

The Losses at Power Grid Caused by Small Nonlinear Loads

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Abstract: The difference between registered active power and spent unregistered power represents the losses at power grid. This paper treats problems related to losses caused by nonlinear loads connected to the power grid. In recent years the load profile of power consumers turned from energy-waster linear to energy-saver but non-linear loads. The main cause of the losses appears due to the lack of adequate measurement equipment. Namely, common household power meters register only active energy, while power meters for industrial application register reactive energy as well. This approach does not follow the change of the end-user profile. Tendency of improving energy efficiency brought wide use of switching mode regulators and replace old incandescent light bulb with new energy saving lamps (CFL – compact fluorescent lamp, LED bulb). Therefore, the number of non-linear load drastically increased. Registering only active component of power at consumer's side does not depict the real profile of the consumption. Therefore, in this paper we analyse and quantify the effects of non-linear loads at power losses. As a result we suggest an efficient method for measuring the distortion component of power. The method relays on low-cost upgrade of commercial electronic power meters. The presented results of measurements on small non-linear loads confirm the proposed technique. Besides, they prove the importance of measuring all components of apparent power and justified their use in billing policy. The implemented set-up is based on power meter manufactured by EWG of Niš.

Keywords: Power quality, Harmonic source, Utility losses.

1 Introduction

Currently the globe is faced with a lack of energy. Therefore one of the most important topic in the world is to develop awareness about the importance of the energy saving. Small power consumption and energy efficiency become the main design goals in all areas of engineering. The main difference between old and modern appliances is their power consumption. All electrical and electronic apparatus are rated according to their energy efficiency and denoted by letters A to G, where A means the most energy efficient.

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Some gadgets, such as dishwashers and washing machines, also have three additional grades A+++, A++ and A+. The correlation between energy saving and money saving represents the crucial *spiritus movens* that motivates common consumers to invest into reduced power consumption. According to recent research made by EST (Energy Saving Trust: <http://www.energysaving-trust.org.uk/>), the new appliances can save between £20 and £40 per year [1]. The replacement of old equipment with energy efficient equivalents goes very fast in fields where relatively small investment provides huge savings of energy.

The classical example represents incandescent lamps. Namely about 20% world consumption of energy is related to the light [2]. Therefore, this area represents the best place for involving a new technology for energy saving. Many governments have already implemented regulations which restrict the use and manufacturing of incandescent lamp. Among the first were the governments of Brazil and Venezuela in 2005. The EU has already banned using of incandescent lamps with nominal power of 100W and plan gradually to withdraw other bulbs until 2013. As alternative solution they suggest using energy saving lamps: CFL - Compact Fluorescent Lamp and LED lamp. Their price is greater than incandescent lamp, but they have longer lifespan. In the literature one can find different information about the viability of CFL and LED bulb over conventional incandescent lamp. For example the lifespan of LED lamp is between 50.000 h [3] and 100.000 h [2], while for CFL the lifetime is from 8.000 to 15.000 h. That is much more than the lifespan of incandescent lamp which is about 1000 h [3]. CFL spends five times less energy than incandescent lamp for the same level of light, while LED lamp needs twice less energy than CFL (for 800 lm consumption of incandescent lamp, CFL, and LED lamp is 0.06 kWh, 0.013–0.015 kWh, 0.006–0.008 kWh, respectively). Because of exploitation rates, lower heat and less environment compromising, the higher initial investment in LED and CFL bulbs are more cost-effective in total.

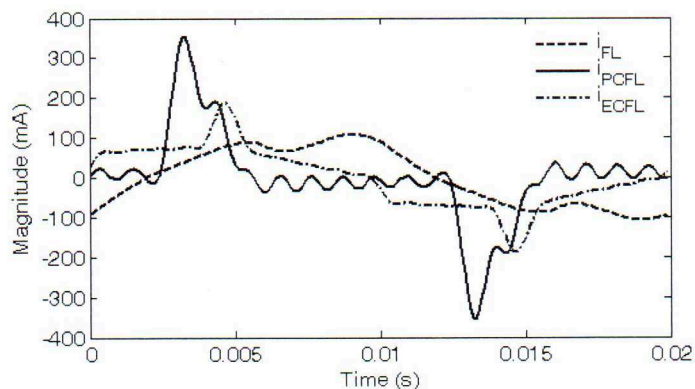


Fig. 1 – Current waveforms for different fluorescent lamps: Philips CFL (PCHL), EcoBubl CFL (ECFL), and fluorescent lamp (FL) [4].

