Measurement of Utility Losses Caused by Nonlinear Loads at Power Grid

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Abstract— **This paper presents results of quantifying losses caused by nonlinear loads in a utility system. As a quantity that the best reflects the value of losses we chose *distortion power*. The reviews of trends related to the change in the character of loads connected to the power grid are given in this paper. The main problem reflects in the form of losses that utility register due to inadequate measurement equipment. We analyze core of the problem and suggest the solution that can be implemented with minor changes of software built in standard power meters. The method is verified by measurements performed by an industrial electronic power meter.**

Keywords- Distortion power; power losses; utility

I. INTRODUCTION

The profile of end-consumers load on the power grid has been drastically changed in last decades. Namely, modern electronic loads have become dominant consumers. Nominal operation voltage is DC voltage with value of 5V while supplied from AC 230V RMS. In order to improve efficiency of rectifiers and voltage regulators their operation frequency is increased from 50Hz to several kHz. This enabled the use of passive reactive components with reduced dimensions. Moreover, transistors operate in switching regime providing considerable savings in dissipation. Consequently, rectifiers and regulators operate with high effectiveness. As result less power dissipate on AC/DC convertors and more power goes to the loads (electronic equipment). However another problem aroused. All such loads introduce harmonics into line currents. Due to the finite resistance of transmission lines they produce harmonics into grid voltage. It is known that any deviation from sinewave voltage could cause malfunction in other equipment connected to the grid. The number of nonlinear loads has increased according to the tremendous rise of electronics appliances. Therefore, the level of power consumption at nonlinear loads becomes comparable or greater than at the linear loads.

The inert power supplying system could not follow the development of electronics. Moreover, power utilities did not pay attention to possible consequences. The largest two blackouts in North American history (1965 and 2003) demonstrate sensitivity of the power system to small unjustly neglected problems. According to [1] "Both blackouts were the result of cascading failures of the power system, in which seemingly small and localized problems caused the system to become unstable and subsequently affect a much wider area." In addition, the current billing politics is not adequate. With the application of non-linear loads to power lines the active energy no longer represents the main part of total energy delivered to customer. Therefore, if distributors do not measure the other components of energy they will have a high level of losses. The leading Italy's power distributor ENEL was one of the first that correlated losses with the non-linear loads. In order to reply to the problem they suggested a change in the billing politic. They proposed measurement of reactive energy as additional quantity and have decided to replace more than 20 million household energy meters with upgraded electronic power meters capable to measure both active and reactive energy.

The current status in Serbia is that the utility still uses electrical power meters that register only active energy consumption. Moreover, recently published tenders for new household electronic power meters does not requests measurements of non-active components of power. The option of reactive power measurements is required only for industrial power meters.

This paper is aimed to show the real level of the utility losses caused by billing only active energy. The subsequent section present a method for improving billing politics and elimination losses that occur at power grid due to connected non-linear loads. The component of power that comes as consequence of higher harmonics of current and voltage on the grid, named *distortion power*, is recognized as the quantity that is in direct relation with the amount of losses. It is important to stress that it could have value comparable to the active power and even to exceed it. Therefore, if the utility does not register this component it will have high level of losses. Measurement results for the typical electronic gadgets that can be found everywhere are given in the third section before conclusion.

II. METHOD FOR IMPROVING BILLING POLITIC AND ELIMINATION LOSSES AT POWER GRID

Definitions of power quality quantities are well known [2], [3], [4]. When one calculates active (P) and reactive (Q_B) powers according to these definitions and compare them with apparent power (S) obtained as product true RMS value of voltage and current, gets inequality

$$S^2 > P^2 + Q_B{}^2 . \quad (1)$$

Referring to the well known relation that is valued for sine-wave condition where $S^2 = P^2 + Q_B{}^2$, it is clear that the difference is caused by harmonics. Budeanu introduced the term *distortion* power (D_B) in 1927 [3] and suggested a new expression for S.

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

where D_B is the distortion power, according to Budeanu. The essence of this revision is the fact that in the absence of harmonics, $D_B=0$ and $S^2=P^2+Q_B{}^2$. Therefore, this definition becomes the special case of (2). According to (2) the distortion power can be expressed as:

$$D_B = \sqrt{S^2 - P^2 - Q_B{}^2} . \quad (3)$$

Direct application of (3) for the billing requires the introduction of certain corrections. Namely, the standards that already exist restrict the allowed amount for each harmonic. The two best known and widely used standards in this area are the IEEE 519-1995 and IEC/EN61000-3-2. Therefore, the utility should not charge the distortion energy for loads which harmonics are within the limits allowed by standard. So it makes sense to define the threshold value for D_B that will distinct the acceptable amount of distortion. If the customer over-crosses this threshold it will pay for additional consumed energy. The next section will demonstrate the proposed methodology on measured results. These results are obtained by using industrial standard power meter manufactured by EWG from Nis [5].

