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DOI: 10.1007/s40313-017-0330-2

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J Control Autom Electr Syst (2017) 28:654–663
DOI 10.1007/s40313-017-0330-2

Effects of Electronic Loads on Electrical Measurements, Power Quality and Billing

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Received: 9 September 2016 / Revised: 30 May 2017 / Accepted: 2 July 2017 / Published online: 17 July 2017
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Abstract This paper presents results from experimental studies carried out using an electronic device called a Dimmer Flex, developed at the Federal University of Mato Grosso, Brazil. The Dimmer Flex is able to evaluate the effects of electronically switched loads regarding electrical measurements, especially focusing on billing. It can be concluded from the studies that, depending on the switching characteristics, a switched load can be "transformed" to the meter in a load with inductive or capacitive behavior, therefore "absorbing or injecting" reactive power to the system it is connected to. This finding shows that electronically switched loads can interfere in electrical measurements and consequently may affect the billing process, underlining the need to evaluate, discuss and even review current measurement and billing methods.

Keywords Switched loads · Dimmer Flex · Power factor · Harmonic distortion

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1 Introduction

The quality of life of the world's population has evolved significantly in recent decades, partly due to technological advances achieved by mankind. In addition to these advances, there has also been a contribution of new materials and techniques having a direct influence on people's lives.

As an example, the introduction of electronic equipment to various sectors of society can be observed (Witherden et al 2010) , whether residential, industrial, commercial or public. In other words, nonlinear electronic loads can be found in today's society and this tendency is ever increasing, given that processes are increasingly being automatized and are becoming more efficient, and more comfort is being offered due to these new technologies.

However, a large part of society is not aware that such loads can cause disturbances in electrical networks (Witherden et al 2010) and, in some cases, even inflict damage, such as burning equipment. Therefore, it is important to note that electric power must be understood as a product and consequently must meet quality parameters. Moreover, this quality is important for utilities and consumers, because they must provide and receive electric power continuously in accordance with these parameters (Passos et al. 2015).

One of the problems of power quality observed in recent years is the level of harmonic distortion in electrical systems. This problem is largely due to an ever increasing amount of power converters and nonlinear loads that distort current waveforms and therefore voltage waveforms in the electrical system (Sepulchro et al 2014). Nonlinear loads generate harmonic currents that are injected into the electrical system and, consequently pollute and distort the waveforms of other connected loads (Alves 2016).

The characteristics mentioned above encourage the scientific community, professionals and other people interested in power quality to discuss this topic. In simple terms, the issue of energy supply has two focal points: the quality of the product, which is the focus of this article, addressing electrical energy technical parameters; and the quality of service, considering how utilities serve their consumers.

Among the various parameters used to evaluate the quality of the product, the following can be included: voltage harmonic distortion and the increasing importance given to massive use of nonlinear loads (Paredes 2011). Other effects of harmonics are anomalies in the operation, such as digital device logic failure, vibrations, failures in capacitor banks, increasing operational costs and heating in transformers causing loss and degradation of isolation (Alves 2016; Beltran-Carbajal and Silva-Navarro 2017; Hansen et al. 2000; Sousa et al. 2016).

Due to the evolution of electric loads, which have mainly become nonlinear (Witherden et al 2010), various power theories were developed, which seek to understand the behavior of electrical quantities considering electrical signals found in a system. It is worth mentioning that there is still no consensus about which theory would be the most suitable and there is controversy regarding the definition, for example, of reactive power and the power factor (PF) in systems with distorted voltage and current waveforms (Suhett 2008; Fiorucci 2015). In spite of this lack of consensus in the scientific community concerning reactive power in non-sinusoidal conditions, active power is well defined for these conditions. It should also be noted that this lack of consensus allows for different methods to measure reactive power and can lead to different results when harmonic distortions are present (Cataliotti et al. 2009). Finally, it should be emphasized that it is widely known that different load profiles directly influence the power factor calculation (Souza et al 2013; Fernandez et al 2011).

Studies also show that commercial meters currently being used produce significant errors in measurements, when there are distorted signals (Rodrigues 2009). For example, a study conducted in China (Vieira 2012) showed that some measuring equipment based on fundamental components failed to record almost 30% of the consumed energy, which entails huge costs to society in general.

Taking this into account, this paper describes experiments performed using an electronic device developed at the Federal University of Mato Grosso called a Dimmer Flex, aiming to analyze the effects of electronically switched loads considering the measurement system and billing process considered in Brazil.

