TECHNICAL ASPECTS OF REACTIVE ENERGY MEASUREMENT

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SUMMARY

The paper gives an image of the theoretical aspects of the reactive energy definition, and then compares different methods used by electronic meters to calculate reactive power. In order to get a better understanding of the differences involved with calculation method, a software simulator was build. The simulator can define a nonlinear regime up to the fifth harmonic by defining amplitude and phase. The reactive calculus is made according to usual methods build inside the meter. Short description of the simulator is presented in a dedicated paragraph. The result of the simulator is compared with measurement results obtained from real life conditions for a nonlinear customer.
Key words: **reactive energy, triangle method, non sinusoidal regime,**

INTRODUCTION

The reactive energy definition widely accepted today was, stated by Constantin Budeanu in the paper "Puisance reactive et fictive" in 1927. Because of increased efficiency, the number of nonlinear loads is continuously increasing. That makes the distribution network, more and more

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polluted by harmonics. Reactive energy measurement made using electronic meters in non sinusoidal condition depends on the algorithm used by internal software. Main factor of stress is the way meters calculate using distorted current and voltage curves. The number of electronic meters used for billing is increasing and that leads to the problem of reactive energy measurement. Doubtful results of reactive measurement leads to less effective management plans.

REACTIVE ENERGY CONSIDERATION

The reactive energy in an alternative current system is defined as the captive electrical energy exchanged continuously between the different electric and magnetic fields associated with the operation of the electrical system [6]. More practical definition we can get from IEEE 100 as expressed by equation (1) below:

$$Q = \sum_{n=1}^{\infty} VnIn\sin(\phi n) \tag{1}$$

Where the notation is:

- Q is the reactive power;
- V_n and I_n are the effective value of the n^{th} harmonic;
- φ_n is the phase difference between the current and the voltage of the harmonic component n;

Getting to the definition (1) is not an easy process. Table 1 presents some of the theories developed during the last century. Depending on application, the analysis of reactive energy is continuing even today.

Table 1 evolution of reactive energy concept

nb	year	Author	Theory	nb of phases			time duration	
				one	three	more	average	Short
1	1924	A. Iliovici	defines reactive power based on field theory	x				X
2	1926	A. Lienard	defines reactive power based on field theory	x				X
3	**1927**	**C Budeanu**	**puisance reactive et fictive**	**x**			**x**	
4	1931	S. Fryze	orthogonal current	x			x	
5	1985	L.S. Czarnecki	frequency domain theory	x			x	
6	1988	J.H.R. Enslin, J.D. Van Wyk	use of non periodical components	x			x	
7	1988	Ferrero	Park power		x			X
8	1992	J. L. Willems	multiple phase P-Q theory			x		X
9	1993	M Depenbrock	multi phase orthogonal currents			x	x	X
10	1994	L Rossetto, P. Tenti	short time orthogonal current components			x		X
11	1996	A. Nabae, T.	polar coodonates		x			X

nb	year	Author	Theory	nb of phases			time duration	
				one	three	more	average	Short
		Tanaka						
12	1996	F.Z. Peng, J.S. Lai	general theory of reactive power		x			X
13	2000	F.Z. Peng, L.M. Tolbert	not active power generalization	x	x	x	x	X

Table 2 presents some of the norms used for reactive energy meters. As could be seen, the oldest one dates from 1963 and is still active. It refers to electromechanical meters. The norm for static meters class 0,5 and 1 is not yet official being a discussion document. The plan of IEC is to revise the static reactive meters norms starting from 2011. Generally the norm applies only to newly manufactured static var-hour meters for measurement of alternating current electrical reactive energy in 50 Hz or 60 Hz networks. For practical reasons, standard are based on a conventional definition of reactive energy for sinusoidal currents and voltages containing the fundamental frequency only.