III. MEASURED RESULTS

The main advantage of the suggested billing method is its applicability. Namely, most of contemporary power meters at the market can be enhanced with the option to calculate distortion power according to (3). The only requirement is that the meter is capable to measure independently S, P and Q_B. Namely, S as product of V_{RMS} and I_{RMS}; P obtained as integral of product of i instantaneous values of $v(t)$ and $i(t)$, while Q_B comes just like P but for $\pi/2$ phase-shifted $v(t)$. This was the case with the meter produced by "EWG" [5]. It is based on standard integrated circuit 71M6533 [6]. The power meter completely fulfils IEC 62052-11 standard [7]. The only additional effort was to gather data provided by the meter and to acquire them using a PC.

Figure 1 illustrates the implemented set-up. The simplicity of the set-up is obvious. It consists of the meter, the load and PC. The meter sends the measured data through its optical port. PC receives them on RS232 port. Dedicated software processes data and forwards them to Matlab script that calculates the distortion power.
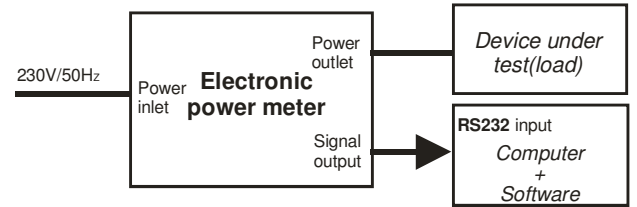

Figure 1. Set-up circuit for distortion power measurement

TABLE I. MEASUREMENT RESULTS FOR DIFFERENT TYPES OF LAMPS

No	Loads	V_{RMS}	I_{RMS}	S	P	Q_B	D_B	P/S	Q_B/S[%]	D/S[%]
1	Incandescent lamp 100W	218.96	0.42	92.32	91.96	0.74	0.00	1.00	0.80	0.00
2	FL18W	218.62	0.08	17.49	11.33	-5.80	11.99	0.65	33.16	68.58
3	ES20Wbulb	218.55	0.13	29.07	18.30	-8.81	20.79	0.63	30.31	71.54
4	ES20Whelix	219.01	0.14	30.66	18.61	-9.38	22.49	0.61	30.59	73.35
5	ES20Wtube	219.46	0.14	31.60	18.73	-9.58	23.58	0.59	30.32	74.62
6	ES15Wbulb	219.74	0.09	19.56	12.10	-5.51	14.34	0.62	28.17	73.34
7	ES11Whelix	221.73	0.08	17.74	10.42	-5.38	13.31	0.59	30.33	75.03
8	ES11Wtube	221.27	0.08	17.92	10.76	5.74	13.13	0.60	32.03	73.28
9	ES9Wbulb	216.06	0.06	12.75	7.58	-3.64	9.58	0.59	28.55	75.16
10	ES7Wspot	217.75	0.04	9.58	5.83	-2.87	7.04	0.61	29.96	73.48
11	EL15Whelix	218.55	0.15	32.13	18.95	-10.26	23.83	0.59	31.93	74.17
12	EL20Wtube	216.91	0.11	24.08	13.86	-7.15	18.34	0.58	29.69	76.19

TABLE II. MEASUREMENT RESULTS FOR DIFFERENT TYPES OF LOADS

Loads	V_{RMS}	I_{RMS}	S	P	Q_B	D_B	P/S	Q_B/S[%]	D/S[%]
Heater	220.29	0.793	174.67	174.60	1.39	4.67	1.00	0.80	2.67
Ventilator	225.41	0.008	1.83	1.19	1.32	0.42	0.65	72.13	23.21
Fridge	225.68	0.641	144.66	98.64	104.78	14.77	0.68	72.43	10.21
LCD- 23 (Dell E2310H)	221.42	0.17	37.64	23.44	-6.78	28.66	0.62	18.01	76.14
CRT-21 HM903DT	220.92	0.37	82.40	77.84	-17.11	20.94	0.94	20.76	25.41