2 Dimmer Flex

A Dimmer Flex is an electronic device (AC/AC converter) which enables full control of electrical voltages per half-cycle. Among the switching possibilities offered by the Dimmer Flex, two main ones can be highlighted: the first (Possibility 1) has similar characteristics to a common dimmer in terms of delaying the triggering angle; however, it is possible to control the triggering angle of the switch from 0 to 180 degrees for the positive half-cycle and from 180 to 360 degrees for the negative half-cycle; the second (Possibility 2) has an inverse feature of the previous one. Thus, the delay angle becomes the interruption or opening angle of the switches and the interruption angle can be controlled from 180 to 0 degrees for the positive half-cycle and from 360 to 180 degrees for the negative half-cycle.

This equipment has the capability of imposing flexible conditions of supply to the loads and can thus evaluate the effects of electronically switched loads on electric power measurements, considering a laboratory experimental assembly.

3 The Brazilian Tariff System–Regulatory Aspects

In Brazil, the body responsible for regulating the electricity sector is the Brazilian Electricity Regulatory Agency (ANEEL), linked to the Ministry of Mines and Energy (MME). Specifically, the Normative Resolution No. 414 of 9th September, 2010 (ANEEL 2012) deals with the General Conditions of Supplying Electricity, i.e., it addresses the relationship between consumers and utilities.

In the Brazilian market, there are two large groups of consumers: those called group A, served at medium and high voltage, and those called group B, served at low voltage. In addition, there is the so-called captive market, where consumers have no option of choosing the electric power supplier, and the free market, where consumers can choose their power supplier.

In the case of consumers from group A, they are charged not only for the active energy consumption, but also for the energy that is associated with the reactive power required by the loads (Santilio et al 2015). Therefore, the Normative Resolution No. 414/2010 establishes that (ANEEL. Normative Resolution No. 414, of September 9, 2010):

- The power factor of reference (fr), which can be inductive or capacitive, has a minimum value of 0.92.
- To calculate the amounts of surplus reactive power and the demand for surplus reactive power, these quantities should exceed the limit informed (0.92), observing the following time intervals:
- Between 23:30 and 06:30 h (i.e., the period of six consecutive hours, understood in this interval at the utility's discretion): the power factors observed in the time interval below 0.92 capacitive are considered;

- For the daily period, apart from the interval stated above, only the power factors observed in the time interval lower than 0.92 inductive are considered.

Therefore, the aim of this article is to analyze the influence that electronically switched loads can have on billing surplus reactive power and, consequently, the power factors considering the consumers which are charged in this situation (group A).

4 Electrical Power Measurements under Non-sinusoidal Conditions in Brazil

According to ANEEL:

> When there is harmonic distortion in the electrical network, the definition of reactive power and, consequently, the power factor is not necessarily the same as that valid for purely sinusoidal systems at 60 Hz (ANEEL 2012).

However, the Agency understands that there is uncertainty as to what the correct way is to measure the reactive power and power factor for non-sinusoidal conditions. Due to this, it published a Technical Note No. 0083/2012-SRD/ANEEL (ANEEL 2012), which outlines proposals for regulatory changes to improve the power factor of consumer units and billing of surplus reactive power, as well as proposing an open public hearing at that time to receive contributions from the community about the issues mentioned above.

It is known that the growth of nonlinear loads, such as computers, compact fluorescent lamps, LED lamps, frequency inverters, air conditioners inverters, among others, cause harmonic distortion in waveforms of electrical signals from distribution networks (Ferreira et al 2015). This feature directly influences power factor measurements, as can be seen in Eqs. 1, 2, 3 and 4, where harmonic distortions are considered in the calculations of these quantities (ANEEL 2012; Belchior et al 2015) In addition, the power factor is used to calculate the amounts of energy and reactive demand, as shown in Eqs. 5 and 6, which are billed when they exceed the limits of Resolution No. 414/2010 (ANEEL. Normative Resolution No. 414, of September 9, 2010).

Power factor:

$$\mathrm{PF} = \frac{P}{\sqrt{P^2 + Q^2}} \tag{1}$$

Active power:

$$P = \sum_{h=1}^{h=m\acute{a}x} V_h I_h \cos(\phi_h) \tag{2}$$

Apparent power:

$$S = VI = \sqrt{\sum_{h=1}^{h=m\acute{x}} V_h^2}\sqrt{\sum_{h=1}^{h=m\acute{a}x} I_h^2} \tag{3}$$

Non-active power:

$$N = \sqrt{S^2 - P^2} \tag{4}$$

Billing of surplus reactive power:

$$E_{\mathrm{RE}} = \sum_{T=1}^{n1}\left[\mathrm{EEAM}_T \times \left(\frac{f_{\mathrm{R}}}{f_T} - 1\right)\right] \times \mathrm{VR}_{\mathrm{ERE}} \tag{5}$$

Billing of surplus reactive power demand:

$$D_{\mathrm{RE}}(p) = \left[\underset{T=1}{\overset{n2}{\mathrm{MAX}}}\left(\mathrm{PAM}_T \times \frac{f_{\mathrm{R}}}{f_T}\right) - \mathrm{PAF}(p)\right] \times \mathrm{VR}_{\mathrm{DRE}} \tag{6}$$

where:

