

## **BEHAVIOUR OF REACTIVE ENERGY METERS IN POLLUTED POWER SYSTEMS**

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**Abstract:** The reactive energy meters used in electric distribution networks are based on a conventional definition of reactive energy (or power) for sinusoidal voltages and currents, containing only the fundamental frequency component. As a consequence, the performances of reactive energy meters in the presence of harmonic distortion are not tested and their accuracy specifications can be very different from the nominal ones, that are evaluated in sinusoidal conditions. In this paper the authors present a comparative study of the performances of different reactive energy meters, both electromechanical and static, in the presence of harmonic distortion; the study is supported by several simulations and experimental tests.

**Keywords:** energy measurement, reactive power, harmonics, static electricity meters.

### **1. INTRODUCTION**

In many countries, the electric energy billing is based not only upon the active energy consumption, but also upon the reactive energy demand. For example, in Italy customers have to pay an additional cost when the demand of reactive energy is greater than 50% of the active energy consumption.

The reactive electricity meters are based on the concept of reactive energy that is well defined for sinusoidal voltages and currents, containing only the fundamental frequency component. On the other hand, in the last years harmonic distortion in power systems has drastically increased, because of proliferation of non-linear loads, that draw non-sinusoidal currents. Thus, the reactive energy meters usually work in the presence of harmonic distortion and the evaluation of their performances in such conditions has become a very important target [1-4].

In the past, the traditional induction var-hour meters were used. These types of meters perform the measurement of the reactive energy related to the fundamental components of voltages and currents, even when harmonic components are present. Nowadays, the use of induction meters has been almost abandoned in the electric utilities while the static var-hour meters are preferred for their stability, accuracy and multi-function metering facilities. There are several types of static var-hour meters on the market, that are based on different construction principles. With respect to this, it has to be observed that in sinusoidal conditions, all the above mentioned solutions are equivalent and lead to the same

response of the meters. On the other hand, it is important to study the behaviour of the static meters when harmonics are present, because a different principle of construction could lead to a different penalization of customers, in terms of cost of energy, for the same working conditions. In literature an in depth comparison of static reactive energy meters based on different technical solutions was not performed until now. Moreover, with respect to the metrological characterization, it has to be observed that the international standards on static meters for reactive energy measurement define the requirements that these instruments have to comply with in sinusoidal conditions [5, 6]. The standards give the test conditions and the accuracy requirements that the meters have to satisfy when some influence quantities change with respect to reference sinusoidal conditions; these quantities are voltage variations, frequency variations, DC components in the current, etc; however, the harmonic distortion is not taken into account. Thus, the accuracy specifications of the energy meters, that are defined in sinusoidal conditions, lose their significance in the presence of harmonic distortion.

Therefore, the aim of this paper is to present a comparative analysis of the performances of different types of reactive energy meters in the presence of harmonic distortion. In the paper, firstly a brief overview of the available solutions for reactive energy meters is given, dedicating a particular attention to the solutions based on the implementation of the analytical expression of reactive power. Secondly, simulations and experimental tests were carried out, in order to analyze the behavior of the different reactive energy meters in the presence of harmonic distortion on voltage and current. In the paper, the obtained results are presented and discussed.

### **2. TECHNICAL SOLUTIONS FOR STATIC REACTIVE ENERGY METERS**

The reactive energy meters, for both single-phase and three-phase applications, can be mainly divided into electro-mechanic and static types.

The traditional electro-mechanic (inductive) types are realized with an induction watt-hour meter and an equipment for the displacement by 90° of the voltage; this can be an autotransformer or a RC circuit; for three-phase applications, the measurement of the reactive energy can be obtained from the active one, by means of a suitable connection of voltage terminals, based upon the relationship

between line-to-neutral and line-to-line voltages in symmetrical systems. The reactive energy measured by the inductive meters is close to the one related to the fundamental components of voltages and currents, even when harmonic components are present (see next section).

The modern static reactive energy meters have almost replaced the traditional electro-mechanic meters, thanks to their advantages as better stability and accuracy, multi-function metering facilities (for example the integration of both active and reactive energy measurements) and the possibility of the transmission of measured data by means of power line carriers or other data transmission technology. The solid-state meters available on the market are realized with several solutions. A first type of meters are realized by means of an analog or digital multiplication of current and voltage; the last one is shifted by  $90^\circ$  by means of an integrator circuit or by a time shifting of a quarter of a period. For three-phase applications, the measurement of the reactive energy can be obtained from the active one, as above mentioned. On the other hand, digital reactive meters, based on numerical conversion of voltage and current signals, can implement the mathematical definition of the reactive energy (or power).

