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# UTILITY NEEDS SMARTER POWER METERS IN ORDER TO REDUCE ECONOMIC LOSSES

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**Abstract**. *Whenever the delivered power is greater than the sum of the registered power at points of common coupling (PCC) the utility will have losses. This paper will show that even in an ideal case, without any abuse of users, the losses occur due to inadequate measurement equipment and to deficient billing policy. Namely, common household power meters register only active energy, while power meters for industrial applications register reactive energy as well. Consequently, the billing policy is based only at one or both values. This approach does not follow the change of the end-user load profile that becomes very nonlinear. Actually, the current trough nonlinear load deviates from sine waveform causing that a part of the delivered power remains invisible for the power distribution system. Therefore, the utility registers significant economic losses. To solve this problem we recommend distortion power to be measured and included into the billing policy. It has not been the case so far because the electric power community has not been aware of the amount of the distortion power in the contemporary grid. Besides, power meters have not been able to measure it. This paper demonstrates how to overcome the obstacle with a minor modification of ordinary electronic power meters. The proposed solution is verified by a set of measurements on different types of loads that are commonly used in households and offices.*

**Key words**: *Electronic meters, harmonics, distortion power, utility losses.*

## 1. INTRODUCTION

One of the main demands facing modern human society is reducing power consumption, or using energy in a more efficient way. Electronics responded to this request with high efficiency appliances that consume less power. However, the battle for every watt at consumer's side is useless if it is not supported at the utility side. The recent researches published in [1, 2] show that the annual value of transmission and distribution losses reaches up to 6% of the total generated energy (2% for transmission and 4% for distribution losses). That represents about 7 billion Euros losses every year. This number includes losses that occur in the medium and low voltage lines and in primary and

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secondary substation. Many countries have brought the law that demands from utility to reduce the losses for 1.5% each year [3].

These losses can be classified as *technical losses* and *non-technical losses*. The technical losses occur due to dissipation on electricity system component (transformers, transmission and distributed lines and measurement system). Therefore, it represents physical losses. Non-technical losses refer to the energy delivered and consumed, but for some reason not recorded as sales, measuring and billing. In order to reduce the level of losses at a power grid, many different approaches exist, some of which are published in [3]. According to Schneider Electric about 90% of non-technical losses occur in the medium and low voltage (MV/LV) grid. It is assumed that they range between 1.000€ to 10.000€ per MV/LV substation per year in European countries [3]. This brought MV/LV grid at the top of the priorities for loss reduction.

The first step in cutting the losses is to monitor and to detect their sources. This request was hardly feasible and very expensive in the past. Fortunately, that is not the case today. Smart meters give inexpensive and precise insight into the current status of particular parameters of the grid. They allow the utility to measure many parameters that define quality of the delivered electric power. Unfortunately, due to the inertia of the acceptance of facts, some decisions affecting the power system are not timely made.

The most obvious misconception is related to understanding the character of consumers connected to the electricity grid. The standpoint of the power grid measurement theory assumes that all loads are entirely linear resistive or reactive. This implies that the current follows voltage sine waveform (with possible phase lead or lag at reactive loads). In general, for centuries the loads in households were basically resistive (heaters, incandescent light) while in industry they usually have large inductive character (AC motors). Consequently, it was sufficient that power meters register only active power in households and/or reactive power with industrial customers. However, the character of loads has been drastically changed since the last quarter of the 20$^{th}$ century. One of the biggest European utility Enel S.p.A. corporation (Ente Nazionale per l'Energiae Lettrica; www.enel.com) located the problem of losses related to the changed load profile. Therefore, they included reactive energy into the billing policy for households. As a result, they have replaced more than 20 million household electric power meters with upgraded electronic power meters capable to measure both active and reactive energy [4]. In this way the losses were lowered, but not completely eliminated.

We will show in this paper that the main source of losses caused by consumers at a contemporary grid is not due to the unregistered reactive power. As was presented in some earlier papers [5, 6, 7] and as will be presented here on some other examples, the main source of losses is due to the non-registered distortion power. We prove that distortion power has the same order of magnitude as active power at most contemporary power-saving electronic devices. Being unregistered in the system it appears as a 'phantom' part of the delivered power that utility sees as a loss. Therefore, we suggest introducing distortion power into billing policy in order to reduce the losses. However, in order to do so, we need a simple and reliable way to quantify it. We claim that there is an unsophisticated and consequently a smart way to enhance features of electronic power meters with the option to register distortion power. Consequently, that new feature will make the existing smart meters to be smarter.

This paper is organized as follows. The next section will contemplate the nature of loads at the contemporary power grid. The third section gives a survey trough historical development of power meters and presents a theory of operation behind the contemporary power meters. The consequent section gives solution how to upgrade the meters and billing policy in order to reduce economic losses at utility. The fifth section presents results measured using the suggested upgrade. It proves that the main cause of losses does not come from reactive but from distortion part of power. The final section concludes the paper analyzing results obtained by measurement on different type of loads that are commonly used in households and offices.