- E_{RE} = value corresponding to the surplus reactive power considering the quantity allowed by the reference power factor "f_{R}" in the billing period in Brazilian currency (Reais - R$);
- EEAMT = amount of active power measured in each 1 h interval "T" for the billing period, in megawatt-hour (MWh);
- f_{R} = reference power factor equal to 0.92;
- f_T = power factor of the consumer, calculated in 1 h interval "T" for the billing period;
- $\mathrm{VR}_{\mathrm{ERE}}$ = reference value equivalent to the energy tariff "*ET*" applicable to subgroup B1, in Brazilian Reais (R $) for megawatt-hour (R $ /MWh);
- $D_{\mathrm{RE}}(p)$ = value, by post time "p" corresponding to the demand for surplus reactive power considering the quantity allowed by the reference power factor "f_{R}" in the billing period in Brazilian Reais (R$);
- PAM_T = active power demand measured as the reference interval of one (1) hour "T" during the billing period in kilowatts (kW);
- $\mathrm{PAF}(p)$ = demand for billable active power in each allocated time "p" in the billing period in kilowatts (kW);
- $\mathrm{VR}_{\mathrm{DRE}}$ = reference value in Reais per kilowatt (R$ / kW). It is equivalent to the power demand charges for the off-peak time. It is equivalent to supply tariffs for subgroups in Group A, for the blue time tariff mode. It is equivalent to the Distribution System Tariff Use (TUSD) for free consumers, according to their Supply Agreement (CUSD);

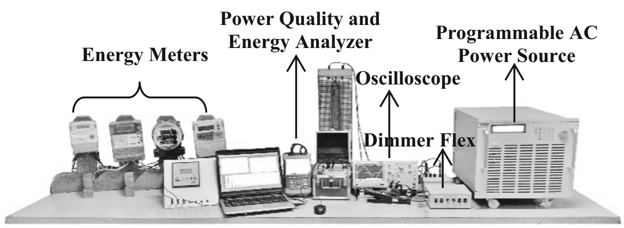

Fig. 1 Experimental assembly

- MAX = function that identifies the maximum value of the equation between brackets corresponding to each time “p”;
- T = indicates the interval of one (1) hour in the billing period;
- p = means the peak or off-peak time, for the hourly tariff arrangements or billing period for conventional tariff mode binomial;
- $n1$ = number of payment intervals “T” billing period for the peak and off-peak time;
- $n2$ = number of payment intervals “T” for time “p” in the billing period.

Moreover, the same resolution defines peak tariff (*in Portuguese*, P), as being the period consisting of three (3) consecutive hours per day defined by the utility, considering the load curve of its electrical system, approved by ANEEL for the whole concession or permission area, except for Saturdays, Sundays and public holidays. The off-peak time (*in Portuguese*, FP) is the daily set of consecutive and complementary hours.

It is worth mentioning that ANEEL proposed to change the definition of the power factor for the purpose of measuring and billing electricity, suggesting, although preliminarily, that the value of this quantity is obtained only on the basis of voltage and current signals of the fundamental frequency −60 Hz (ANEEL 2012).

It is important to highlight that commercial energy meters meet international standards and follow the classical power theories, such as the IEEE Standard 1459, that represents nowadays the most extended model for the decomposition of the apparent power terms, in conditions of asymmetry and distortion (Thomas et al. 2016).

5 Experimental Assembly

Figures. 1 and 2 illustrate the assembly and a block diagram, respectively. Table 1 describes the equipment used.

It should be noted that, according to Osnach 2010, switched circuits with purely active elements (resistive) generate in-depth discussions regarding the presence or absence of reactive power. This is one of the aspects analyzed in this paper. The author compares the results with the IEEE Std. 1459 theory, which is also used in this study.

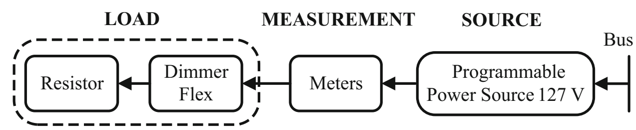

Fig. 2 Block diagram of the experimental assembly

Table 1 Equipment used

Programmable AC Power Source Chroma 61702
Resistor (110 ohms)
Power Quality and Energy Analyzer (FLUKE 434)
Power Meter SAGA 1000 (Landis+Gyr)
Power Meter SAGA 3000 (Landis+Gyr)
Power Meter E34A (Landis+Gyr)
Power Meter SL7000 (Actaris)
Power Meter A1055 (Elster)
Oscilloscope Tektronix (MSO 2022B)
Dimmer Flex

6 Experimental Results

In order to evaluate the effects of electronic load switching presented in Fig. 2, as well as collecting data which can evaluate the proposal of this study, three scenarios were set up. They are the following:

(a) Scenario 01 - Without switching
(b) Scenario 02 - Possibility 01
(c) Scenario 03 - Possibility 02

It was recorded that all instruments used present converging results. For this reason, only the screens with the results showing the FLUKE Power Quality and Energy Analyzer and the images of the oscilloscope screen were presented.