With respect to the last solution, it has to be observed that, under sinusoidal conditions, the reactive power  $Q$  is univocally defined as well as the active power  $P$ , the apparent power  $S$  and the power factor  $PF$ ; for a single-phase system, with sinusoidal voltage and current, the above mentioned power quantities can be expressed as follows:

$$P = VI \cos \phi \quad (1)$$

$$Q = VI \sin \phi \quad (2)$$

$$S = VI = \sqrt{P^2 + Q^2} \quad (3)$$

$$PF = P/S = \cos \phi \quad (4)$$

where  $V$  and  $I$  are the rms values of voltage and current and  $\phi$  is their displacement.

Thus, the reactive energy measurement can be obtained by means of expressions (2) or (3). This is in accordance with the requirements of standard [6], that is referred to the ideal sinusoidal conditions, thus recalling the above-mentioned formulation for reactive power.

Unfortunately, in nonsinusoidal conditions the above-mentioned definition of the reactive power is not meaningful anymore [4]. The concept of reactive power (as well as that of apparent power) in nonsinusoidal situations has been widely discussed in literature; several power theories have been formulated in order to extend the well known concepts in sinusoidal conditions to systems with distorted voltages and currents. In brief, they can be mainly classified into time-domain and frequency-domain approaches [7].

The time domain approach is based on the concept of splitting the load current into two or more components, that are meant to be responsible for different energy phenomena. The most general time-domain power theory is due to *Fryze*. Its approach is essentially based on the separation of the

current  $i$  into two components; the first one, namely the “active” current  $i_a$ , is in phase with the voltage and has the same waveform, the second one, namely the “nonactive” or “reactive” current,  $i_r = i - i_a$  is the remaining part of the current. Starting from this approach, the apparent power can be divided into active and reactive power, (like in the sinusoidal case) and the reactive power  $Q_F$  can be expressed as follows:

$$Q_F = VI_r = \sqrt{S^2 - P^2} \quad (5)$$

where  $V$  and  $I_r$  are respectively the rms values of the voltage and the nonactive current,  $S$  is the apparent power and  $P$  is the active power.

On the other hand, the first power theory in the frequency-domain was formulated by *Budeanu*: it is based on the assumption that in nonsinusoidal situations, a power system can be ideally decomposed into a number of elementary sinusoidal systems, each one corresponding to a singular harmonic of the spectrum of the voltage or of the current. In this sense for each elementary sinusoidal system, the traditional electrical quantities can be defined (rms values of voltage and current, active, reactive and apparent powers and power factor). According to this, the reactive power  $Q_B$  is defined as the sum of the reactive powers related to each harmonic [4, 7].

Starting from the *Fryze* and *Budeanu* approaches, other power theories have been developed and different definitions of reactive power have been formulated in literature (*Kusters-Moore*, *Page*, *Shepherd-Zakikhani*, *Sharon*, *Czarnecki*, etc) [4, 7].

The attempt of most of these theories was to extend to the distorted systems the properties of the reactive power in sinusoidal conditions. However it was demonstrated that these properties cannot be extended to the nonsinusoidal conditions. Thus, some of the proposed definitions have been strongly criticized from the physical point of view. As a consequence, this matter is still actively discussed and there is not yet a generalized power theory that can be assumed as a common base for power quality evaluation, harmonic sources detection and compensation in power systems.

In 2000 the IEEE Std 1459 was published, which provides a set of definitions for the definition and measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced or unbalanced conditions [8]. The key concept for apparent power resolution is the separation of the fundamental components of voltages and currents from all other components, that are detrimental. This allows one to perform a measurement of the traditional billing quantities, now defined as the fundamental active, reactive and apparent powers, and power factor. In this sense, the suggested quantity for billing purposes is meant to be the fundamental reactive power  $Q_I$ :

$$Q_I = V_1 I_1 \sin \phi_1 \quad (6)$$

where  $V_1$  and  $I_1$  are the rms values of the fundamental components of voltage and current and  $\phi_1$  is their displacement. In the three-phase case, the fundamental positive sequence components are considered. The IEEE

Std. 1459 do not give a specific definition of reactive power in nonsinusoidal conditions; on the other hand, it introduces some other components of apparent power, apart from the fundamental ones, that are meant to be used to assess the harmonic pollution level at the metering section.

