Harmonic Distortion as an Influence Quantity on Reactive Static Electrical Energy Meters

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Abstract. This article presents test results from static electrical energy meters, indicating their susceptibility to the total harmonic distortion (THD) present at the mains line. This particular characteristic impacts directly in measuring reactive energy and power factor for billing purposes.

1. Introduction
Historically, generation, transmission, and distribution of electrical energy is held in a fixed frequency of 60Hz in Brazil. However, the extensive use of non-linear loads changed continuously over time, turning purely sinusoidal waveforms into complex nonsinusoidal signals.

Although the definition of active electrical energy for measurement purposes has long been established – even in terms of its equations and mathematical formulation [1] – the same doesn’t occur for reactive electrical energy. There is no international agreement on the concepts of power factor and reactive electrical energy in nonsinusoidal situations for measurement and billing purposes [1].

The Brazilian Electrical Energy Agency (ANEEL) defines active power, reactive power and power factor as (in a free translation):

**XXXI** – active electrical energy: that one which can be converted in another form of energy, expressed in, kilowatt hour (kWh);

**XXXII** – reactive electrical energy: that one which flows through diverse both electric and magnetic fields in an alternate current system, without producing work, expressed in reactive kilovolt-ampere hour (kvarh);

...

**XXXV** – power factor: quotient between active electrical energy and the square root of the sum of the squares of the active electrical energy and reactive electrical energy, consumed at the same period of time.

Active electrical energy can be seen as the integral of average power through time, yielding simple mathematical formulas [1] suitable for both sinusoidal and nonsinusoidal situations.

However, it is not possible to derive simple formulas using the above reactive electrical energy definition in nonsinusoidal situations. The above definition does not arise from the concepts of voltage and current neither contemplates the scenario of modern electrical systems, where total harmonic distortion (THD) levels makes the waveforms substantially nonsinusoidal.
The power factor calculation is also influenced by the reactive energy definition, yielding a quantity strongly dependent on harmonics in the mains line.

An attempt to characterize the electrical powers and energies that arise in non-sinusoidal environment is described in IEEE Standard 1459-2010 [1], which was taken as a basis for the present study.

In order to improve the regulation regarding power factor and billing for excess reactive power, ANEEL called the public hearing 065/2012 [3]. Among its key proposals is that, even in environments with non-sinusoidal waveforms, one should perform the calculation of the power factor for billing purposes exclusively on nominal frequency of the power grid.

In practical terms, the measurement of electrical energy for power factor calculation should be performed at 60 Hz for both, active and reactive energy. This would require electricity meters extremely selective in frequency, capable of perform the measurement of energy only at 60 Hz.

This study aims to evaluate how electronic electricity meters, with models approved by Brazilian Institute of Metrology, Quality and Technology (Inmetro) [4], would behave in an environment with non-sinusoidal waveforms [5-8]. To do so, shall be measured reactive power measurement errors in various situations of harmonic distortion in waveforms of voltage and current, trying to characterize them as influence quantities in the measurement of electricity.

In order to obtain experimental data, various electronic electricity meters were subjected to a series of situations with forms of non-sinusoidal wave. The meters were submitted to two test plans in order to characterize:

A. A most unfavorable condition for reactive power measurement in an harmonic environment;
B. The behavior of the tested static meters in the condition identified in (A), searching for correlations between errors and THD.

It was found that the meters are particularly susceptible to the harmonic content of the power grid, provided specific harmonic voltage and current of the same order occurring simultaneously, showing the correlation between the harmonic distortion and errors of energy measurement, characterizing the former as influence quantity of the second.

2. Power in the IEEE 1459-2010 Standard Definitions
This sections aims to state a brief description of IEEE 1459-2013 Standard Definitions to the reader not familiar with its concepts.

Aware of the challenge of standardize the concepts of electric power at both sinusoidal and nonsinusoidal environments, for symmetrical and nonsymmetrical loads, IEEE took efforts creating an workgroup to propose modern and broadly accepted concepts of electrical power, reflecting the state of art in electrical energy measuring understanding.