Table 2 Reactive energy measurement norms

Nb	Organization	standard code	standard title	issue date	Maintenance
1	IEC	60145	Var-hour (reactive energy) meters	1963	2011
2	IEC	62053-23	Electricity metering equipment (a.c.) - Particular requirements - Part 23: Static meters for reactive energy (classes 2 and 3)	2003	2012
3	IEC	62053-24	EPWI Electricity metering equipment (a.c.) -Particular requirements - Part 24: Static meters for reactive energy (classes 0,5 and 1)	under development	
4	CENELEC	EN 61268	Alternating Current Static VAR-Hour Meters for Reactive Energy (Classes 2 and 3)	1996	
5	CENELEC	EN 62053-23	Electricity metering equipment (a.c.) Particular requirements Part 23: Static meters for reactive energy (classes 2 and 3)	2003	

For instance the paragraph 3.1.1 of EN61268 defines the reactive energy but the definition has a note on the fact that the definition is used only in sinusoidal regime from practical reasons.

One of the good examples of the way reactive problem is treated for the moment is the result of OIML TC 12 and its Working Group meeting for the revision of R 46 *Electricity meters* document [1]. The meeting was held in Borås (Sweden) on 24–27 January 2005. The first Committee Draft (1 CD) was issued in the summer of 2004 and received a very large response with almost 800 comments from 18 countries. The number of attendees also confirmed the high level of interest in the work of TC 12: 23 delegates from 14 countries were present. The scope was also discussed and it was decided to concentrate efforts on having a standard for active

energy meters ready as soon as possible. **This means that all references and requirements for reactive energy meters and apparent energy meters were removed for the time being.** It was also decided to proceed with one document for all active meters, covering all accuracy classes, all technologies and all connections modes.
If we put things together, it seems there will be no change in the way static meters treat reactive energy, at least until 2011.

Reactive energy - theoretical aspects

Average active power is expressed by equation (2) as follows:

$$P = \frac{1}{T}\int_t u \cdot i dt \qquad (2)$$

Where *u* and *i* are *instantaneous* values of the voltage and current; T is the time duration of the period and P, is the average active power. In a real system, voltage and current are not pure sine values. In this case, considering voltage and current as periodic functions of time, we can develop the both of them in a Fourier series. In this case, the power is:

$$P = \sum_n UnIn\cos(\phi n) \qquad (3)$$

Where *n* is the rank of spectral line of the voltage or current and Φn is the phase shift between similar current/voltage spectral components. If current and voltage are sine waves, then equation (3) leads to a simplified form:

$$P = UI\cos(\phi) \qquad (4)$$

All these definitions are based on real life physical aspects. Active power could be transformed in mechanical or thermal energy and then measured. That's why equation (1)...(4) are not contested. When it comes to apparent (S) and reactive power (Q), there is no clear physical link to a real life phenomenon. These quantities are useful with sine waves of voltage and current. The reactive power is:

$$Q = UI\sin(\phi) = \sqrt{S^2 - P^2} \qquad (5)$$

And the apparent power:

$$S = UI = \sqrt{P^2 + Q^2} \qquad (6)$$

If the sine curve of the voltage and/or current is distorted, for the apparent energy, commonly accepted definition is:

$$S = UI \qquad (7)$$

Where U and I are root mean square values of voltage and current. This leads to:

$$S = \sqrt{\sum_n U_n^2 \sum_n I_n^2} \qquad (8)$$

For the reactive power similar to definition (3) we have:

$$Q = \sum_n U_n I_n \sin(\phi_n) \qquad (9)$$

This is Budeanu's definition from 1927 and at the moment is widely used since is accepted by ANSI and IEEE. Sometimes, in order to avoid confusion is noted Qb. The main problem with this definition is that the triangle of power is no longer valid. That's way Budeanu introduced another quantity, the deformant energy. The relation between deformant, apparent, active and reactive energy is:

$$D^2 = S^2 - P^2 - Q^2 \qquad (10)$$

Since there is no uniform physical support to reactive concept, we think a split in the way we think about it could be useful:

- for the relation of supplier/distributor with the client the reactive energy has to give a measure to supplemental losses determined by the non efficient way of consuming energy;
- for the customer, the way voltage is affected could be the point of interest.

We will all have to agree one way or another to a common approach to this subject.