## 2. NATURE OF LOADS AT CONTEMPORARY POWER GRID

The orientation towards energy efficient electronic devices caused that transistors within most of consumer's electronics operate in a switching mode. For the power grid they represent nonlinear loads. At the beginning of the energy saving era their nominal power was low, so they did not jeopardize the operation of the utility. The requests for energy efficiency rapidly increased the number of such gadgets connected to the grid. Therefore, the community is faced with the fact that the total load becomes mostly nonlinear.

At a nonlinear load the current waveform is distorted in comparison with voltage due to the presence of higher order harmonics. Let us assume that the grid is supplied from an ideal voltage source with zero resistivity. Then voltage will retain the basic frequency of $f_1$=50Hz (60Hz) and current will have harmonic components at frequencies of $f_n= nf_1$, $n$=2, 3... Active power will appear only at $f_1$. Therefore, the power meters capable to measure only active power will not register power caused by all other components of current. As any other unregistered power, this causes economic losses at the utility side. The losses increase with the rise of nonlinearity. Moreover, knowing that resistance of transmission lines is not zero, it is obvious that harmonics of current will introduce harmonics into grid voltage as well. The existence of harmonics within voltage and current additionally complicates measuring of active, reactive and apparent power established on linear loaded grid model. In reality, the harmonics contribute to active and reactive power with less than 3% of the total active or reactive power [8].

The main contribution of harmonics reflects trough additional component of power that is known as *distortion* power. Unfortunately standard power meters, including modern smart meters, do not register this component. Accordingly, utilities suffer huge losses. As we, and other authors, proved by measuring [5], [6], [7], this component of power cannot be neglected. In addition, harmonics will produce indirect losses to the utility due to malfunction in other power grid equipment [9], [10]. We claim that it is necessary to upgrade the meters with the possibility to register all components of power. Otherwise the end users will not take care about the level of nonlinearity of their load. In contrast, they will be stimulated to use energy saving devices that reduce the bill but spoil the grid voltage with harmonics.

The purpose of this paper is to show the real level of utility losses caused by billing only active energy and to offer a low-cost solution. The solution implemented within contemporary electronic power meters turns the smart meters to *smarter*. The subsequent section presents an overview of power meters, their advantages and disadvantages.

## 3. HISTORY AND DEVELOPMENT OF POWER METERS

The meter is a crucial part of the electric utility infrastructure. It registers the amount of electricity transferred from the service to a customer. Consequently, they both, the utility and the customer should trust measured results. Conventional electromechanical power meters earned the broad trust because they are accurate, simple, low-cost, and durable.

The principle of operation of electromechanical meter is based on interaction between phase shifted magnetic fluxes whose intensities are proportional to the value of current and voltage. An orthogonal phase angle provides a maximum electromagnetic torque. Therefore, a $90^{o}$ phase shift is added when the voltage and current are in phase. As a result, the meters do not register an active component of power in case of completely reactive loads. They are reliable for what they were designed: for energy metering at grid loaded with linear loads. Consequently, they have been in use persistently in their original form regardless of the level of development of electronics.

However, they could not resist the solid-state revolution. Eventually, after a century of consistent usage, their withdrawal from the market has begun. The major power meter manufacturers have replaced electromechanical with solid state models. This opened the market of the meter business to new enterprises. Fig. 1 illustrates the trend of the replacements between 1998 and 2010 [11].

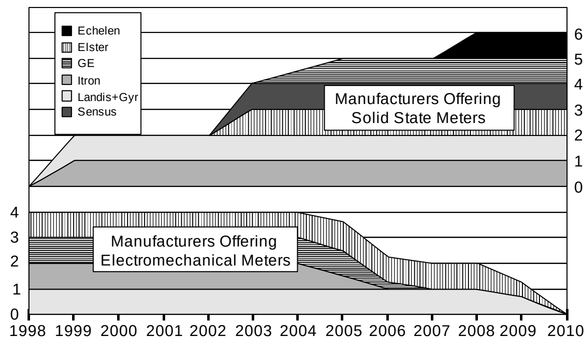


**Fig. 1** Replacement of electromechanical meter production with solid state versions, (the diagram has been taken from [11])

The new technology of power metering has enriched the meter with options to register RMS voltage and current, to measure frequency, apparent power, and power factor.

The electronic power meters relay on digital signal processing. Instantaneous values of the attenuated line voltage are sent to ADC where they are sampled at least two per a period (according to the Nyquist-Shannon theorem) and digitalized. Simultaneously, at another channel, the voltage equivalents of current acquired by current transformers are converted to digital signals, as well. Thereafter, a DSP unit calculates all the necessary power line quantities using the digitalized voltage and current samples according to the following mathematical procedure.

Instantaneous value of power line signal (current or voltage) in time domain can be expressed as:

$$x(t) = \sqrt{2}\sum_{h=1}^{M} X_{RMSh} \cdot \cos(2\pi f_h t + \varphi_h)\,. \tag{1}$$

where $f_h$, $\varphi_h$ denotes frequency and phase angle of $h^{th}$ harmonics, $h$ is order of harmonic while $M$ is the highest harmonic.