The IEEE 1459-2010 Standard Definitions are based on apparent power calculations through voltage and current root mean square (RMS) values. Here one analyses the single phase case, which can be easily extended to three phase systems.

Assume that voltage and current continuous time signals, \(v(t)\) and \(i(t)\), respectively. Their RMS values can be calculated through their integrals over time along an integer number \((k \in \mathbb{N})\) of time periods \((T)\):

\[
V^2 = \frac{1}{kT} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} v(t)^2 dt \tag{1}
\]

\[
i^2 = \frac{1}{kT} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} i(t)^2 dt \tag{2}
\]

Apparent power \(S\) (VA) is calculated through the product between voltage and current RMS values (1) and (2):
First harmonic waveforms, both for voltage and current, as well as the sum of the remaining harmonics, are defined as:

\[ S = VI \]  \hspace{1cm} (3)

\[ v_1(t) = \sqrt{2}V_1 \sin(\omega t - \alpha_1) \]  \hspace{1cm} (4)

\[ i_1(t) = \sqrt{2}I_1 \sin(\omega t - \beta_1) \]  \hspace{1cm} (5)

\[ v_h(t) = V_0 + \sqrt{2} \sum_{h \neq 1} V_h \sin(h \omega t - \alpha_h) \]  \hspace{1cm} (6)

\[ i_h(t) = I_0 + \sqrt{2} \sum_{h \neq 1} I_h \sin(h \omega t - \beta_h) \]  \hspace{1cm} (7)

where \( V_0 \) and \( I_0 \) are average (DC) values of voltage and current, \( V_1 \) and \( I_1 \) are voltage and current fundamental harmonic RMS values, \( V_h \) and \( I_h \) are voltage and current high order harmonic RMS values of \( h \) order, \( \alpha_h \) and \( \beta_h \) are phase angles for voltage and current \( h \) order harmonics, \( v_1(t) \) and \( i_1(t) \) are voltage and current fundamental waveforms, \( v_h(t) \) and \( i_h(t) \) are \( h \) order harmonics voltage and current waveforms.

Full voltage and current waveforms (8) and (9) can be posed as the sum of fundamental waveforms (4) and (5) with the respective harmonic waveforms (6) and (7).

\[ v(t) = v_1(t) + v_h(t) \]  \hspace{1cm} (8)

\[ i(t) = i_1(t) + i_h(t) \]  \hspace{1cm} (9)

RMS values of both fundamental and harmonic voltages (10) and currents (11) are intertwined by:

\[ V_H^2 = V_0^2 + \sum_{h \neq 1} V_h^2 = V^2 - V_1^2 \]  \hspace{1cm} (10)

\[ I_H^2 = I_0^2 + \sum_{h \neq 1} I_h^2 = I^2 - I_1^2 \]  \hspace{1cm} (11)

One can notice that, although voltage and current average values \( V_0 \) e \( I_0 \) aren’t harmonics, their values are included in \( V_H \) and \( I_H \), considering that in alternate waveform systems, they are Always low amplitude values.

Active power (12) is calculated as the instantaneous power \( p(t) = v(t)i(t) \) average value:

\[ P = \frac{1}{kt} \int_{t}^{t+kt} v(t)i(t)dt \]  \hspace{1cm} (12)

Fundamental active power \( P_1 \) (W) and harmonic active power \( P_H \) (W) are defined as:

\[ P_1 = \frac{1}{kt} \int_{t}^{t+kt} v_1(t)i_1(t)dt = V_1 I_1 \cos \theta_1 \]  \hspace{1cm} (13)

\[ P_H = V_0 I_0 + \sum_{h \neq 1} V_h I_h \cos \theta_h = P - P_1 \]  \hspace{1cm} (14)

In the same trend, fundamental reactive power \( Q_1 \) (VAR) is defined as:

\[ Q_1 = \frac{\omega}{kt} \int_{t}^{t+kt} \left[ \int_{t}^{t+kt} v_1(t)dt \right] dt = V_1 I_1 \sin \theta_1 \]  \hspace{1cm} (15)
where $\omega$ is the angular frequency and $\theta_1$ is the fundamental harmonic phasor angle between voltage and current.