### 3. THE BEHAVIOR OF REACTIVE ENERGY METERS IN DISTORTED CONDITIONS

In order to analyze the behavior of the different reactive energy meters in the presence of harmonic distortion on voltage and current, firstly simulations were carried out. Secondly experimental tests, by means of a power calibrator, were developed.

#### 3.1. Simulations

The different solutions for the measurement of the reactive power and energy were implemented on a computer, programmed through the software package SIMULINK<sup>®</sup> of MATLAB<sup>®</sup>. More in detail, the operation of the following var-hour meters were simulated: two static meters, with three and two elements, whose reactive energy measurement is obtained by means of the artificial connection of voltage terminals; two static meters, with 90° shifting of voltage signals, obtained by means of an integrator circuit and by a time shifting of a quarter of period; two traditional induction meters, with two and three moving elements. Moreover, the various definitions for the reactive power were also implemented, in order to make a comparison with the readings of the above mentioned meters. In this sense, particular attention was dedicated to the Fryze's definition (5); in fact, the choice of this formula for the digital implementation of a var-hour meter is the most reasonable, from the technical and economical point of view, as it is the simplest to be implemented.

The measurements were performed on a test power system, implemented by means of the software package POWER SYSTEM BLOCKSET<sup>®</sup> of MATLAB<sup>®</sup>. The test system was realized with: a three phase symmetrical voltage supply, either sinusoidal or distorted with a known harmonic content; a linear and balanced load (resistive-inductive load) a non linear and balanced load (a diode bridge rectifier feeding a dc load) [7]. Simulations were carried out for different cases, with both sinusoidal and distorted supply and both linear and non linear load. For a better understanding, the results are all expressed in terms of reactive power.

The obtained results show that, in sinusoidal conditions, the behavior of the static reactive meters is analogous to the one of the traditional inductive meters. In particular, all the above-mentioned definitions for the reactive power are equivalent and lead to compatible results. As a consequence, manufacturers are allowed to use one of the above mentioned solutions for the construction of the reactive energy meters. In fact, this is in total agreement with the in force Standards [5-6], that consider only the sinusoidal situation.

On the other hand, when harmonic distortion is present, the behavior of the meters changes. For example, in figures 1a and 1b two cases are reported that are referred to the following working conditions:

- a distorted three phase symmetrical voltage supply and a linear and balanced load;
- a distorted three phase symmetrical voltage supply and a non linear and balanced load.

In both test conditions, the traditional induction var-hour meters measure a reactive power that is almost equal to the one related to the fundamental components of voltages and currents, because of their intrinsic filtering characteristics. Similarly, the static meters based on artificial connections of voltage terminals and on 90° shifting of voltage signals, measure approximately the fundamental reactive power. On the other hand, the meter where the formula (5) is implemented measures a reactive energy that is greater than the fundamental component; the difference with the fundamental reactive power is more significant when the harmonic distortion arise on voltage and current and when the non linearity of the load is stronger [7]. Finally, the comparison with the other reactive powers calculations shows how the different implementations for reactive power calculation would lead to different responses of the meters.

Moreover, the standards do not define any reference conditions for the characterization of the energy meters under nonsinusoidal conditions. As a consequence, the actual test conditions reported in [5-6] cannot allow one to identify the operation principle or the reactive power definition used for the construction of the meters under test. On the contrary, some significant test conditions should be provided, with defined harmonic content in both voltages and currents, in order to better understand the behavior of the var-hour meters in the presence of distorted signals.

In this sense it must be underlined that in the old Standard EN 61268 [9] (substituted by [5] and withdrawn on March 2006) harmonic distortion was included among the influence quantities that were considered for the tests on the accuracy of the var-hour meters. More in detail, a test condition with a 10% of third harmonic in the current was defined. This kind of test was suppressed in [5]. Probably, the reason for this choice deals with the problematic issue of the definition of the concept of reactive power in nonsinusoidal conditions; however, it has created a gap in the Standards, that, from the point of view of the authors, should be filled.