(a) Scenario 01 - Without switching

For this scenario, or base case, load switching was not carried out and, therefore, both signals remained sinusoidal (voltage and current), obtaining the waveforms as shown in Fig. 3.

Figure 4 shows the power value measurements (active, apparent and reactive), as well as the power factor value, fundamental power factor which considers only the fundamental signals 60 Hz (IEEE Std 1459 2010), effective voltage and current. It should be noted, in this case, that the power factor is unity and the reactive power is equal to zero.

Figure 5 shows the phasor diagram for scenario 01. It is worth mentioning that this diagram refers to the fundamental

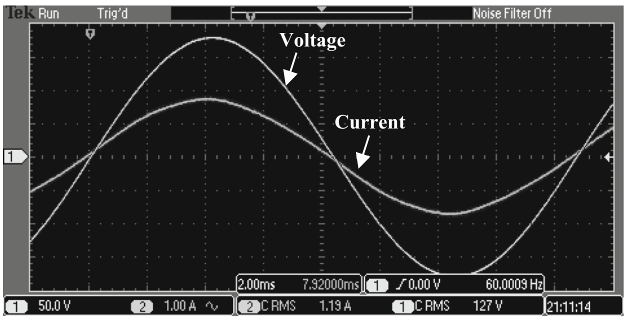

Fig. 3 Voltage and current waveforms—scenario 01

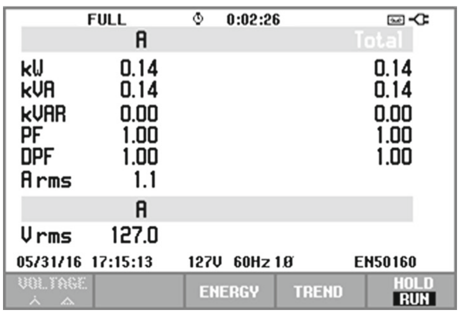

Fig. 4 Electrical quantity measurements—scenario 01

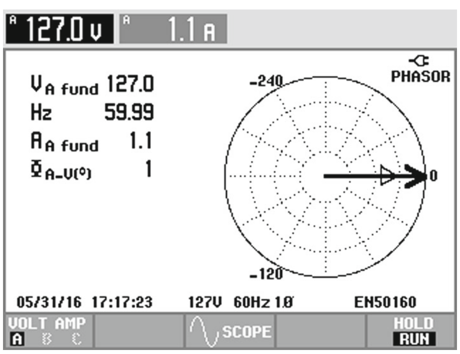

Fig. 5 Phasor diagram—scenario 01

components of the voltage and current signals (only 60 Hz) and that, in this scenario, there is no discrepancy between them.

(b) Scenario 02 - Possibility 01

Based on the initial situation, or base case, the Dimmer Flex was adjusted to carry out switching in order to verify the behavior of the electrical quantities recorded by the commercial meters for billing purposes. The angles defined for the switching in this scenario were manually adjusted close to 90 degrees for the positive half-cycle and consequently 270 degrees for the negative half-cycle. It should be noted that this non-accuracy in the angles does not interfere in the results, whose aim is to observe the effects caused by switching on the electrical measurements.

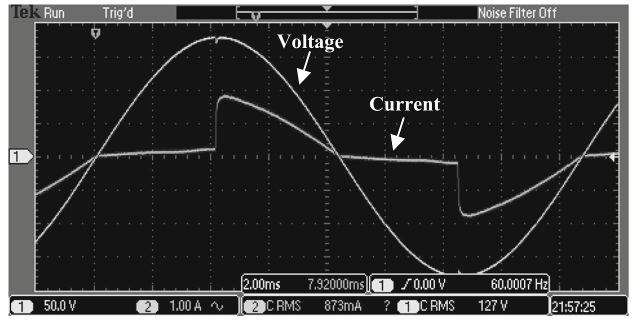

Fig. 6 Voltage and current waveforms—scenario 02

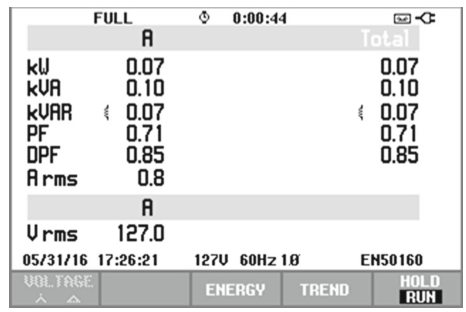

Fig. 7 Electrical quantity measurements—scenario 02

Figure 6 shows the voltage and current waveforms. It can be observed that in this figure the current waveform no longer displays the sinusoidal form due to the effect caused by switching.