Fundamental apparent power $S_1$ (VA) is defined as the product between voltage and current fundamental RMS values:

$$S_1 = V_1 I_1$$

$$S_1^2 = P_1^2 + Q_1^2$$

Apparent power $S$ (VA) is split into fundamental apparent power ($S_1$) and nonfundamental apparent power ($S_N$):

$$S^2 = (VI)^2 = (V_1^2 + V_H^2)(I_1^2 + I_H^2)$$

$$S^2 = (V_1 I_1)^2 + (V_1 I_H)^2 + (V_H I_1)^2 + (V_H I_H)^2$$

$$S^2 = S_1^2 + S_N^2$$

Nonfundamental apparent power $S_N$ (VA) can be defined as the difference between apparent power (18) and fundamental apparent power (17):

$$S_N = \sqrt{S^2 - S_1^2}$$

Nonfundamental apparent power can be described also as a three term quadratic sum: current distortion power $D_I$, voltage distortion power $D_V$ and harmonic apparent power $S_H$:

$$S_N^2 = D_I^2 + D_V^2 + S_H^2$$

Current distortion power $D_I$ (VAR) is stated as:

$$D_I = V_1 I_H$$

Voltage distortion power $D_V$ (VAR) is stated as:

$$D_V = V_H I_1$$

Harmonic distortion power $S_H$ (VA) can be stated as composed by harmonic active power $P_H$ (W) and harmonic distortion power $D_H$ (VAR):

$$S_H = V_H I_H = \sqrt{P_H^2 + D_H^2}$$

Harmonic distortion power, $P_H$, defined by (14), is determined by the product of voltage and current harmonics of order. Harmonic distortion power is composed by the product of voltage and current harmonics of different orders.

$$D_H = \sqrt{S_H^2 - P_H^2}$$

Nonactive power $N$ (VAR) is defined as the difference between apparent power and active power taken as orthogonal vectors:
\[ N = \sqrt{S^2 - P^2} \]  

(27)

The fundamental power factor can be defined by taking into account only fundamental active and fundamental apparent power:

\[ PF_1 = \cos \theta_1 = \frac{P_1}{S_1} \]  

(28)

Power factor is defined by taking into account active and apparent power:

\[ PF = \frac{P}{S} \]  

(29)

According to [1], one can define the following power zoo (Table 1):

| Quantity or indicator | Combined | Fundamental | Nonfundamental |
|------------------------|----------|-------------|---------------|
| Apparent Active        | S (VA)   | S_1 (VA)   | S_N e S_H (VA)|
| Nonactive Line utilization | P (W)   | P_1 (W)   | P_H (W)       |
| Harmonic pollution     | Q_1 (VAR)| D_1, D_H e D_H (VAR)|
|                        | PF = P/S | PF_1 = P_1/S_1  |               |
|                        |          | \(S_N/S_1\)    |               |

One can notice that in [1] the concept of Budeanu’s reactive power \(Q_B\) (30) was ruled out, because it represents an immeasurable and nonphysical indicator:

\[ Q_B = \sum_{h=1}^{\infty} V_h I_h \cos \theta_h \]  

(30)

In a nutshell, one can summarize quantities and indicators presented previously through Figure 1, where each rectangle represents one species in the power zoo. Each power is defined as a quadratic sum of the internal rectangles, as defined in (17), (20), (22) and (25).

**Figure 1** – Pictorial Representation of Powers in IEEE 1459-2010
3. Harmonic Distortion
In this section one presents a brief description of harmonic distortion concepts into order to unify the reader’s understanding. One considers that a waveform of voltage \( v(t) \) or current \( i(t) \) is represented by the generic signal \( x(t) \).