However, as loads at a power grid, CFL and LED bulbs exhibit non-linear nature. Therefore, due to harmonic components the current waveform differs from the voltage. That creates a problem to the utility as well as to other consumers. The waveforms of current for Philips CFL (PCHL), EcoBubl CFL (ECFL), and fluorescent lamp (FL) are shown in Fig. 1 [4].

The basic theory that explains the phenomena in power grid, starts from the assumption that all consumers are linear resistive or reactive (inductance, capacitive) loads. The current and voltage waveforms at these loads have the same shape. Only difference is lead or lag of current in respect to voltage at reactive loads (depending on the reactance character). According to this, the used measuring instrumentation is aimed to register only active power at households with addition of reactive power at industrial customers. Due to the change of the end-user load's character this approach is not adequate anymore. As we will show later on, this causes considerable losses at the utility. Namely, harmonic component of current interact with finite resistance of transmission lines and introduces harmonics into grid voltage. The existence of harmonics within voltage and current requires a correction in equations that calculate active, reactive and apparent power. Their effect must be taken into account. It should be noted that in reality, the actual contribution of harmonics to reactive and active power is small, less than 3% of the total active or reactive power. The main effects of harmonics to the grid one can register through *distortion power*, which will be defined later.

Moreover, it is known that any deviation from sine-wave voltage could cause malfunction in other equipment connected to the grid [5, 6]. Therefore it is important for the utility to detect and discourage customers to pollute the grid with harmonics.

The main goal of this paper is to show that the level of losses caused by energy efficient bulbs is not negligible due to their nonlinear character. Moreover the paper offers an effective solution to eliminate financial losses through the change of billing politics.

The paper is organized as follows. Section 2 gives a brief comparison between electromechanical meters and modern electronic meters. Section 3 suggests a method capable to eliminate losses at the utilities, caused by non-linear load at grid. Section 4 shows results that confirm successfulness of the presented method. The paper concludes with Section 6.

2 The Theory of Operation of Electromechanical and Electronic Power Meters

Electromechanical power meters are based on principle of interaction between magnetic fluxes, whose intensities are proportional to the value of current and voltage. These fluxes are generated at the same fundamental

frequency of 50 Hz. An additional mechanism which causes a phase shift of 90° between the fluxes is built-in in order to produce a maximum electromagnetic torque 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.

The calibration of these power meters is done at fundamental frequency. Therefore, it does not register precisely consumed active energy when harmonics exist. The amount of the error depends on frequency of harmonics. For example, the meters make an error of 40% of the true (real) value at the third harmonic (150 Hz), whereas at the seventh harmonic (350 Hz) the error is almost 80% [7]. This fact can be explained as follows: the intensity of magnetic fluxes decreases proportionally with the order of harmonic, consequently the speed of rotating disk slows down. In case when the phase angle between voltage and current of the same harmonic is 90° , disk should not rotate, but it does. The meter registers some amount of consumed “phantom energy” that presents the error. This can reach up to a few percents of the voltage-current product for harmonic. The error can be positive or negative. The sign depends on the character of reactance (inductance/capacitance). That inaccuracy forced utilities to replace electromechanical meters with electronic power meters.

The electronic power meters rely on digital signal processing of voltage and current samples. Namely, instantaneous value of the line voltage attenuated through a voltage divider is sent to ADC where is sampled at discrete time points (at least two per a period, according to the Nyquist-Shannon theorem) and digitalized. At the same time the voltage equivalent of current obtained by current transformers are converted to digital signals using appropriate ADC channel. DSP processes digital voltage and current samples and calculate all necessary power quantities. Instantaneous value of signal (current or voltage) in time domain can be express as:

$$x(t) = \sqrt{2}X_{RMS} \cos(2\pi ft + \varphi). \quad (1)$$

After the discretization in equidistant time intervals it transforms to

$$x(nT) = \sqrt{2}X_{RMS} \cos\left(2\pi \frac{f}{f_{semp}} n + \varphi\right), \quad (2)$$

where f and f_{semp} , are frequency of the signal and the sampling frequency, respectively. The RMS value of signal is calculated according to (3)

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

where N represents number of samples per second. The active power is obtained as an average of the product of instantaneous values for current and voltage in form:

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

The similar equation calculates the reactive power (Q) after the samples of voltage are phase-shifted for $\pi/2$:

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

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

$$S = V_{RMS} I_{RMS}. \quad (6)$$

The detailed information about integrated power meters can be found in [8].