It is worth mentioning that during the experiment, we observed a reduction in the effective current value caused by switching, as observed in the numbers shown in Fig 7. It is also worth noting that the electrical quantities recorded have changed.

As stated, there was a decrease in the effective current value due to switching. This fact explains the reduction in the demanded active power and the apparent power, which went from 0.14 kVA to 0.10 kVA. However, considering the measurement and billing energy system, the load began to consume reactive power from the network, behaving as an RL load, as illustrated in Fig. 7.

For scenario 02, the total current harmonic distortion was 65.0%, as shown in Fig. 8, i.e., there was a significant amount of distortion for the current.

It should be noted that this level of distortion in the current will vary according to the triggering angle adjusted in the Dimmer Flex, reaching more than 100% in the most critical condition.

The findings mentioned in this scenario are validated in Fig. 9, where the inductive behavior of the circuit can be observed. This diagram refers to the fundamental component of the signals. In the example, the angle between the voltage and current signals was equivalent to −32 degrees.

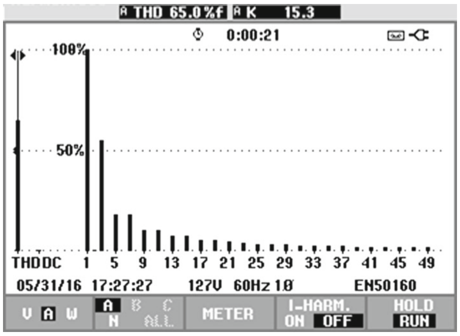

Fig. 8 Total current harmonic distortion—scenario 02

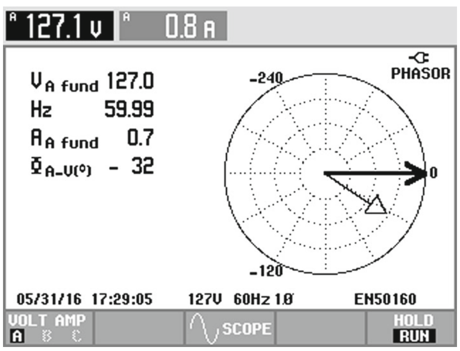

Fig. 9 Phasor diagram—scenario 02

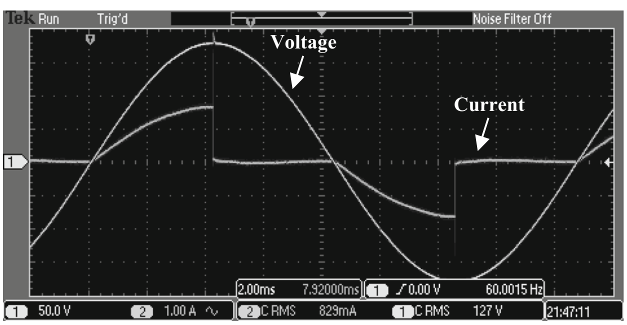

Fig. 10 Voltage and current waveforms—scenario 03

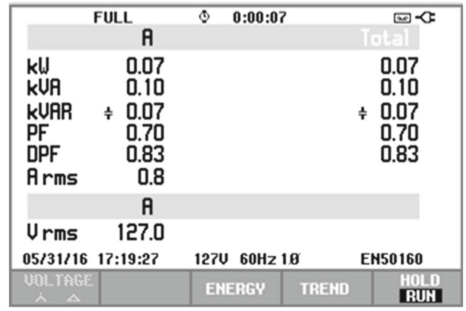

Fig. 11 Electrical quantity measurements—scenario 03

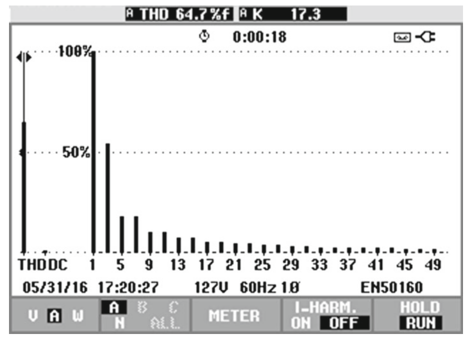

Fig. 12 Total harmonic distortion of the current—scenario 03

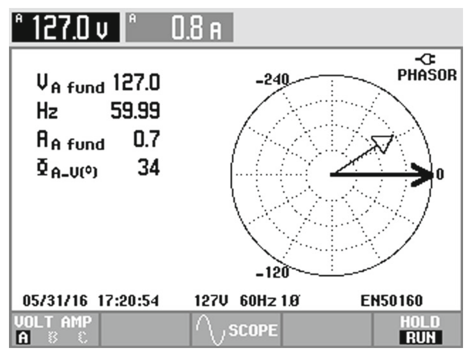

Fig. 13 Phasor diagram—scenario 03

(c) Scenario 03 - Possibility 02

In the third and final scenario analyzed (scenario 03), the switching was set for possibility 02, i.e., interruption of triggering pulses for switches at 90/270 degrees. Figure 10 shows the effect of this operative condition in the required current, which is again clearly non-sinusoidal. The conducting times are complementary to those observed in scenario 02 (which was expected).