Load											
DELL-Optiplex980		221.25	0.30	66.15	55.83	-33.05	12.92	0.84	49.96	19.54
Air conditional-cooling		217.14	4.73	1026.86	1006.03	107.44	175.48	0.98	10.46	17.09
Printer HP1505 StandBy		211.26	0.04	8.24	3.60	-3.35	6.61	0.44	40.66	80.23
Printer HP1505 Printing		208.19	2.68	557.32	548.39	-8.05	99.07	0.98	1.44	17.78
Printer HP M2727 StandBy		208.20	0.12	24.78	13.06	-5.01	20.45	0.53	20.22	82.54
Printer HP M2727 Printing		206.78	3.23	667.90	630.82	-6.53	219.35	0.94	0.98	32.84
3 Phase motor (25% speed)	I phase	224.58	0.22	50.31	28.60	34.20	23.30	0.57	67.98	46.32
	II phase	225.70	0.30	67.94	53.13	29.88	29.99	0.78	43.98	44.15
	III phase	225.94	0.19	43.38	36.82	10.71	20.28	0.85	24.69	46.76
3 Phase motor (40% speed)	I phase	224.30	0.26	58.99	37.14	34.44	30.24	0.63	58.38	51.26
	II phase	225.17	0.36	80.16	61.82	33.75	38.27	0.77	42.10	47.75
	III phase	225.89	0.26	58.73	48.44	12.61	30.72	0.82	21.47	52.31

Table I summarises measured results related to different types of lamps. Except incandescent light bulb and fluorescent lamp the other loads represent group of compact fluorescent lamp (CFL), known as energy saving lamps. Since recently their number has rapidly increased and they have become very interesting for research. Namely, the replacement of incandescent light with CFL bulbs is often mentioned as one of the easiest ways to shrink your power bill and your carbon footprint. They represent the typical green-green situation, saving money and helping the environment. However price for improving the "green" features is paid from a quite different account. The basic problem with CFL lies in their non-linear nature. Consequently, they generate harmonics in currents so that I_{RMS} increases proportionally to harmonics. This reflects through the increase of S and D_B, as well. The last column in Table I indicates the seriousness of the problem. The unregistered distortion power occupies between 68.58% and 76.19%. Obviously it exceeds the registered active power that ranges between 0.58 and 0.63 of apparent power for CFLs. Practically for all nonlinear loads from Table I D_B is greater than P between 1,06 and 1,32 times. Figure 2 compares active with distortion component of power for all loads in Table I.
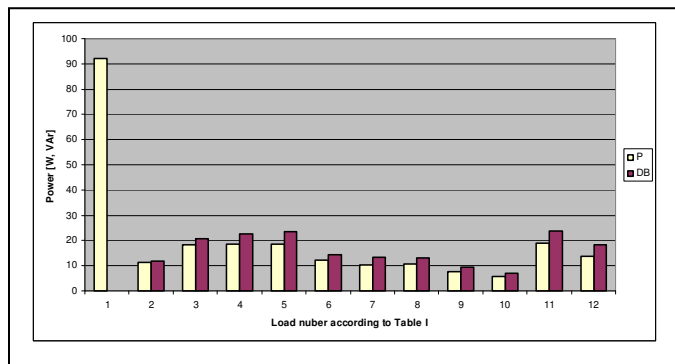

Figure 2. Comparison between active and distortion power spent on loads given in Table I

A careless observer could neglect these results claming that CFLs are small loads ($P < 20W$). However one should not overlook the number of these loads in the grid. Moreover, in terms of total energy, when the power is multiplied with the operation time, this issue becomes even more serious. Only for the public lightening the average operating time reaches more then 12 hours per day during the winter and is not less than 9 hours per day during the summer in this region (Balkan).

Table II presents results measured at loads usually used in households and offices. Their nominal power (active) ranges from 1W to 1kW.

According to expectations, on linear resistive loads (heater and ventilator) the active power is equal to apparent power and, consequently, D_B is zero. The third load in Table II (fridge) represents a linear reactive load that consumes considerable part of reactive power Q_B. Namely it is greater than active component of power P. The measured results show some small amount of distortion power D_B, as well. It is caused with harmonics that exist at voltage supply. Actually, according to standard IEEE 519-1995 the utility has to provide voltage with THD < 3% (*Total Harmonic Distortion*). Therefore the voltage is not pure sinewave but has small amount of harmonics. The reactive loads explore different impedance at different harmonics ($Z_1 \neq Z_3 \neq ... \neq Z_h$, h denotes the hth harmonics). In effect the currents at different harmonics will not be equal which reflects as $D_B \neq 0$. Other rows in Table II summarize results related to nonlinear loads. Therefore, they explore considerable values of D_B. These values reach up to 82% value of apparent power, in case of Printer HP M2727 during Stand-by mode. In comparison with active power it is 1,6 times greater. Although the real value of P is relatively small (13W) one should not neglect the fact that the utility measures loses in terms of real money that is correlated to energy i.e. integral of power in time. It is well known that most of time electronic equipments spend in stand-by mode. Besides, in printing mode the absolute value of D_B reaches almost 100VAR.