CALCULATION METHOD

When it comes to static meters, different methods can be used to calculate the reactive power. The theoretical definition of the reactive power is difficult to implement in an electronic system at a reasonable cost. It requires a dedicated DSP to process the Hilbert transform necessary to get a constant phase shift of 90° at each frequency.

Method 1: Hilbert transform

For instance with AT73C500 chip we have such a development. Before multiplying the current and voltage samples AT73C500 performs a frequency independent 90 degree phase shift of the voltage signal. This is realized with a digital Hilbert transformation filter. The bandwidth of reactive power measurement is limited to 360 Hz [3]. Based on the active and reactive results apparent power and power factors are determined. RMS phase voltages are calculated by squaring and summing the voltage samples and finally taking a square root of the results. Current is determined by dividing apparent power result by corresponding phase voltage. Step by step calculation is:

- using current and voltage samples we calculate RMS values;
- active power is calculated using time domain definition;
- apparent power is calculated from RMS values;
- reactive power is calculated using relation (9), where the 90 degrees phase shift was build by a Hilbert transform filter.

This method is quite expensive to implement in a meter chip. Several solutions have been developed to overcome this limitation. They can be categorized in three groups:

Method 2: Power triangle

Equation (5) leads to this method of calculating reactive power The Power triangle method is based on the assumption that the three energies, apparent, active and reactive, form a right-angle triangle [7]. The reactive power can then be processed by estimating the active and apparent energies and applying:

$$kVAR = \sqrt{(kVA^2 - kW^2)} \quad (11)$$

Although this method gives excellent results with pure sinusoidal waveforms, noticeable errors appear in presence of harmonics [5]. Calculation step by step for this method is:

- using current and voltage samples we calculate RMS values;
- active power is calculated using time domain definition;
- apparent power is calculated from RMS values;
- reactive power is calculated using relation (11).

Method 3: Time delay

In an electronic DSP system, this method can be implemented by delaying the samples of one input by the number of samples representing a quarter-cycle of the fundamental frequency:

$$\textbf{Reactive energy=}\ 1/T\int_0^T v(t) * i(t + T/4)dt \quad (12)$$

This method presents drawbacks if the line frequency changes and the number of samples no longer represent a quarter-cycle of the fundamental frequency. Significant errors are then introduced to the results. One example of this type of calculation is given in [4]. Instantaneous power signals are generated by multiplying the current and voltage signals, for active power = V x I x Cos (ø) and for reactive power = V x I x Sin (ø). The power signals are continuously added to the respective energy registers. Positive power will be added to the energy register contents and negative energy will be subtracted. A time delay is introduced to shift one of the waveforms by 90° at the fundamental frequency and multiply the two waveforms: where T is the period of the fundamental. Calculation step by step for this method is:

- using current and voltage samples we calculate RMS values;
- active power is calculated using time domain definition;
- apparent power is calculated from RMS values;
- Reactive power is calculated using delayed voltage according to relation (12).

Method 4: Low-pass filter

A constant 90° phase shift over frequency with an attenuation of 20 dB/decade is introduced. This solution, which has been implemented by many chip producers, can be realized with a single pole low-pass filter on one channel input. If the cut-off frequency of the low pass filter is much lower than the fundamental frequency, this solution provides a 90° phase shift at any frequency higher than the fundamental frequency. It also attenuates these frequencies by 20 dB/decade. Similarly to method 3, this solution is susceptible to variations of the line frequency. However, a dynamic compensation of the gain attenuation with the line frequency can be achieved by evaluating the line period of the signal.