For this scenario (Fig 11), as well as in the previous example, the power, current, power factor and fundamental power factor differ from those reached in the base case. The finding that is worth mentioning is that the reactive power shows capacitive characteristics. In other words, the load began to "inject" reactive power into the network, shown by the symbol of a capacitor displayed on the analyzer screen.

In scenario 03, for the adjusted switching value, the total harmonic distortion of the current was 64.7%, as shown in Fig. 12.

It should also be pointed out that, although close by, the angles used in scenarios 02 and 03 were not exactly the same, however due to the reasons mentioned, this does not affect the results obtained.

Finally, the phasor diagram of scenario 03 can be observed in Fig. 13, whereby the current is advanced compared to the voltage. This diagram refers to the fundamental component of the signals. For this scenario, the angle between the voltage and current signals was equivalent to 34 degrees.

Table 2 Details of the meters—scenario 02

Meter	Information
Power Meter SAGA 1000	PFi
Power Meter SAGA 3000	+PF
Power Meter E34A	
Power Meter SL7000	
Power Meter A1055	

Table 3 Details of the meters—scenario 03

Meter	Information
Power Meter SAGA 1000	PFc
Power Meter SAGA 3000	−PF
Power Meter E34A	
Power Meter SL7000	
Power Meter A1055	

The results obtained from the measuring equipment used showed that, in fact, the type of switching changes the load characteristic considering the measurements. Another study reinforces this analysis. In Osnach (2010), switching was carried out using thyristors from a single-phase load, with RL characteristics. After calculating, harmonics with capacitive characteristics appeared, which contradicts the logic as the circuit being analyzed only had an inductive element (as well as the resistive).

To prove that the characteristic of the load converged in all the meters (between inductive or capacitive), the simultaneous information from the meter screens used in the experiments is shown in Tables 2 and 3, when switching was carried out. It is worth highlighting that each meter shows information about the characteristic of the load in one way. In other words, the representation of a given inductive or capacitive load can be shown by index "i" or "c", a signal (positive or negative) or by an arrow (positive or negative).

It should be noted that, in the case of the SAGA 1000 and 3000 meters, the power factor appears, respectively, as follows: PFi (inductive) and +PF (also showing the inductive characteristic). In the other meters, the power factor appears only in the module and the indication of the inductive load is given by the direction and reactive power sign (+Q or Q+ and upward arrow).

Table 4 Current tariffs in 2016-EMT

Tariff modality	Tariff (R$/kWh)	Tariff FP (R$/kWh)	Tariff P (R$/kWh)
Conventional A4	0.34160	–	–
Green Time A4	–	0.32978	1.33124
Blue Time A4	–	0.32978	0.47165

Similar to the previous analysis, in the case of the SAGA 1000 and 3000 m, the power factor appears, respectively, as follows: PFc (capacitive) and −PF (also showing the capacitive characteristic). In the other meters, the power factor only appears in the module and the indication of the capacitive load is given by the direction and sign of reactive power (-Q or Q- and downward arrow).

7 Impacts on Billing

Based on the results, we present the analyses carried out by focusing on the impacts of electricity billing. Therefore, the following data is considered:

- Active power: 0.07 kW;
- VR_{ERE}: 0.26757 R$/kWh;
- Reference power factor: 0.92;
- Power factor of the consumer unit: 0.70.

Table 4 presents the energy price tariffs, comprising the TUSD + ET (energy tariff) portions, not including taxes, for each tariff modality, based on the values in 2016 for the Mato Grosso Energisa Utility (EMT). These tariffs were used to illustrate the impact on billing electricity. However, it should be noted that the price tariffs can be changed to other regions of the country or even to other countries, paying attention to the billing rules. The latter may be different to Brazil.