After the discretization at equidistant time intervals ($T$), for the $n^{th}$ interval it transforms to

$$x(nT) = \sqrt{2}\sum_{h=1}^{M} X_{RMSh} \cdot \cos(2\pi \frac{f_h}{f_{sempl}} n + \varphi_h)\,, \tag{2}$$

Where $f_{sempl}$, is the sampling frequency ($f_{sempl}=1/T$). According to the definition the RMS value of signal per second is:

$$X_{RMS} = \sqrt{\frac{\sum_{n=1}^{N} x(nT)^2}{N}}\,, \tag{3}$$

where $N$ is number of samples per second.

The active power is an average of the product of instantaneous values of current and voltage in form:

$$P = \frac{\sum_{n=1}^{N} v(nT)i(nT)}{N} = \frac{\sum_{n=1}^{N} p(nT)}{N}\,. \tag{4}$$

The reactive power ($Q$) is defined similarly after shifting the phase of voltage samples for $\pi/2$:

$$Q = \frac{\sum_{n=1}^{N} v_{\pi/2}(nT)i(nT)}{N} = \frac{\sum_{n=1}^{N} q(nT)}{N}\,, \tag{5}$$

where $v_{\pi/2}(nT)$ denotes the $n^{th}$ sample of the phase shifted voltage.

The product of RMS values of voltage and current represents apparent power (6):

$$S = V_{RMS} \cdot I_{RMS}\,. \tag{6}$$

In addition, electronic meters offer better accuracy. Following the new features American National Standards Institute (ANSI) suggested new regulative with more severe accuracy requirements. ANSI C12.20 established accuracy classes 0.2 and 0.5. The class numbers correspond to the maximum percentage of metering error at normal loads. Typical household electronic power meters of Class 0.5, have replaced electromechanical meters, typically built to meet Class 1 standard (ANSI C12.1), as Fig. 2 illustrates [11]. Moreover, the lower measuring limit for ANSI C12.1 was 0.3A (72 Watts) while ANSI C12.20 requires from solid state meters to register power greater than 24W (0.1A). This introduced a significant accuracy improvement.

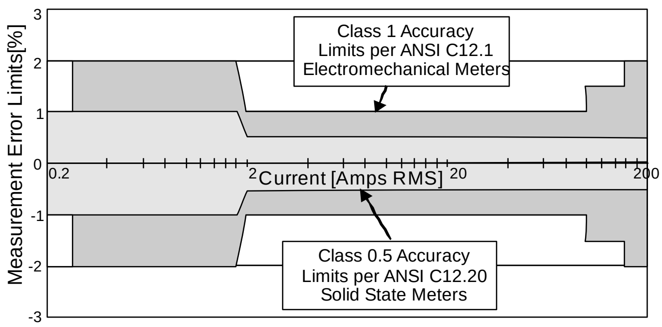


**Fig. 2** Accuracy Class Comparison, [11]

One of important issues in metering development is how much the better accuracy will cost. After more than a century long experience in power metering and two decades of solid state meters usage this is not a secret. The interrelation between practical needs and the cost of improved accuracy is obvious. An interesting benefit to cost analysis regarding the profitability of improving metering accuracy was published in [12]. It took into account contribution of metering inaccuracies and errors of voltage and current transformers to the total system error. The system considered the meter error of 0.2% and errors for voltage and current transformers of 0.15% each. That results in the total system error of 0.292%. Adopting price of \$0.03/kWh the analysis has shown that the system error will make economic losses of \$7,661.87 per year at load whose nominal power is 10 MW. The improved meter with error of 0.1% at the same circumstances yields \$1,498.66 difference. Taking the meter error down to 0.05% would result in an additional \$435 over the 0.1% error meter. Fig. 3 shows how the benefit of better accuracy decreases rapidly below 0.1% [12].

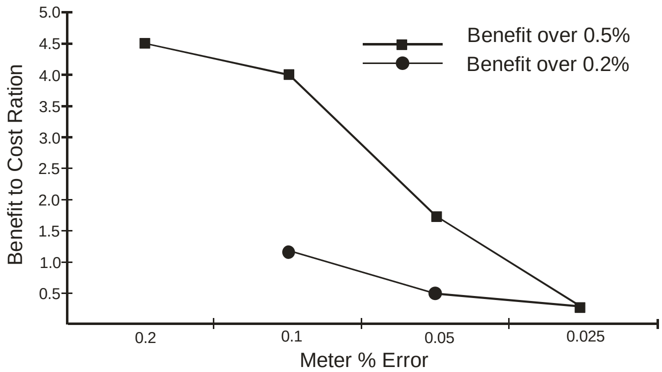


**Fig. 3** Benefit to cost analysis for improving metering accuracy at a 10MW site, [12]

## 4. Method for Elimination Losses Caused by Nonlinear Loads at Power Grid

Both manufacturers and utilities use a set of tests to verify if meters meet the requirements of the appropriate standards [13], [14]. During the manufacturing process, each individual meter is calibrated and verified. The utility does the additional accuracy test, either on each meter or on a sample basis upon receiving power meters from the manufacturer.