#### 3.2. Experimental tests

The experimental tests were carried out on a commercial static reactive energy meter by means of a power calibrator Fluke Electric Power Standard 6100A. Moreover, two "virtual" meters, implementing a static meter with an integrator circuit and with a time shifting of a quarter of period were simulated using the same voltage and current generated by the calibrator. For sake of simplicity, the results are all expressed in terms of reactive power. The realized test bench is reported in figure 2.

The harmonic content of voltages and currents were chosen in accordance with Standards EN 50160 [10] and IEC 61000-3-2 [11]. In Table 1 the test conditions are reported; they are synthesized in terms of total harmonic distortion factors (THD), for both voltages and currents;  $\phi$  represents the displacement angle between the fundamental components of voltage and current (resistive-inductive

load); the phase angles of harmonic components of voltages and currents were chosen according to the example A1 reported in [8]. In the case a) of Table 1, both voltage and current THD factors were maintained constant; in the cases b) and c), the variations of the current THD factor were due to the limits imposed by [11] for the amplitudes of the different harmonics.

Finally, a comparison of the measured results was performed with the reactive powers obtained by means of the definitions by Fryze, Budeanu, Kusters-Moore, Shepherd-Zakikani, and Sharon, which are calculated by the power calibrator itself.

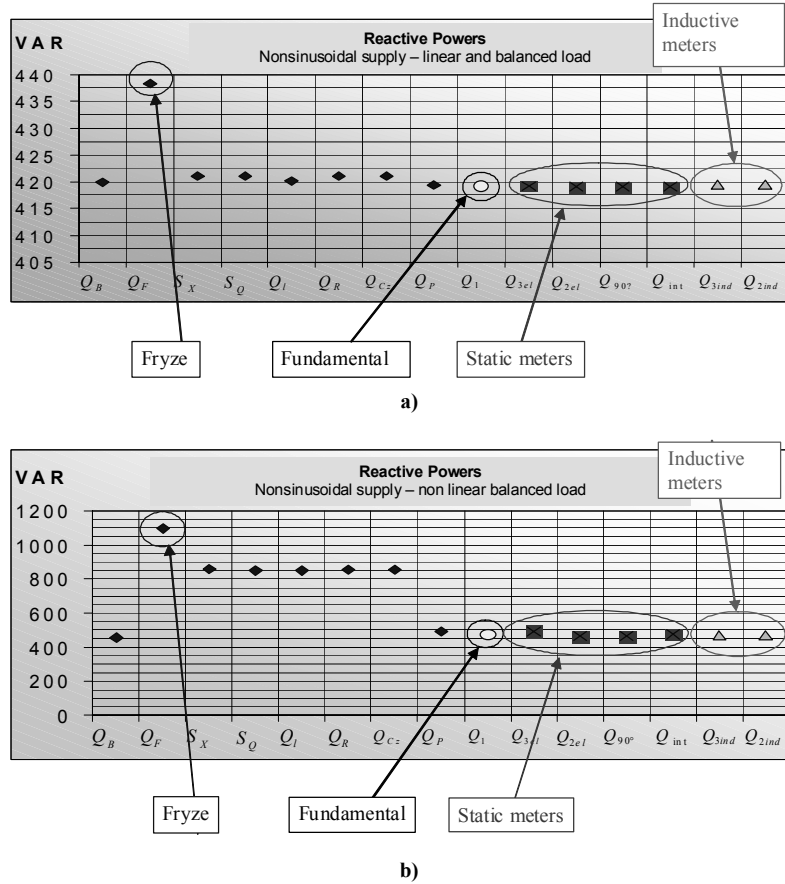


Fig. 1. Simulation results – a) nonsinusoidal supply, linear load; b) nonsinusoidal supply, non linear load

Keys:  $Q_B$  = Reactive power by Budeanu,  $Q_F$  = Reactive power by Fryze,  $S_X$  = True Reactive Power by Shepherd-Zakikani,  $S_Q$  = Quadrature Reactive Power by Sharon,  $Q_I$  = Reactive power by Kusters, Moore e Page,  $Q_R$  = Reactive power by Emanuel,  $Q_{Cz}$  = Reactive power by Czarnecki,  $Q_P$  = Park's Imaginary power (medium value),  $Q_I$  = Fundamental reactive power (IEEE Std 1459),  $Q_{3el}$  = Reactive power measured by a static reactive energy meter with artificial voltage terminals connection – three elements,  $Q_{2el}$  = Reactive power measured with a static reactive energy meter with artificial voltage terminals connection – two elements,  $Q_{90^\circ}$  = Reactive power measured with a static reactive energy meter with voltage time shifting of a quarter of period,  $Q_{int}$  = Reactive power measured with a static reactive energy meter with voltage shifting by means of integrator circuit,  $Q_{3ind}$  = Reactive power measured with a induction reactive energy meter with three elements,  $Q_{2ind}$  = Reactive power measured with a induction reactive energy meter with two elements.