One of the first utilities that located the problem of losses related to the changed load profile was Enel S.p.A. corporation (Ente Nazionale per l'Energia eLettrica: www.enel.com). It represents the most important power distributor in Italy and the second in Europe according to the installed capacity. They concluded that the change at end-user profile caused the losses at power grid. Therefore, they proposed measurement of reactive energy as additional quantity that should be introduced into the billing policy for households. Consequently they have replaced more than 20 million household energy meters with upgraded electronic power meters capable to measure both active and reactive energy. Installations of these power meters have started in 2001 and until now they replaced 99% in Italy [9]. In this way the losses are lower but not fully eliminated. In this paper we will show that apart from reactive power, the distortion power needs to be measured.

The common status of power grid in Serbia is that utility register only active energy using electromechanical power meters. Currently utility spends a lot of money to replace the old meters with contemporary electronic meters. Unfortunately the new equipment is able to register only active and reactive power with possibilities to measure RMS values of voltage/current, the power factor, maximal load and apparent power on request. The part of the power caused by harmonics is practically delivered to the customers but is not visible at the side of power distributor.

3 Components of Apparent Power at Non-linear Loads

When one calculates active, reactive, and apparent powers according to (4), (5), and (6), respectively, gets for sine-wave condition well known relation:

$$S^2 = P^2 + Q_b^2. \quad (7)$$

However if harmonic distortion exists, this equation turns to:

$$S^2 > P^2 + Q_B^2. \quad (8)$$

Firstly this noticed Budeanu in 1927. He introduced the term *distortion power* and corrected the equation for apparent power as:

$$S^2 = P^2 + Q_B^2 + D_B^2, \quad (9)$$

where D_B denotes distortion power. The essence of this revision is the fact that in the absence of harmonics, $D_B = 0$ and $S^2 = P^2 + Q_B^2$. It is obviously that this definition becomes special case of (8). In case when one knows S , P and Q_B the distortion power can be calculated as:

$$D_B = \sqrt{S^2 - P^2 - Q_B^2}. \quad (10)$$

This equation is very suitable for implementation within electronic power meters. Two of three required values (P and Q_B) already are explicitly available. The third, S , is available implicitly because the meters provide RMS values of voltage and current. Therefore, only small modification in applied software or in DSP hardware is needed to obtain S using (6) and to implement (10) in order to provide distortion power. Thereafter, the utility is able to take into account D and to introduce it in a new billing policy. This arms utility with the possibility to charge all components of delivered power and to eliminate the losses that exist at the system.

The authors will prove the previous claim with measured results using a commercial power meter manufactured by EWG from Niš [10]. The subsequent section presents the obtained results.

4 Measurement Result Obtained by Using Commercial Power Meters

The validation of the proposed method is done in two steps. Firstly we did simulation using Matlab. With that purpose we wrote an original Matlab script that emulates virtual power meter. The simulation results confirmed the suggested theory [11]. The second step was verification by measurement. Therefore we realized the set-up as Fig. 2 illustrates.

The used commercial power meter fulfills standards IEC 62053-22 [12] and IEC 62052-11 [13]. The meter calculates active, reactive and apparent power according to (4), (5) and (6) and stores them in appropriate registers. Unfortunately it cannot provide distortion power. Therefore additional hardware or software is needed. As Fig. 2 indicates additional computation engine is needed in a form of external personal computer. It is aimed to acquire data obtained from the power meter and to calculate D according to (10). Optical head is used to read P , Q_B and S from the meter. The data are sent to personal

computer through RS232 port. In this paper we present results obtained for different type of light lamps. The measured results are shown in **Table 1**.

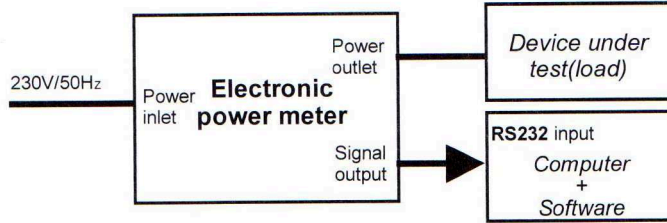


Fig. 2 – Set-up circuit for distortion power measurement.

Table 1
Measurement result for different types of lamps.