The meters are calibrated at fundamental frequency. Therefore, they do not register precisely the total of consumed energy when harmonics exist. In classic electromechanical meters the error rises with frequency of harmonics because the intensity of magnetic fluxes decreases proportionally to the order of harmonic. The meters make an error of 40% of the true value at the third harmonic (150Hz), whereas it is almost 80% at the seventh harmonic (350Hz) [15]. The error can be positive or negative regarding the character of reactance (inductance/capacitance). As stated in the introduction section and as will be proved in the next section, the contemporary power grid is polluted with harmonics. Therefore, even the well calibrated solid state meters will not register all delivered power. They will measure active and reactive energy with accuracy that meet the standards (IEC 62053-22 and IEC 62053-23 standard [13, 14]) but distortion power will not be registered.

The distortion power is practically delivered to the customers, but is not visible at the side of power distributor. Namely, when one calculates active, reactive, and apparent powers according to (4), (5), and (6), respectively, they get for sine-wave condition a well known relation:

$$S^2 = P^2 + Q^2 . \tag{7}$$

However, in presence of harmonics, this equation turns to inequality:

$$S^2 > P^2 + Q^2 . \tag{8}$$

Budeanu noticed this as early as 1927. He introduced the term *distortion power* and revised the equation for apparent power:

$$S^2 = P^2 + Q^2 + D^2 , \tag{9}$$

where $D$ denotes distortion power. The revision states that in the absence of harmonics, $D$=0 and $S^2$=$P^2$+$Q^2$. Obviously this definition represents special case of (9). With known $S$, $P$ and $Q$ one can find the distortion power as:

$$D = \sqrt{S^2 - P^2 - Q^2} . \tag{10}$$

Equation (10) is appropriate for implementation within solid state power meters. In order to meet the regulative, electronic meters already provide $P$,$Q$, and often $S$, as well. However, if an electronic power meter does not provide information of apparent power, it is possible to upgrade the feature using (6) within its DSP block. Therefore, one can easily implement (10) to calculate the distortion power. The implementation requires small modification of software or DSP. Thereafter, the utility is able to take into account $D$ and to introduce it in a new billing policy. This arms the utility with the possibility to charge all components of the delivered power and to eliminate the losses that exist at the system.

Direct application of (10) for the billing requires certain corrections. Namely, the existing power quality standards define the allowed value for each harmonic. The two best known standards in this area are the IEEE 519-1995 and IEC/EN61000-3-2. Therefore, the utility should not charge the distortion energy caused by harmonics amounts less than the limits allowed by standard. So, it makes sense to define the threshold value for $D$ which will be deducted from the measured value using (10). This value presents the acceptable amount of distortion. It is quite appropriate to relate it in terms of the apparent power. One way is to define the threshold value $D_t$ as:

$$D_t = \gamma \cdot S\,, \tag{11}$$

where $\gamma$ denotes a constant which should be defined (by a standard or the utility).

The authors of this paper analyzed the allowed limit for each harmonic of current and voltage defined by the IEEE 519-1995 standard and suggest that correction factor $\gamma$ should be equal to maximum allowed amount of $THD_I$. Notice that the value of $THD_I$ that is used as correction factor is not the measured value. According to IEEE 519-1995 the allowed value of $THD_I$ is 10% in case where $I_{SC}/I_L$ <20 ($I_{SC}$ is the maximum short circuit current at PCC while $I_L$ is maximum current of fundamental harmonic measured in 15- or 30-minute interval at PCC). This is important because the measured value $THD_I$ can be significant and reach up to 90%.

In this way only customers that over-cross the threshold will be charged for additional consumed power, $D_p$:

$$D_p = D - D_t\,, \tag{12}$$

where $D$ denotes measured distortion power. Therefore, the customer will not be penalized for using loads with allowed limit of harmonic defined by IEEE 519-1995 standard.

The standard IEC 61000-3-2 cannot be used for correction factor calculation because it applies different philosophy to define the allowed amount of harmonic. Namely, IEEE 519-1995 limits harmonics primarily at the service entrance (PCC) while IEC 61000-3-2 is applied at the terminals of end-user equipment. Therefore, IEEE 519-1995 defines maximal allowed value of each harmonic (as percentage of fundamental current) in order to prevent interactions between neighboring customers within the power system. However, the intention of IEC limits is to reduce harmonic pollution in an industrial plant. Moreover, IEC 61000-3-2 defines four classes of equipment (Class A, B, C, D), by assigning different limits for harmonics in each class. These limits are given as maximum allowed harmonic current for classes A, B and D, or as percent of fundamental current for classes C.