Afterward, the amounts of surplus reactive energy were calculated based on Eq. (5) for peak times (P) and off-peak times (FP). In addition, the period between the inductive and capacitive intervals was divided as shown in item III, according to the hours of the day. Considering an annual base, it is known that, on average, a month has 730 h. Therefore, according to the definitions of hour divisions for billing purposes (also shown in item III) and making appropriate distributions, we have the following:

- Average hours in 1 month: 730 h;
- Average hours in 1 month, off-peak period for the inductive interval: 482.25 h;
- Average hours in 1 month, peak period for the inductive interval: 65.25 h;
- Average hours in 1 month, off-peak period for the capacitive interval: 182.5 h;

Table 5 Surplus reactive energy *vs* active energy consumed—inductive case

	Tariff modality				
	Conventional	Green time		Blue time	
	–	FP	P	lFP	P
% partial reactive/active	–	18.59	6.10	18.59	17.21
% total reactive/active	18.46	15.04		18.42	

Table 6 Surplus reactive energy *vs* active energy consumed—inductive case

Power factor	Conventional (%)	Green time (%)	Blue time (%)
0.1	481.72	392.46	480.51
0.2	211.49	172.30	210.96
0.3	121.41	98.91	121.10
0.4	76.37	62.22	76.18
0.5	49.35	40.20	49.22
0.6	31.33	25.53	31.25
0.7	18.46	15.04	18.42
0.8	8.81	7.18	8.79
0.9	1.31	1.06	1.30
1	0.00	0.00	0.00

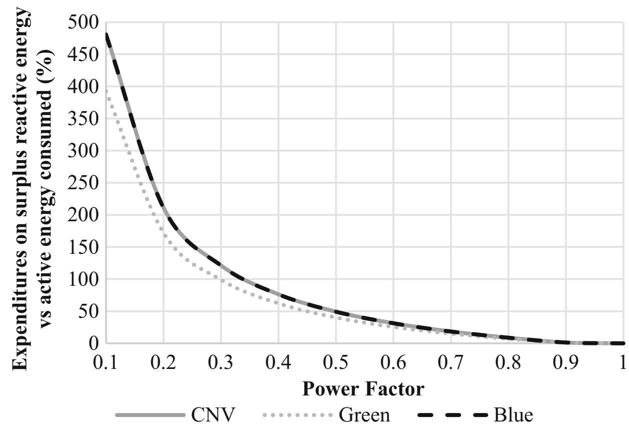

Fig. 14 Relation between surplus reactive energy costs and active energy costs—inductive case

- Average hours in 1 month, peak period for the capacitive interval: there is no peak period.

Therefore, based on the assumptions presented, some calculations were made to identify the percentage spent on surplus reactive power compared to the total spent on the amount of active energy consumed in a given time interval. In other words, the aim was to analyze how much surplus reactive power can influence electricity billing when compared to the active energy that was consumed. It should be noted that taxes were not included in this analysis.

Table 5 presents the results, considering only the inductive period of the day. To determine the values shown in this table, we identified how much was spent on active energy, based on the data presented at the beginning of this item and the average number of hours in a month (730 h), maintaining the active load constant throughout the day. Afterward, the amount of surplus reactive power was calculated by Equation (5). Taking this into account, the data presented at the beginning of this item were also considered, but the number of hours was 547.5 h (65.25 h for the peak period and 482.25 h for the off-peak period), as only the inductive period was analyzed (i.e., the 182.5 h for the capacitive period were not considered).

It is important to highlight how these hourly intervals were found, so that the following analysis is clearer. These intervals were based on an average number of days per month on an annual basis. For the capacitive period, this average was multiplied by 6 h, due to what was stated in item 3. Thus, the difference between the average value of hours in a month (730 h) and the value for the capacitive period (182.5 h) is precisely the number of hours of the inductive period (547.5 h). The latter was divided, considering the above in item 3, between the hours in the inductive peak period (65.25) and the hours in the inductive off-peak period (482.25 h).

In Table 5, it can be concluded that the expenditures on surplus reactive power for the example analyzed can represent between 15.04 and 18.46% of the total amount spent on active energy. Still considering only the inductive interval (06:31 until 23:29), we calculated the percentages shown in Table 5, however for other values of the consumer power factor. The results are presented in Table 6.

As shown in Table 6, depending on the power factor value of the consumer, expenditures on surplus reactive energy can have a significant impact on electricity billing. It may represent more than 50%, compared to expenditures on active energy, if the power factor is below 0.5. If typical values of real facilities are considered (power factor between 0.6 and 0.9), the costs of such surplus represents up to 30%, which is very significant.

Figure 14 shows a curve representing the data in Table 6.

As shown in Fig. 14 and, as expected, the expenditures spent on surplus reactive energy decrease, while the power factor increases. When the power factor of the consumer is higher than 0.92, there is no charge for this surplus.

Table 7 Surplus reactive energy *vs* active energy consumed—capacitive case

	Tariff modality		
	Conventional	Green time	Blue time
	–	FP	FP
% Total reactive/active	6.15	5.01	6.14

Table 8 Surplus reactive energy *vs* active energy consumed—capacitive case

Power factor	Conventional (%)	Green time (%)	Blue time (%)
0.1	160.57	130.82	160.17
0.2	70.50	57.43	70.32
0.3	40.47	32.97	40.37
0.4	25.46	20.74	25.39
0.5	16.45	13.40	16.41
0.6	10.44	8.51	10.42
0.7	6.15	5.01	6.14
0.8	2.94	2.39	2.93
0.9	0.44	0.35	0.43
1	0.00	0.00	0.00

The same calculations were made for the capacitive period. Obviously, the necessary adjustments were made regarding the number of hours considered for this case. Table 7 shows the results.