According to [2], the total harmonic distortion is defined by (1):

\[
\text{THD}_x = \frac{X_h}{X_1} = \sqrt{\left(\frac{X}{X_1}\right)^2 - 1} \quad (1)
\]

where \( X \) represents the rms value of the quantity in question, \( V \) or \( I \), calculated from the integration of the squared waveforms over an integer \( (k \in \mathbb{N}) \) of periods (T) of the fundamental harmonic (2):

\[
X^2 = \frac{1}{kT} \int_{t}^{t+kT} x(t)^2 \, dt \quad (2)
\]

The voltage signals or current can be decomposed as:

\[
x(t) = x_1(t) + x_h(t) \quad (3)
\]

where \( x_1(t) \) is the fundamental waveforms of voltage or current, given by:

\[
x_1(t) = \sqrt{2}X_1 \sin(\omega t - \alpha_{x1}) \quad (4)
\]

where \( X_1 \) is the RMS value of (4), \( \omega \) is the fundamental angular frequency and \( \alpha_{x1} \) is the phase angle for the current or voltage.

Likewise, one may define the waveforms of voltages and currents by the sum of its harmonic components plus each of their respective average values:

\[
x_h(t) = X_0 + \sqrt{2} \sum_{h \neq 1} X_h \sin(h\omega t - \alpha_{xh}) \quad (5)
\]

where \( h \) is the order of harmonics, \( \alpha_{xh} \), the phase angle for the current or voltage for the \( h \)-th order harmonics, \( X_0 \), the \( v(t) \) or \( i(t) \) mean values, defined by:

\[
X_0 = \frac{1}{kT} \int_{t}^{t+kT} x(t) \, dt \quad (6)
\]

Finally, \( X_h \) in (5) is defined as the RMS value of the \( h \)-th harmonic of voltage or current.

4. Methodology
This study consists in two sets of tests: set A with two static electrical energy meters and set B, with six meters, all of them approved by Inmetro [4]. Table 2 depicts the static meters tested:
Table 2 – Static meters under test

| Meter | Meter type | Rated Voltages (V) | Rated Current (A) | Accuracy Class | Kh (Wh/pulse) | Test Set |
|-------|------------|--------------------|-------------------|----------------|---------------|----------|
| M2    | Direct     | 120                | 15                | 1%             | 2             | A        |
| M3    | Indirect   | 120 / 220          | 2.5               | 0.2%           | 0.2           | A/B      |
| M7    | Indirect   | 120 / 220          | 5                 | 0.2%           | 1.8           | A/B      |
| M10   | Indirect   | 120 / 240          | 2.5               | 0.5%           | 1.8           | A/B      |
| M11   | Indirect   | 120 / 240          | 2.5               | 0.2%           | 1.8           | A/B      |
| M12   | Indirect   | 120 / 220          | 2.5               | 0.2%           | 3.6           | A/B      |
| M16   | Direct     | 120 / 240          | 30                | 0.5%           |               |          |

The test sets area:
A. Identification of worst scenario for reactive energy metering in an harmonic environment;
B. Correlation between THD and measurement error.

The two sets of tests are described below.

4.1 Test set A – Scenario identification
The aim of this set of tests is to identify the worst scenario for reactive energy measurement in a concise schedule of harmonics. Each meter was subject to eight three-phase tests, each one with a different set of harmonics. Voltage was set at 120V, current was held at rated values when possible, with a maximum of 8A, and power factor of 0,707. At each test, none or three harmonics of magnitude 17% from fundamental were injected at both voltage and current. This yields a THD of approximately 30% in each phase.

Table 3 – Test Set A

| Test | Voltage Harmonics | Current Harmonics | Energy Measured |
|------|-------------------|-------------------|-----------------|
| 1    | -                 | -                 | -               |
| 2    | 2                 | 3                 | 4               | Active         |
| 3    | 3                 | 5                 | 7               | Active         |
| 4    | -                 | -                 | -               | Reactive       |
| 5    | 2                 | 3                 | 4               | Reactiva       |
| 6    | 3                 | 5                 | 7               | Reactive       |
| 7    | 3                 | 5                 | 7               | Reative        |
| 8    | 2                 | 3                 | 4               | Reactive       |

Tests 2 and 5 presents overlapping harmonics at both current and voltage while measuring, respectively, active and reactive energy. Tests 1 and 4 presents no harmonics at all. Tests 3 and 6 presents no overlapping harmonics at both current and voltage.