The next section will demonstrate the suggested methodology on real examples. These results are obtained by using industrial standard power meter manufactured by EWG [16].

## 5. Confirmation of the Method by Measuring

The main gain of the suggested billing method is its applicability. Namely, most of ordinary electronic power meters at the market can be enhanced with the possibility to calculate distortion power according to (10). The only requirement is that the meter is capable to measure separately *S*, *P* and *Q* according to (4), (5), (6). In our case we use meter produced by “EWG” [16]. The operation of this meter is based on standard integrated circuit 71M6533 [17]. This power meter completely fulfils standard IEC 62053-22 and IEC 62053-23 [13, 14]. The only additional effort was to collect data provided by the meter and to acquire them. For the research purpose we used a PC to perform this task.

Figure 4 shows the realised set-up. The simplicity of the set-up is obvious. It consists of the meter, the load, and PC. Communication between the meter and PC is done through the optical port and RS232 interface. Dedicated software processes data and forwards them to *Matlab* script that calculates the distortion power.

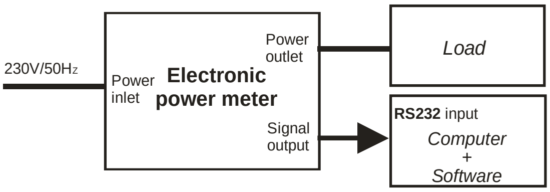


**Fig. 4** Set-up circuit for distortion power measurement

**Table 1** Measurement results for different types of loads

| Row | Loads | $V_{RMS}$ | $I_{RMS}$ | *S* | *P* | *Q* | *D* | *P/S* | *Q/S* | *D/S* | *D/P* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | ILB Philips 100W | 219.9 | 0.42 | 92.48 | 92.32 | 0.74 | 2.54 | 1.00 | 0.01 | 0.03 | 0.03 |
| 2 | Water Kettle | 216.24 | 7.906 | 1709.59 | 1709.54 | 0.39 | 13.51 | 1.00 | 0.00 | 0.01 | 0.01 |
| 3 | Fan | 225.41 | 0.008 | 1.83 | 1.19 | 1.32 | 0.42 | 0.65 | 0.72 | 0.23 | 0.35 |
| 4 | Fridge | 225.68 | 0.641 | 144.66 | 98.64 | 104.78 | 14.77 | 0.68 | 0.72 | 0.10 | 0.15 |
| 5 | FL18W | 218.62 | 0.08 | 17.49 | 11.33 | -5.80 | 11.99 | 0.65 | 0.33 | 0.69 | 1.06 |
| 6 | ES20WBulb | 218.55 | 0.13 | 29.07 | 18.30 | -8.81 | 20.79 | 0.63 | 0.30 | 0.72 | 1.14 |
| 7 | ES20Whelix | 219.01 | 0.14 | 30.66 | 18.61 | -9.38 | 22.49 | 0.61 | 0.31 | 0.73 | 1.21 |
| 8 | ES15Wbulb | 219.74 | 0.09 | 19.56 | 12.10 | -5.51 | 14.34 | 0.62 | 0.28 | 0.73 | 1.19 |
| 9 | ES11Whelix | 221.73 | 0.08 | 17.74 | 10.42 | -5.38 | 13.31 | 0.59 | 0.30 | 0.75 | 1.28 |
| 10 | ES9Wbulb | 216.06 | 0.06 | 12.75 | 7.58 | -3.64 | 9.58 | 0.59 | 0.29 | 0.75 | 1.26 |
| 11 | ES7Wspot | 217.75 | 0.04 | 9.58 | 5.83 | -2.87 | 7.04 | 0.61 | 0.30 | 0.73 | 1.21 |
| 12 | Led Reflector 10W | 223.05 | 0.093 | 20.74 | 10.81 | -3.75 | 17.30 | 0.52 | -0.18 | 0.83 | 1.60 |
| 13 | Led Reflector 30W | 222.72 | 0.272 | 60.58 | 32.23 | -8.96 | 50.51 | 0.53 | -0.15 | 0.83 | 1.57 |
| 14 | Led bulb 6W | 222.65 | 0.042 | 9.35 | 5.10 | 0.96 | 7.78 | 0.55 | 0.10 | 0.83 | 1.53 |
| 15 | Monitor G2320HDBL | 222.9 | 0.179 | 39.90 | 23.65 | -4.67 | 31.79 | 0.59 | 0.12 | 0.80 | 1.34 |
| 16 | Monitor W2241S | 223.88 | 0.289 | 64.70 | 40.28 | -9.40 | 49.75 | 0.62 | 0.15 | 0.77 | 1.24 |
| 17 | Monitor1909W | 221.79 | 0.20 | 43.91 | 24.69 | -7.15 | 35.61 | 0.56 | 0.16 | 0.81 | 1.44 |
| 18 | DELL-Optiplex360 | 220.57 | 0.39 | 85.80 | 61.09 | 10.24 | 59.37 | 0.71 | 0.12 | 0.69 | 0.97 |
| 19 | Air conditioner (cooling-mode) | 217.14 | 4.73 | 1026.86 | 1006.03 | 107.44 | 175.48 | 0.98 | 0.10 | 0.17 | 0.17 |
| 20 | Printer HP1505 StandBy | 211.26 | 0.04 | 8.24 | 3.60 | -3.35 | 6.61 | 0.44 | 0.41 | 0.80 | 1.84 |
| 21 | Printer HP1505 Printing | 208.19 | 2.68 | 557.32 | 548.39 | -8.05 | 99.07 | 0.98 | 0.01 | 0.18 | 0.18 |