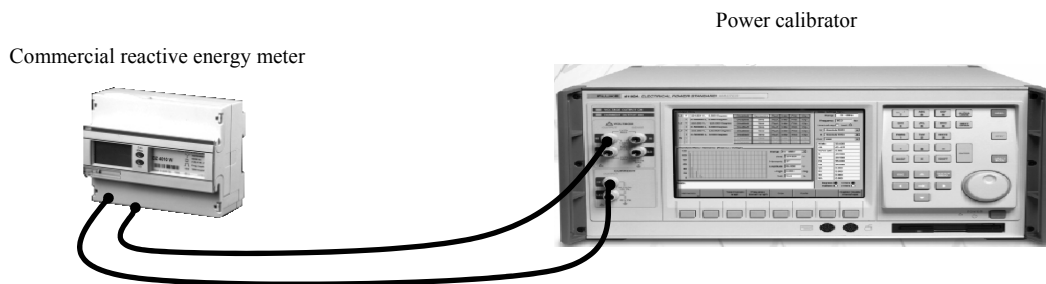


Fig. 2 Test bench

Table 1. Test conditions.

Voltage and current harmonic content (EN 50160 and EN 61000-3-2)	sen $\phi$	THDv%	THDi%
Case a) odd harmonics not multiple of 3 <sup>th</sup> order	1	7,9	13,9
	0,5		
	0,25		
Case b) odd harmonics multiple of 3 <sup>th</sup> order	1	5,3	6,6
	0,5		25,9
	0,25		29,05
Case c) odd and even harmonics up to 24 <sup>th</sup> order	1	7,9	17,3
	0,5		31,2
	0,25		33,8

The comparison was made with respect to the following parameter:

$$\Delta Q_j \% = \frac{Q_j - Q_1}{Q_1} \cdot 100, \quad (7)$$

where  $Q_j$  was the measured reactive power and  $Q_1$  was the fundamental reactive power. The parameter  $\Delta Q_j \%$  was defined starting from the definition of the “percentage error” reported in [6] and [9]. This parameter is significant because it is referred to the fundamental reactive power that represents, in terms of energy, the only quantity presently defined in the standards. Moreover, it allows one to make a comparison with the traditional inductive meters; in fact, in practical terms, it represents the percentage difference between the reactive power measured by the static meter and the reactive power measured by an inductive meter (that is close to the fundamental one, even in the presence of harmonics). The experimental results are reported in figure 3; they show that the reading of the commercial energy meter is very close to the one obtained by means of the *Fryze* definition and the related values of  $\Delta Q_j \%$  are high; on the contrary, the values of  $\Delta Q_j \%$  obtained from the meters with the integrator circuit and the time delay are small, thus their readings are close to the value of the fundamental reactive power, even in presence of harmonics, and their behavior is similar to the one of the traditional induction meters. This is in accordance with the results obtained during the simulation tests. At the light of the obtained results, the commercial meter under test seems to implement the formula (5) (i. e. the *Fryze*'s reactive power definition), but the manufacturer do not declare the operating principle of the instrument. Therefore, as shown by both the simulations and the experimental tests, a meter that implements *Fryze*'s reactive power definition measure a reactive energy that can be significantly greater than the one measured with other meters based on different technical solutions. Thus the customer would be differently penalized, as example in case of a distorted three phase symmetrical voltage supply and a linear and balanced load shown in Fig. 1a, depending on the type of static meters used.