REACTIVE CALCULATION SIMULATOR

In order to study the way non sinusoidal regime affects the reactive energy calculated on different method, we've build a software simulator. The main screen of the simulator is presented in figure 1. The simulator is Excel based spreadsheet. It has four workbooks named: U panel, I panel, P panel and *centraliz*. First three workbooks build the voltage, current and power waveforms. The resolution of the waveforms builds is equivalent to a 50 KHz sampling rate with a 21 bit conversion resolution. The shape of the waveform could be configured by introducing values in a table defined inside *centraliz* workbook. Practical reasons limited the number of harmonics to the fifth. Every spectral line could be defined by amplitude and phase. When it comes to phase, the reference is the voltage for the A phase. Besides this, we can the prescribe RMS values for the fundamental component of the current and voltage. Another element of the simulator is the output data table. In this table we present:

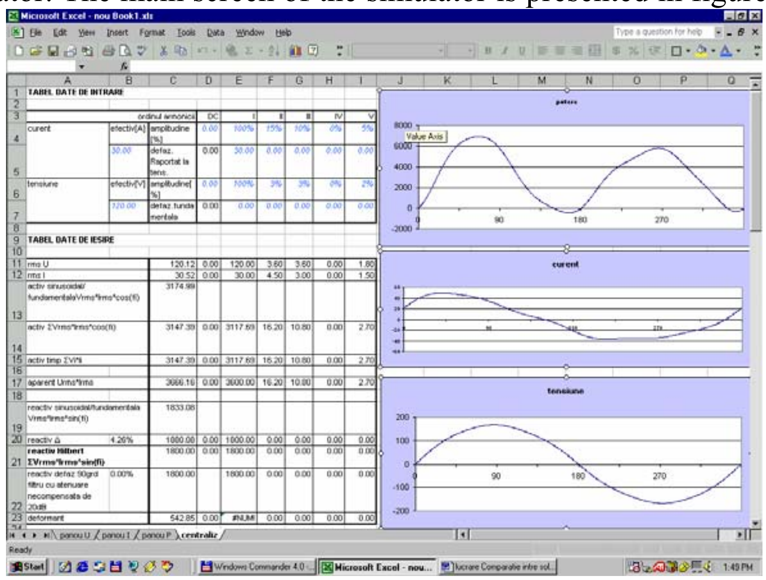

Figure 1 reactive energy simulator

- RMS values for voltage and current,
- active and reactive power according to sinusoidal regime definition,
- active power calculated in time and frequency domain;
- apparent power; reactive power calculated according to - IEEE definition using Hilbert transform; Triangle method; Filter method; Time delay method.

PRACTICAL RESULTS

In table 3 the results of two month measurements are presented. The consumer has two 11KW fixed consumption motors and three 7,5KW motors variable frequency controlled.

Table 3 energy registered by four meters at Calarasi PT 4 Braila

	active energy [KWh]	reactive energy [KVARh]
triangle method meter 1	7924	6042
triangle method meter 2	7922	6038
Hilbert transform	7933	2070
electromechanical meter		2120

As could be seen, the meters that use triangle method are registering almost three times more reactive energy. In order to explain this, we continued the investigation. First of all we analyzed the load profile for the meters involved. This is presented in figure 2. Then we analyzed the voltage and current waves. Relevant for this analysis is current and voltage wave spectrum presented in figure 3.

Figure 2 load profile for electronic meters

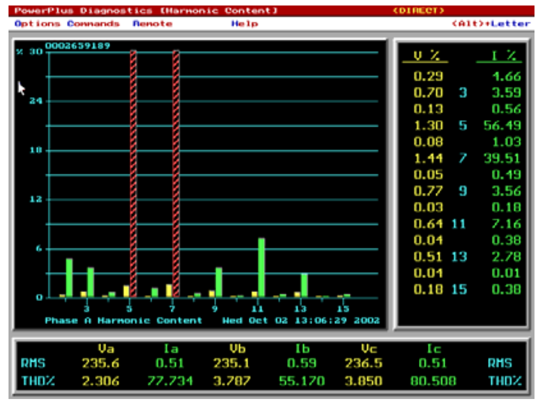

Figure 3 spectral analysis for voltage and current

Despite the fact results could be intriguing; by using the simulator we managed to explain the client that the differences are determined by the high THD value for current. Usually, the triangle method meters are adding the deformant energy to the reactive energy.

CONCLUSION

Reactive energy measurement is a complex problem. Getting to a commonly accepted definition of the reactive energy must balance between legal requirements and technical capabilities. Using triangle method must be completed by a current and voltage curve analysis.

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