set of individual harmonics can then be transformed into absolute errors which must be added (this is allowed because of the linearity property) resulting in the total absolute measurement error. In this way the obtained results could be corrected when the characteristics of the load are known.

### B. Results

In nominal operation conditions, the meters behave linearly, which can be proven both theoretically and by means of practical tests. This method proves to work for simple artificially generated signals in the laboratory.

Tests on a real supply grid are subject of further research. For this kind of application, a fast and reliable measuring system has to be developed which is capable of performing an accurate calculation of the harmonic spectra of the voltage and the current.

## VII. CONCLUSIONS

In this paper, the results of extensive tests, performed to determine the effect of harmonic pollution on single-phase energy meters, are presented.

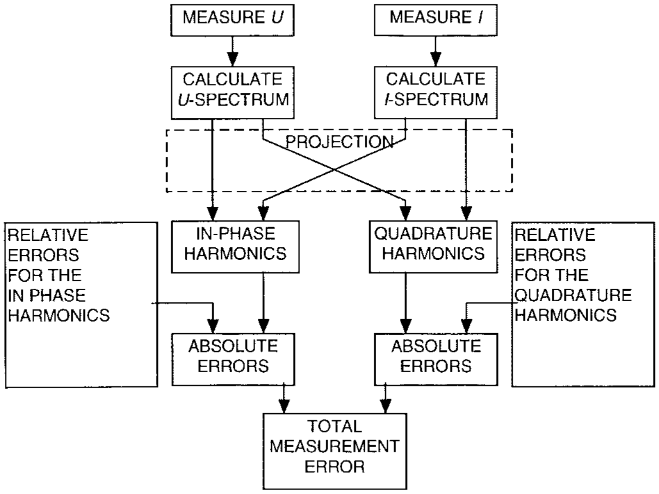

Fig. 5. Algorithm for the calculation of the measurement error when measuring a harmonic load.

Active energy meters of the electromechanical kind are subject to two error causing effects. First, a flux weakening causes a rather large negative relative error in the registration of active harmonic energy. An erroneous registration of nonexistent "phantom energy" occurs when voltage and current harmonics in quadrature are applied to the meter.

Digital meters are less subject to measurement errors as long as the signals are still compatible with the sampling process.

Comparative tests on meters which integrate reactive power are also conducted. Here the need for a standardized reference base is evidenced and calls for an urgent international agreement. The tests show a small registration difference between reactive energy meters which register according to the same power definition.

An algorithm to predict the measurement error when signals with a known harmonic content are applied to the (linear) meter is presented and discussed.

## REFERENCES

[1] IEEE Task Force on the Effects of Harmonics on Equipment (conv. V. E. Wagner), "Effects of harmonics on equipment," *IEEE Trans. Power Delivery,* vol. 8, Apr. 1993.
[2] IEEE Working Group on Nonsinusoidal Situations: Effects on Meter Performance and Definitions of Power (conv. A. E. Emanuel), "Practical definitions for powers in systems with nonsinusoidal waveform and unbalanced loads: A discussion," in 95 WM 040-6 PWRD, IEEE/PES Winter Meeting 1995.
[3] P. S. Filipski, "Apparent power—A misleading quantity in the nonsinusoidal power theory: Are all nonsinusoidal power theories doomed to fail?," *Eur. Trans. Elect. Power Eng.,* vol. 3, Jan./Feb. 1993.
[4] A. Domijan, E. Embriz-Santander, A. Gilani, G. Lamer, C. Stiles, and C. W. Williams, "Watthour meter accuracy under controlled unbalanced harmonic voltage and current conditions," *IEEE Trans. Power Delivery,* vol. 11, pp. 64–72, Jan. 1996.
[5] P. S. Filipski and P. W. Labaj, "Evaluation of reactive power meters in the presence of high harmonic distortion," *IEEE Trans. Power Delivery,* vol. 7, pp. 1793–1799, Oct. 1992.
[6] F. Tschappu, "Meßmethoden zur bestimmung des einflusses von netzoberwellen auf die messgenauigkeit der elektrizitätszähler, Teil I," Archiv für technisches Messen, Feb. 1968, pp. 33–36.
[7] ——, "Meßmethoden zur bestimmung des einflusses von netzoberwellen auf die messgenauigkeit der elektrizitätszähler, Teil II," Archiv für technisches Messen, Mar. 1968, pp. 53–58.
[8] G. Claus, "Der Einfluß von oberschwingungen auf die anzeigegenauigkeit von elektrizitätszählern," Archiv für technisches Messen, Apr. 1965, pp. 85–91.

**Johan Driesen** (S'94–M'96) graduated in 1996 as Electrotechnical Engineer from the Katholieke Universiteit Leuven (K.U. Leuven), Heverlee, Belgium, where he is pursuing the Ph.D. degree in electrical engineering.

Since 1996, he has been a Research Assistant of the Fund for Scientific Research of Flanders (F.W.O.-VI.). His research topics are the finite element solution of coupled thermal-electromagnetic problems and power quality issues.

Mr. Driesen received the 1996 R&D Award of the Belgian Royal Society of Electrotechnical Engineers (KBVE) for his master's thesis on the influence of power quality on energy measurement.

**Thierry Van Craenenbroeck** (M '95) received the electrotechnical engineer and Ph.D. degrees from the Katholieke Universiteit Leuven (K.U. Leuven), Heverlee, Belgium.

From 1990 to 1992, he was Lecturer at the Anton-de-Kom University of Surinam. Since 1992, he has been with K.U. Leuven, first as Assistant, and now as Postdoctoral Researcher. His research interests include nonlinear and transient phenomena in transmission and distribution networks and power quality related problems.

**Daniel Van Dommelen** (M'71–SM'78) graduated as an Electrotechnical Engineer from the Katholieke Universiteit Leuven (K.U. Leuven), Heverlee, Belgium, and received the M.Sc. degree in electrical engineering from the University of Wisconsin, Madison, and the Ph.D. degree from the K.U.Leuven.

Since 1977, he has been a Full Professor at K.U. Leuven and Head of the Laboratory for Power Systems, High Voltage, and Electroheat. He is teaching both undergraduate and graduate courses in these fields. He is author of a book on production, transmission, and distribution of electric power, presently in its fourth reprint, and author of numerous publications in both national and international journals.

Dr. Van Dommelen is Belgian representative in the Education and Research Committee of the UIE. He has been chairman of the IEEE Benelux Section, and is a member of IEEE Power Engineering Society, CIGRE, SEE, and national electrical engineering societies.