#### 4. CONCLUSIONS

This paper presents a comparative analysis of different types of reactive energy meters in presence of harmonic

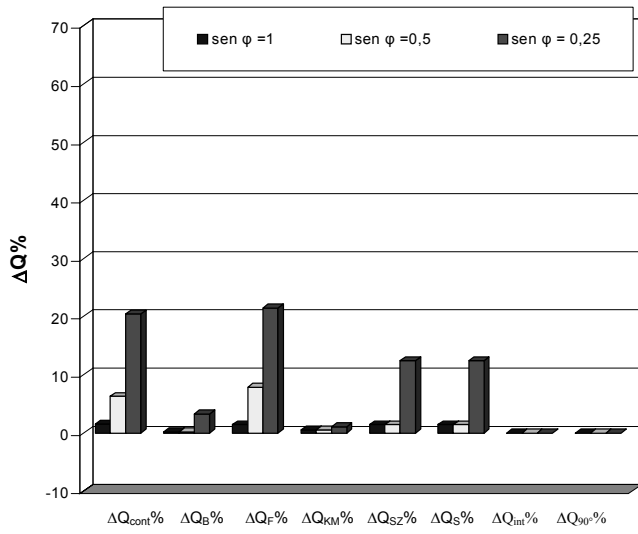
distortion. The study is supported by several simulations and experimental tests on a commercial static varhour meter and on other virtual meters, implementing different technical solutions for reactive energy measurement.

The obtained results show that the use of different technical solutions for the development of reactive energy meters can lead to a different penalization of customers, for the same working conditions, in case of polluted power systems. Thus, the manufacturers should always specify the principle of construction of the meter, in order to assess which quantity they measure in the presence of harmonics.

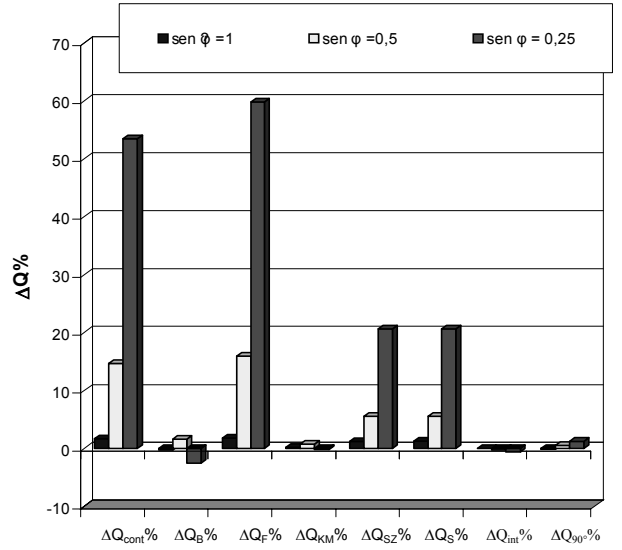
On the other hand, it is necessary to define the test conditions for the characterization of the performance of the meters in presence of harmonic distortion.

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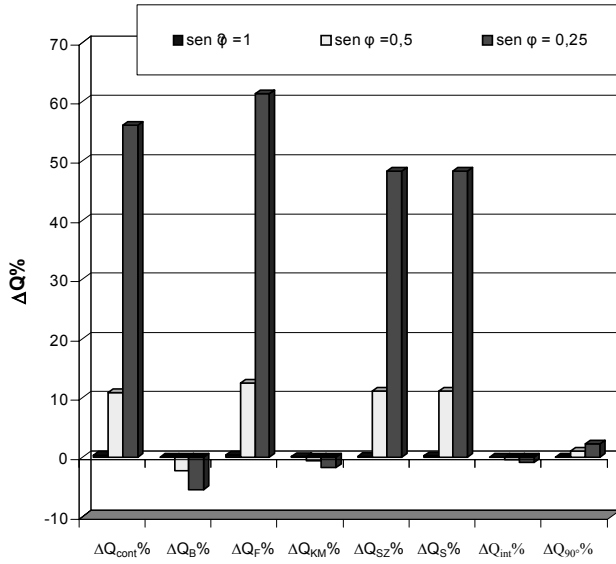
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a)



b)



c)

keys:  
 $\phi$  = displacement angle between the fundamental components of voltage and current .  
 cem = commercial static reactive energy meter,  
 B = Budeanu,  
 F = Fryze,  
 KM = Kusters-Moore,  
 SZ = Shepherd-Zakikani,  
 SH = Sharon,  
 in = reactive energy meter with integrator,  
 T/4 = reactive energy meter with time delay (T/4)

Fig. 4. Experimental results.

a) odd harmonics not multiple of 3<sup>th</sup> order; b) odd harmonics multiple of 3<sup>th</sup> order; c) odd and even harmonics up to 24<sup>th</sup> order