Loads	U_{RMS}	I_{RMS}	S	P	Q_B	D_B	$D_B/S[\%]$
Incandescent lamp 100W	218.96	0.42	91.96	91.96	0.74	0.00	0.00
FL18W	218.62	0.08	17.49	11.33	-5.80	11.99	68.58
CFL20W bulb	218.55	0.13	29.07	18.30	-8.81	20.79	71.54
CFL 20W helix	219.01	0.14	30.66	18.61	-9.38	22.49	73.35
CFL 20W tube	219.46	0.14	31.60	18.73	-9.58	23.58	74.62
CFL 15W bulb	219.74	0.09	19.56	12.10	-5.51	14.34	73.34
CFL 11W helix	221.73	0.08	17.74	10.42	-5.38	13.31	75.03
CFL 11W tube	221.27	0.08	17.92	10.76	5.74	13.13	73.28
CFL 11WE14	215.51	0.08	17.24	10.79	-5.26	12.38	71.78
CFL 9W bulb	216.06	0.06	12.75	7.58	-3.64	9.58	75.16
CFL 7W spot	217.75	0.04	9.58	5.83	-2.87	7.04	73.48
CFL 7W	219.83	0.04	9.67	6.03	-2.57	7.11	73.54
CFL 15W helix	218.55	0.15	32.13	18.95	-10.26	23.83	74.17
CFL 20W tube	216.91	0.11	24.08	13.86	-7.15	18.34	76.19
LED Parlamp	217.27	0.157	34.11	16.9	-3.87	29.38	86.12
LED Parlamp (6×1.5W)	217.51	0.114	24.80	12.89	-2.74	21.00	84.71
LED Bulb(7×1W) Warm White	218.02	0.083	18.10	9.7	-2.84	15.01	82.95
LED Bulb (6×1W) Warm White	217.93	0.042	9.15	7.76	-0.14	4.85	53.00
LEDBulb (6×1W) White	217.85	0.045	9.80	8.34	-0.16	5.15	52.53
LED Bulb 3×1W	217.9	0.034	7.4086	3.96	-0.89	6.20	83.66
LED MiniBulb 3×1W	215.86	0.034	7.33924	3.91	-1	6.13	83.52

As expected, the measured distortion power of incandescent lamp, that represents a linear resistive load, is zero. The other loads shown in **Table 1** are nonlinear. Therefore their current contains harmonics that do not exist in the supply voltage. Consequently, they will consume some amount of distortion power. The value will be greater if the current is rich with harmonics. Obviously, the measure of the distortion power is in direct relation with the nonlinearity of a particular load. Losses caused by nonlinear loads expressed as distortion power could range up to 86% relative to the apparent power. This was the case for LED Parlamp 15 W. The obtained results are in consistence with data recently published in [14, 15] for similar types of energy saving lamps. Although the nominal power of the loads in the considered examples is small, usually less than 20 W, their total number at a power system is not negligible. Moreover, the general trend in the world is to replace classic bulbs (linear loads) with energy saving but nonlinear loads (CFL and LED bulbs).

The aim of this paper is not to discard usefulness of energy saving policy but to point out the problem related to increased number of nonlinear loads at the grid.

The possible direction toward the problem solution is an effective compensation of harmonics. Until then, the only way to eliminate financial losses caused by nonlinear loads at grid is the change in the billing politics. However this requires power meters which are able to register distortion power.

This research proves that small upgrade of the built-in software in contemporary power meters can extend their features to provide distortion power metering. Practically, it is sufficient to calculate only one new component of power in terms of already measured values according to (10). It is feasible to perform this activity with the existing computation engine within the power meter and to avoid usage of the external computer.

5 Conclusion

The increased number of energy-saving equipment connected to the grid has reduced the total needs for energy but has increased the amount of nonlinear loads. Harmonics caused by nonlinear loads threatens to spoil the purity of sine-wave voltage at the grid. This jeopardizes functionality of most equipment connected to the grid. Moreover, the lack of the insight into all components of delivered power produces considerable financial losses at utility. The results presented in **Table 1** undoubtedly justify the need to measure distortion power for all customers. Our goal is not to oppose the energy-saving policy but to indicate the importance of a small problem that threatens to increase in the near future. Therefore, the authors suggest upgrading electronic power meters to register all three components of power. The current standards do not require from manufacturers of power meters to register distortion component of power.

However, the presented research showed that the upgrading of commercial power meters to the required specification is feasible in a cost-effective manner.

6 Acknowledgment

This work has been partly funded by the Serbian Ministry of Education and Science under the contract No. TR32004.

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