Table 1 summarises the measured results obtained for different types of loads. The first four rows represent a group of linear loads while the rest are nonlinear. According to expectations, for linear resistive loads (incandescent lamp and heater) the active power almost equals apparent power. Small difference occurred due to the accuracy of power meters. The more accurate power meter, the smaller the difference and consequently, the more precise the measured value of $D$. In our case we used power meter that measures active and apparent power with error less than 0.5%, and reactive power with error less than 2%. More information about measuring error at power meter can be found in [18]. Due to the errors obtained while the active, reactive and apparent powers are measured, some small value of distortion power appears.

The next two loads in Table 1 (fan, fridge) represent linear reactive loads that consume significant part of reactive power $Q$. Namely, in this case, the value of reactive power is greater than the value of active power. Moreover, the measured results at these loads show some small amount of distortion power $D$. The main reason of the existing distortion power at the linear reactive load is harmonics in voltage supply. Actually, according to standard IEEE 519-1995 the utility has to provide voltage with $THD < 5\%$ (*Total Harmonic Distortion*). Therefore, in reality, the waveform of voltage is not pure sine-wave. It has a small amount of harmonics. Due to these harmonics the impedance at reactive loads at different harmonics are not equal ($Z_1 \neq Z_3 \neq \ldots \neq Z_h$, $h$ denotes the $h^{th}$ harmonic). Consequently, the currents at different harmonics will not be equal, which reflects as $D \neq 0$ [9].

The loads presented from rows 5 to 14 in Table 1 represent group of energy saving lamps. Their number on grid has rapidly increased in the recent past and they are becoming very interesting for research. Namely, one of the easiest ways to shrink power bill and carbon footprint is using the energy saving lamps (LED bulbs, CFLs) insted of incandescent light bulbs. The energy saving lamps represent typical green-green situation, saving money and helping the environment. However the price for improving the 'green' features is paid from a quite different account. The basic problem with energy saving lamps lies in their non-linear nature. Namely, they generate harmonics in currents, so $I_{RMS}$ increases proportionally to harmonics. This reflects through the increase of $S$ and $D$, as well. The columns $P/S$ and D/S in Table 1 indicate the seriousness of the problem. The unregistered distortion power occupies between 0.53 and 0.83 of the apparent power. Obviously, it exceeds the registered active power that ranges between 0.52 and 0.65 of apparent power for energy saving lamps. Practically for all nonlinear loads from Table 1, $D$ is greater than $P$ and rated between 0.18 and 1,84 times. The obtained results are in consistence with data recently published in [6] for similar types of energy saving lamps. It is important to notice that the measurements in [6] were based on a quite different approach. Actually, it was grounded on FFT analysis.

Fortunately, the number of manufacturers being aware of the problems caused by their product increases. So, they try to improve their product using different filtering methods in order to reduce the value of generated harmonics. For example, most of Phillips branded LED use the Valley-fill circuit [19, 20]; Toshiba lamp contains a passive filter [21, 22], while Osram decides to embed an active filter [21, 22]. Despite the used filter, the current of these loads is not sinusoidal [21]. Consequently, loads with PFC filters still produce the considerable value of harmonics and some improvement of their filters is necessary. However, the question is whether it is of worth to the manufacturer. An alternative is to employ some active harmonic compensation systems at PCC [23].

Therefore, harmonics produced by all nonlinear loads connected at PCC will be diminished and manufactures' cost will be less. However, this opens a new topic of who should pay for this system: customer or utility.

Fig. 5 compares active with distortion component of power for light bulbs in Table 1. Only for the first case, Incandescent Lamp Bulb (ILB) Philips 100W, that is a linear load, active power is much greater then distortion power. In all other cases, the distortion power is of the same order of magnitude but greater than active power.