4.2 Test set B – Correlation between THD and error
Each tested static meter was subjected to three-phase energy with harmonic distortion, in an electric energy meter bench Nansen brand, Precision Lab model, with internals single-phase energy patterns Radian RD-20, each one with 0,01% of accuracy.

Simultaneously, data from voltage and current was acquired through an oscilloscope Tektronix, model TDS-5104B, with voltage and current pointers. Data acquired was processes in Scilab in order to calculate the power zoo proposed by [1].

The electrical energy meter test bench can generate harmonics from 2\textsuperscript{nd} to 15\textsuperscript{th} order, with maximum THD of 30% per phase. The digital meters analyzed were subject to a test plan, consisting of eighteen different measurement accuracy tests, with increasing harmonic amplitudes. Voltage and current harmonics are coincident in order, subjecting the meter to a more severe environment, according to [10].
At all three phases, harmonics of 2\textsuperscript{nd}, 3\textsuperscript{rd} and 4\textsuperscript{th} orders were injected, along with fundamental voltage and current set at rated values. Table 4 summarizes the harmonic profile of the test plan, with harmonic amplitudes rated as percentage from nominal values.

### Table 4 – Test Set B

| Test | Voltage Harmonic Amplitude (%) | THD\textsubscript{V} (%) | Current Harmonic Amplitude (%) | THD\textsubscript{I} (%) |
|------|-------------------------------|--------------------------|-------------------------------|--------------------------|
|      | 2    | 3    | 4    | 2    | 3    | 4    |
| 0    | 0    | 0    | 0    | 0.00 | 0    | 0    | 0    | 0.00 |
| 1    | 1    | 1    | 1    | 1.73 | 1    | 1    | 1    | 1.73 |
| 2    | 2    | 2    | 2    | 3.46 | 2    | 2    | 2    | 3.46 |
| 3    | 3    | 3    | 3    | 5.20 | 3    | 3    | 3    | 5.20 |
| 4    | 4    | 4    | 4    | 6.93 | 4    | 4    | 4    | 6.93 |
| 5    | 5    | 5    | 5    | 8.66 | 5    | 5    | 5    | 8.66 |
| 6    | 6    | 6    | 6    | 10.39| 6    | 6    | 6    | 10.39|
| 7    | 7    | 7    | 7    | 12.12| 7    | 7    | 7    | 12.12|
| 8    | 8    | 8    | 8    | 13.86| 8    | 8    | 8    | 13.86|
| 9    | 9    | 9    | 9    | 15.59| 9    | 9    | 9    | 15.59|
| 10   | 10   | 10   | 10   | 17.32| 10   | 10   | 10   | 17.32|
| 11   | 11   | 11   | 11   | 19.05| 11   | 11   | 11   | 19.05|
| 12   | 12   | 12   | 12   | 20.78| 12   | 12   | 12   | 20.78|
| 13   | 13   | 13   | 13   | 22.52| 13   | 13   | 13   | 22.52|
| 14   | 14   | 14   | 14   | 24.25| 14   | 14   | 14   | 24.25|
| 15   | 15   | 15   | 15   | 25.98| 15   | 15   | 15   | 25.98|
| 16   | 16   | 16   | 16   | 27.71| 16   | 16   | 16   | 27.71|
| 17   | 17   | 17   | 17   | 29.44| 17   | 17   | 17   | 29.44|

Table 2 shows some rated characteristics from the digital energy meters tested in the study, where Kh is the calibration constant, that relates the pulse rate to the energy measured. Its unity is Watt.hour per pulse emitted.

The digital electric energy meters in Table 2 have had their measurement errors registered, for each one of the eighteen tests, gradually increasing THD\textsubscript{V} and THD\textsubscript{I} (since their value is the same).

One should notice that the test plan in Table 1 is only one scenario among several others. Although 30% THD\textsubscript{V} is improbable for a real power system, 30% THD\textsubscript{I} is very likely in several situations. Test conditions 6 and 7, for example, with THD between 10% and 12%, are very probable both for voltage and current at delivery.

Although the harmonics injected as not usual, they were chosen as a logical order sequence. More tests are being planned with several harmonics combinations.