In Table 7, it can be concluded that the surplus reactive energy costs (in this case) can represent between 5.01 and 6.14% of the total expenditure on active energy. It is worth mentioning that in the capacitive interval, there is no peak period and, due to this, only the total percentage was calculated. Still considering only the capacitive interval (23:30 until 06:30), we calculated the percentages for the other power factor values of the consumer. The results are presented in Table 8.

As shown in Table 8, depending on the power factor value of the consumer, the surplus reactive energy costs can have a significant impact on electricity billing. If typical values of real facilities are considered (power factor between 0.6 and 0.9), the costs of such surplus represent up to 10.44 %, which is significant.

Figure 15 shows a curve representing the data in Table 8.

As presented in Fig. 15 and, as expected, the expenditures on surplus reactive power decrease, while the power factor increases. When the power factor of the consumer unit is greater than 0.92, there is no charge for this surplus.

Based on the results, it can be concluded that electronically switched loads can directly affect measurements and, consequently, electricity billing. The experimental assembly shown in item 5 supports this claim. As an example, the following situations can be cited:

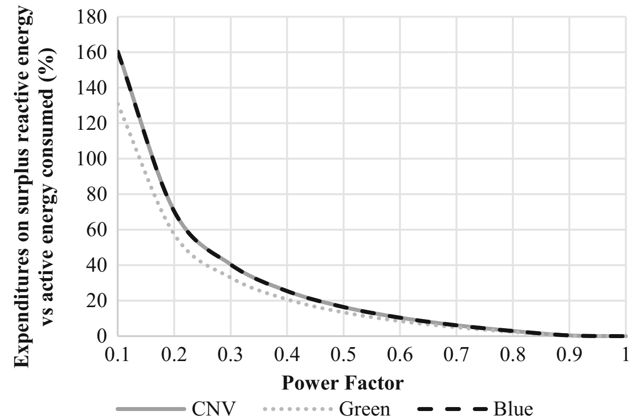

Fig. 15 Relation between the surplus reactive energy costs and expenditures on active energy—capacitive case

1. If the Dimmer Flex is programmed to operate in possibility 01, the power system measurements will recognize an inductive load. Therefore, if the power factor is below the value established by law (in the case of Brazil, 0.92), the consumer will pay for the surplus reactive power, as shown in this section (Table 6). In terms of percentages, the expenditures spent on reactive power may vary between 1.06 and 481.72%, compared to expenditures on active energy;
2. However, if the Dimmer Flex is programmed to work in possibility 02, the power system measurements will recognize a capacitive load. Therefore, if the power factor is below the value established by law (in the case of Brazil, 0.92), the consumer will pay the surplus reactive power, as shown in Table 8. In terms of percentages, the expenditures spent on reactive power may vary between 0.35 and 160.57%, compared to expenditures on active energy;
3. However, if the Dimmer Flex is programmed to have a capacitive characteristic during the inductive period or an inductive characteristic during the capacitive period, even if the power factor is below the established limit (0.92), there will be no payment associated with reactive surplus.

8 Conclusions

It can be concluded that electronically switched loads, which have a nonlinear behavior, such as the cases shown in this article, influence and affect electricity measurement and billing systems. As shown in this paper, there is interference in the measurements of surplus reactive power, as well as in the power factor.

It can also be observed that electronic switching of a resistive (linear) load results in inductive or capacitive behavior. This shows that the electricity billing system being recorded can be changed in the way that surplus reactive power will not be paid for. Considering the possibilities of switching addressed, it has been shown that a consumer from Group A may not pay for surplus reactive power, even though the power factor of the installation is lower than the limit established by Brazilian law. This fact shows the need to discuss the question of dividing inductive and capacitive periods in terms of billing surplus reactive power.

In other words, the injection of capacitive reactive power and absorption of inductive reactive power recorded by meters and power quality analyzers on consumers common coupling points are affected by the different types of switching. Furthermore, this can contribute to changing the power factor in the consumer and, consequently may affect the calculations of surplus reactive energy in the inductive and capacitive periods.

Therefore, it is important to develop additional research in this area, analyzing the behavior and influence of various electronically switched loads in power systems (such as frequency converters, computers and electronic lamps) in an isolated and integrated way, including measurements carried out in the field.

Regulatory aspects and measurement methods also need to be discussed in terms of the electrical quantities in non-sinusoidal conditions, aiming to establish a model for electricity billing, based on existing theories or even new theories.

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