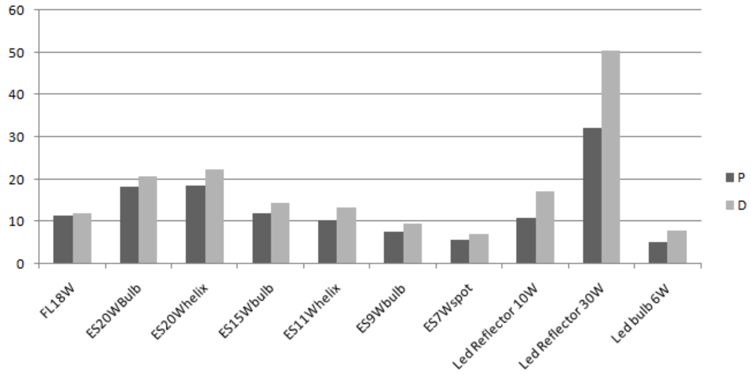


**Fig. 5** Comparison between active and distortion power spent on different types of light bulb

Fig. 6 shows timing diagrams of power consumption for five bulbs switched according to the schedule in Table 2. Obviously, the proposed method successfully detects all changes. When Incandescent lamp bulb (Philips 100W) turns-on (events denoted as 3 and 8) the total apparent and active powers rise while distortion and reactive powers remain of the previous values. Similarly, when it turns off (event 6), active and apparent power decreases while distortion and reactive power stay constant. Figure 6 clearly shows that the distortion power is registered only when any of nonlinear loads is turned on.

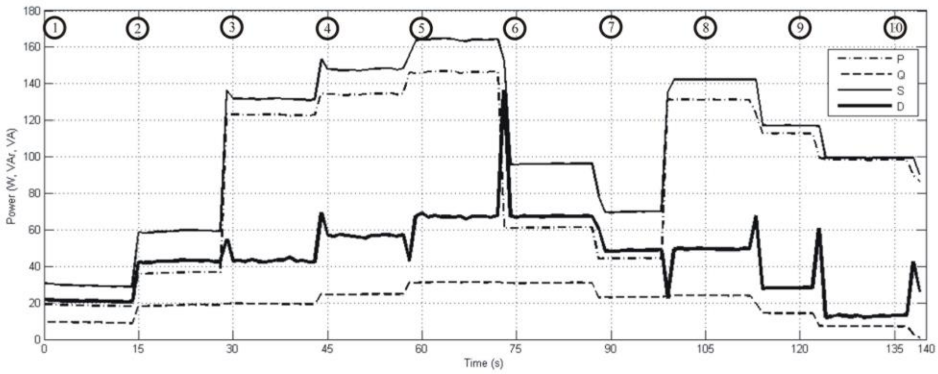


**Fig. 6** Power consumption timing diagram measured for a group of five bulbs switched according to the schedule in Table 2.

**Table 2** Schedule of switching different types of bulbs

| State | ES20WBulb | ES20Whelix | ILB Philips 100W | ES15WBulb | ES11Whelix |
|---|---|---|---|---|---|
| 1 | ON | OFF | OFF | OFF | OFF |
| 2 | ON | ON | OFF | OFF | OFF |
| 3 | ON | ON | ON | OFF | OFF |
| 4 | ON | ON | ON | ON | OFF |
| 5 | ON | ON | ON | ON | ON |
| 6 | ON | ON | OFF | ON | ON |
| 7 | ON | ON | OFF | OFF | ON |
| 8 | ON | ON | ON | OFF | ON |
| 9 | ON | ON | ON | OFF | OFF |

Someone could disregard these results claiming that energy saving lamps are small loads ($P$< 20W). However, one should not overlook the number of these loads at the grid. Namely, about 20% of world electricity consumption is closely related to light [24]. Only for the public lightening the average operating time reaches more than 12 hours per day during the winter and is not less than 9 hours per day during the summer in this region (the Balkans).

The last seven loads in Table 1 present results measured at loads usually used in households and offices. The most interesting load from all the observed loads is the Printer HP M1505 during the Stand-by mode. Namely, in this mode the value of distortion power is 1.84 times greater, than the value of active power. Someone may argue that the real value of $P$ is relatively small (3.6W), so it not important for power distributor. The authors of this paper do not agree with them. Namely, we should not neglect two important facts. Firstly, electronic equipment spends most of the time in a stand-by mode. Secondly, the utility measure loses in terms of real money that is correlated to energy, i.e. integral of power in time. Moreover, in printing mode the absolute value of $D$ reaches almost 100VAR.

It is interesting to observe power consumption of typical nonlinear loads during some time interval. We have tracked consumption of a personal computer and an air conditioner. The power consumption of a PC during setup is shown in Fig.7. For the entire observed interval the distortion power is greater than active power. Without doubt the unregistered or wasted energy is greater than the active part. This is the main reason of losses for a utility. Fig. 8 presents power consumption of an air conditioner during starting the heating mode. It is interesting to see that distortion power has the same order of magnitude as reactive power and excesses 200VAR.