Measurements have been repeated several times, discarding random errors as main interference source.

### 5. Results

Results were obtained from test sets A and B. Test set A results are showed in Tables V and VI for meters M2 and M3, respectively. From them, it is possible to conclude that test 5, measuring reactive energy with overlapping harmonics at both voltage and current is the worst case for harmonic influence. Therefore, test set B was run with condition 5 for meters M3 to M16.
After running tests with the method presented in the previous section, measurement errors on reactive electrical energy have been obtained, for each meter in Table 2, at each test point in Table 1, as seen in Tables 5 and 6.

Figure 2 shows measurement errors against THD for meters M3, M7 and M12, of accuracy class D. Horizontal lines represent the boundaries of class D accuracy, 0.2%. One should notice that, starting from a relatively low THD (between 5% and 7%), all meters present measurement errors greater than their accuracy class.

Figure 3 is similar to Fig. 2, but related to digital meters M11 and M16, accuracy class C. One should notice that the errors of the meter M16 are outside its accuracy class from 4% THD up. Errors of M11 meter are outside its accuracy class from 11% THD, approximately.

Table 5 – Errors for test set A meter M2

| Test | Energy Measured | Error (%) | THD (%) |
|------|-----------------|-----------|---------|
| 1    | Active          | -0.06     | 0.00    |
| 2    | Active          | 0.14      | 29.44   |
| 3    | Active          | -0.12     | 29.44   |
| 4    | Reactive        | 0.11      | 0.00    |
| 5    | Reactive        | -4.96     | 29.44   |
| 6    | Reactive        | 0.08      | 29.44   |
| 7    | Reactive        | -0.85     | 29.44   |
| 8    | Reactive        | -0.94     | 29.44   |

Table 6 – Errors for test set A meter M3

| Test | Energy Measured | Error (%) | THD (%) |
|------|-----------------|-----------|---------|
| 1    | Active          | 0.07      | 0.00    |
| 2    | Active          | 0.09      | 29.44   |
| 3    | Active          | 0.24      | 29.44   |
| 4    | Reactive        | 0.08      | 0.00    |
| 5    | Reactive        | -6.53     | 29.44   |
| 6    | Reactive        | 0.06      | 29.44   |
| 7    | Reactive        | -1.23     | 29.44   |
| 8    | Reactive        | -1.24     | 29.44   |

Figure 2 - Measurement errors for class D meters
Similar behaviour is shown by meter M10, accuracy class B, with measurement errors greater than 1% just above 11% THD, as seen in Fig. 4.

Supposing a linear relationship between THD and measurement errors, Table 7 shows correlation coefficients [11] for each meter tested.

One should notice, in Table 7, the high values of correlation coefficients between THD and measurement errors. One can conclude that, considering the meters under test and the test plan executed, measurement errors are directly influenced by THD values, so one can consider THD as a direct influence quantity in digital reactive energy meters.

Despite 30% THD values are very improbable (at least in voltage), the extent of the curves in Fig.1, 2 and 3 clearly depicts the strong positive correlation between THD and reactive power measuring error.
Table 7 – Errors for test set A meter M2

| Meter | Correlation Coefficient |
|-------|-------------------------|
| M3    | -0.9673                 |
| M7    | 0.9608                  |
| M10   | -0.9573                 |
| M11   | 0.9595                  |
| M12   | 0.9599                  |
| M16   | -0.9585                 |

6. Conclusions
Analyzing results obtained from the tests performed using previously stated methods, one can pinpoint the following remarks:

The presence of overlapping harmonics at both voltage and current waveforms represent the worst environment for energy measurement, among the eight tests in set A.

The digital reactive electrical energy meters tested are susceptible to THD as influence quantity in reactive electrical energy measurement;

The correlation coefficients \( R \) [11] between THD and measurement errors are significantly high \( (|R| \geq 0.95) \) for all meter tested. As the THD is the only quantity altered along the tests, this confirms the meter susceptibility on the harmonic content present in the electric grid;

A unified, clear and consistent definition of both reactive power and energy would be helpful in establishing criteria for billing reactive power and low power factor, independent of harmonics content.

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