It is interesting to observe power consumption of nonlinear load during some time interval. As a remarkable example we took PC. Figure 3 shows power consumption of a PC during setup. For the duration of the whole observed period the distortion power is greater than active power. Undoubtedly the unregistered or wasted energy is greater than the active part. This is the main cause of losses for a utility. Therefore the billing policy should change. It would be fair to bill higher the consumers that introduce more harmonics into the grid. (The harmonics in currents pollute the sinewave voltage due to the finite resistance of transmission lines.) However this requires meters capable to register all three components of energy. In this paper we demonstrated that contemporary electronic meters could be upgraded at software level to provide all desired quantities. Namely, it is not difficult to implement the part of calculations performed in PC (Fig. 1) within dedicated

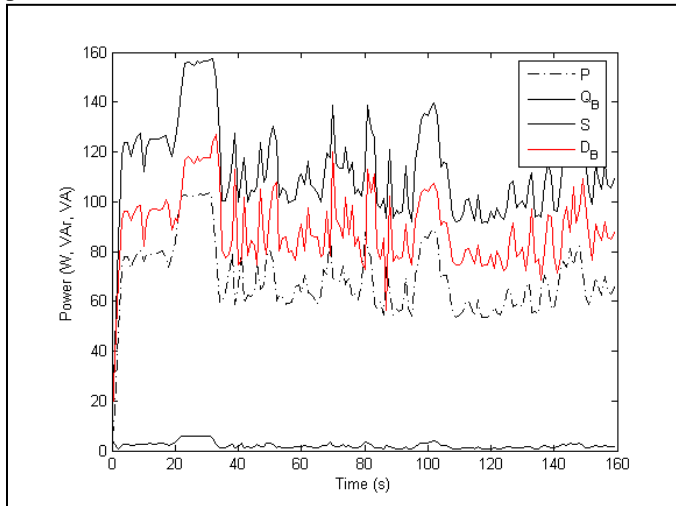DSP or microprocesor unit that already exist in electronic power meters.

Figure 3. Typical power consumption of PC during setup

IV. Conclusion

This paper presented results that should alert electric power utilities that the main cause of registered loses comes because of inadequate measuring. Moreover the paper offers an easy solution to the problem. The presented measured results prove that utility may have large losses due to the lack of registering distortion part of delivered power. Actually, as far as the authors were able to find out almost all utilities in Europe (Serbia is not an exception) relay billing only on active power measurements. However, in real life the number of nonlinear loads increases rapidly. That comes as the cost for greater interest for energy saving apparatus than before. For example, in case of energy efficient compact fluorescent lamps that replace classic light bulbs CFL the losses due the distortion power overcome 60% in comparison to the active power. Although each CFL 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 equipments and gadgets commonly used at households and offices (air conditioners, monitors, PCs, printers,...). Measurements during the set-up phase of a PC shows that the distortion power is greater than active power all the time. The same is with printers during stand-by mode.

Therefore the presented results undoubtedly indicate that utilities suffer a lot of losses just because power meters measure only the active power. It is interesting that utilities in some countries recently have invested money to replace power meters that measure only active power with the new that are capable to measure reactive power as well. However, all results presented in this paper indicate that the reactive part of power is smaller than distortion power in all apparatus without winding coils. For PC it is more than ten times smaller. Accordingly, involving reactive power as component of consumer's bill without measuring distortion power will not solve problems related to losses.

Some may argue that it is sufficient to register only the apparent power and separate active from non-active power. In our opinion this would be step back because contemporary power meters are capable to measure independently apparent, active and reactive power consumption. As presented in this and some previous papers of the same authors [8], only slight 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 provide to utility an opportunity to determine the source of nonlinear pollution at the grid [9]. This opens capability to bill separately every component of power. In our opinion this will cut the losses and will serve as mighty tool to manage the loading profile of the consumers.

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