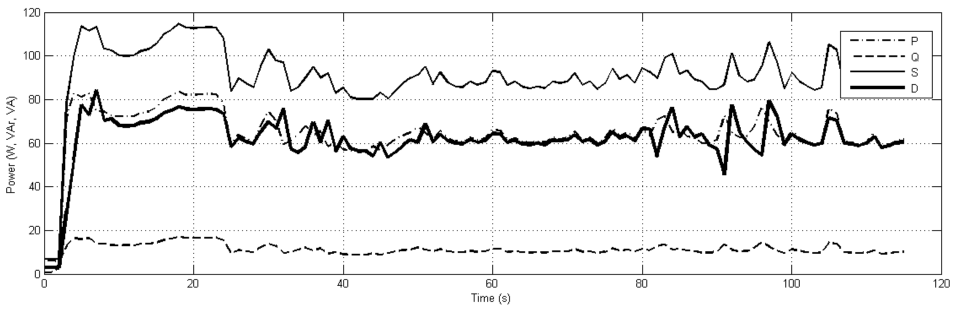


**Fig. 7** Typical power consumption timing diagram of a PC (Dell Optiplex 360) during setup

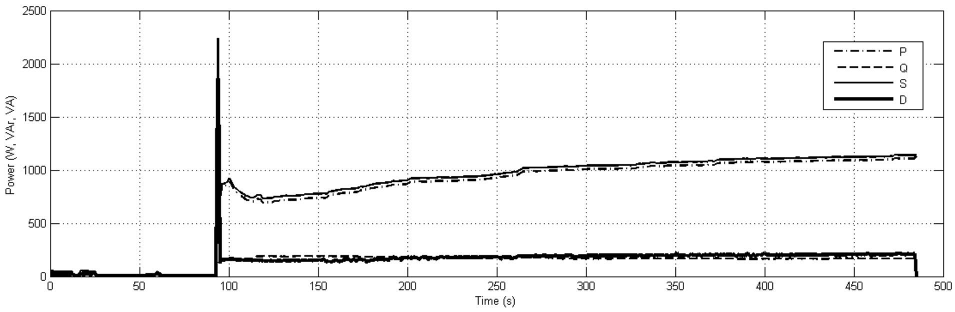


**Fig. 8** Typical power consumption timing diagram of an air conditioner

All examples confirm that distortion power exists at the grid. However, the awareness about the losses caused by nonlinear loads does not exist. Therefore, the billing policy might change. It would be reasonable to bill higher the consumers that pollute grid with harmonics. However, this requires meters capable to measure all components of apparent power according to (10). The suggested modification can be done at software level or at hardware. Namely, it is not difficult to implement the part for distortion power calculation within dedicated DSP [25] or a microprocessor unit that already exists in electronic power meters. Of course, in both cases the manufacturer’s intervention is needed. Software upgrade requires access to the source code change. Hardware intervention requires replacement of the metering integrated circuit. Besides, we have a solution based on a new pice of hardware that is able to collect the required data trough optical head and to calculate and display data about distorted power. That will be reported in a separate paper. The hardware has been prototyped on FPGA.

Such meters are little smarter than the contemporary electronic meters because they have one feature more than others. Therefore, they are able to solve the problem of economic loses at utility side caused by non-registering distortion power.

## 6. Conclusion

The results presented in this paper should inform utility that the main cause of registered losses comes due to inadequate measuring equipment. Moreover, the paper offers an easy, reliable and low cost solution to the problem. The measured results show, that utilities have large losses because they do not register distortion part of the delivered power. Actually, as far as the authors were able to find out, almost all utilities in Europe based their billing policy only on active and reactive power measurements. However, in real life the number of nonlinear loads increases rapidly. That comes as the cost for a greater usage of energy efficient equipment that reduces carbon footprint. For example, in the case of energy efficient light equipment (CFLs and LED lamps) that replaces classic light bulbs the losses due the distortion power rise above 60% in comparison to the active power. Although each energy saving lamps is a small power consumer, their total number could not be ignored. Moreover, their operation time is usually very long in comparison to some other devices, so that the total consumed energy becomes significant.

This paper proves that the contribution of distortion power to consumed apparent power is similar for other equipment and gadgets commonly used in offices and households (air conditioners, monitors, PCs, printers, etc). Moreover, measurements during particular operating regimes (set-up phase of a PC, printer stand-by) show that the distortion power is greater than active power all the time.

All presented results show that utilities have the increased level of losses when using power meters that measure only active power. Therefore, some countries have already started to replace old electromechanical power meters that measure only active power with the new electronic meters that are capable to measure reactive power as well. However, they eliminated losses for a few percent but the problem related to losses is not solved. Therefore, as a solution the authors of this paper suggested using distortion power as an addition parameter in the billing policy. For this to happen it is necessary to provide information of spent distortion power at customer connection point. We claim that this is possible with a minor upgrade of smart electronic power meters that will make them smarter.

Someone may suggest that it is enough to register only the apparent power and separate active from non-active power. However, this would be a step back because ordinary electronic power meters are capable to measure separately apparent, active and reactive power. As presented in this and some previous papers [24], only minor modification in dedicated DSP hardware or software for DSPs or MCUs built-in the meters is sufficient to enable them to measure distortion power, as well. Armed with this feature, the meters installed at PCC allow utility an opportunity to identify the source of harmonics at the grid [5], [7]. This opens the possibility to bill separately each component of power. In our opinion this will diminish the losses and will serve as a powerful tool to manage the loading profile of the consumers.

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