HARMONIC ANALYSIS OF SOLID-STATE WATT-HOUR METERING : PRELIMINARY INVESTIGATION

J.E.R. Alves Jr. M.Q.F. Balthazar
CEPEL – Centro de Pesquisas de Energia Elétrica
P.O. Box 68007
CEP 21944-970 - Rio de Janeiro - RJ- Brazil
alves@cepel.br mqfb@cepel.br

E.H. Watanabe
Federal University of Rio de Janeiro
P.O. Box 68504
CEP 21945-970 - Rio de Janeiro - RJ- Brazil
watanabe@ufrj.br

***Abstract* –More and more non-linear loads are connected to distribution lines bringing with it harmonic voltages and currents, which may influence power revenue meters. This paper presents an investigation about harmonic analysis focused on solid-state watt-hour metering. More specifically it presents a systematic analysis of methods used for measurement of active energy including time-division-multiplier (TDM) principle and digital multipliers. Some preliminary conclusions are made concerning the application of two both methods on static revenue power meters.**

KEYWORDS

Power measurement; power revenue metering; solid state meters; harmonic analysis

I. INTRODUCTION

More and more non-linear loads are connected to distribution lines bringing with it harmonic voltages and currents. Several equipment including revenue solid-state meters have to handle these harmonics components correctly. If this approach is not correctly done, harmonic distortion power may modify the registers in an unpredictable way.

The influence of harmonics in power revenue meters has been carefully studied in literature comprising electromechanical and solid-state meters [1,2,3,4]. Elham B. Makran [1] performs a careful frequency analysis of electromechanical meters. A. Domijan [2] studies several meters, concluding that they may present more than 10% errors due to harmonics. Besides, the results depend on not only the input signals of voltage and current but also the basic principle of the solid-state meters.

As it is well known, the basic way to calculate the power in a circuit is by calculating the power through the product of the voltages and current. Then this power has to be integrated to calculate the energy (watt-hour). However, this product is normally made in a simplified way. Also, the integration is made in a simplified way. Therefore, it is not clear in the literature if the response of these meters is always guaranteed. The objective of this paper is to analyze the operation of several power meters with different calculation method.

The basic principle of most of the energy meters is depicted in Figure 1. The voltage and current transducers conform the signals in a suitable pattern for the multiplier. The multiplier output is filtered by the low-pass filter producing a dc level proportional to the average value of the active power. Using this signal as input, an integrator produces a signal proportional to the active energy. This can be done in a lot of ways. One possibility is by using a voltage-controlled-oscillator which provides pulses with a frequency proportional to the active power. This train of pulses is integrated and the result is the active energy. There are several approaches for obtaining the voltage-by-current multiplication: time-division-multiplication (TDM), analog multiplication, digital multiplication, Hall Effect multiplication, transcondutance multipliers [7]. All the blocks may affect the harmonic response of the meter. This work will focus the influence of harmonics on the multiplier block. Two types of multiplication blocks will be investigated: time-division-multiplier principle and digital multipliers as they are used in a great extent in revenue power meters [7]. Some preliminary results using state-of-the-art power revenue meters are finally shown.

Normally, the accuracy class of revenue power meters used by the utilities depends on the load. For example, for normal residence consumer loads, a 2% class is usual and electromechanical meters are used. For small commercial loads 1% and 0.5% accuracy classes are used. Usually, for the situations when large amounts of energy are transferred, the accuracy class of the power revue meters is 0.2%.

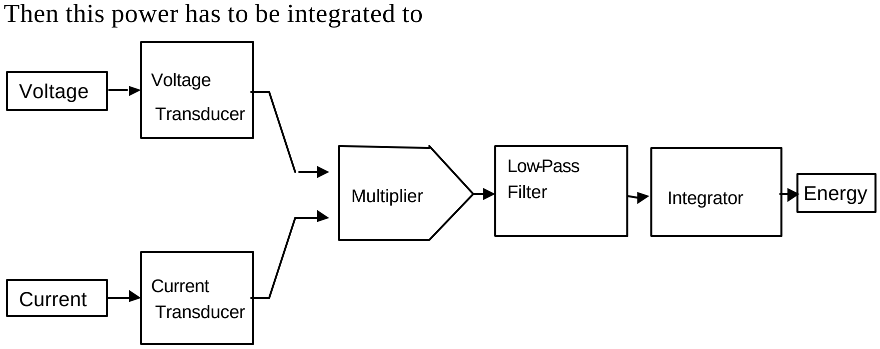

FIGURE 1 – Basic Principle for Measuring Active Energy.

II. PRINCIPLES OF TDM (TIME DIVISION MULTIPLIER) AND DIGITAL MULTIPLIER

The general principles of time-division-multiplier (TDM) principle and digital multipliers are presented in this section:

II.1 Time-Division-Multiplier (TDM) Principle

The time-division-multiplier (TDM) principle was used in the earliest commercial solid-state meters and many metering transducers and standards [7]. At that time, it was the straightforward approach in order to obtain multiplication with a high degree of accuracy. It is based on the fact that the mean value of a pulse train is proportional to the product of the pulse amplitude and the duty cycle of the pulses. Therefore, voltage is normally used for controlling the duty-cycle (pulse width modulation – PWM) and current is used for modulating the amplitude of the signal (amplitude modulation – AM), as depicted in Figure 2. Voltage is compared to a high frequency triangular wave, producing a pulse width modulated train of constant amplitude (signal C). It is important to define the amplitude modulation ratio m, given by:

$$m = \frac{\text{maximum input of voltage}}{\text{maximum voltage}} \quad 0 \quad m \quad 1 \qquad (1)$$

If the value of m is near to 0, the output signal is too low and offset may affect the results. On the other hand, if m is near 1, when an overvoltage occurs, the input signal may become greater than the triangular wave, bringing non-linearity. Current is used to produce an amplitude modulation of signal C, resulting in the signal Vp, which is filtered by a low-pass filter and the final result is a signal proportional to the active power. The integrator block is responsible for providing the active energy. One example of values of the triangular wave frequency and of the amplitude modulation ratio m are 1100Hz and 0.5, respectively [5].

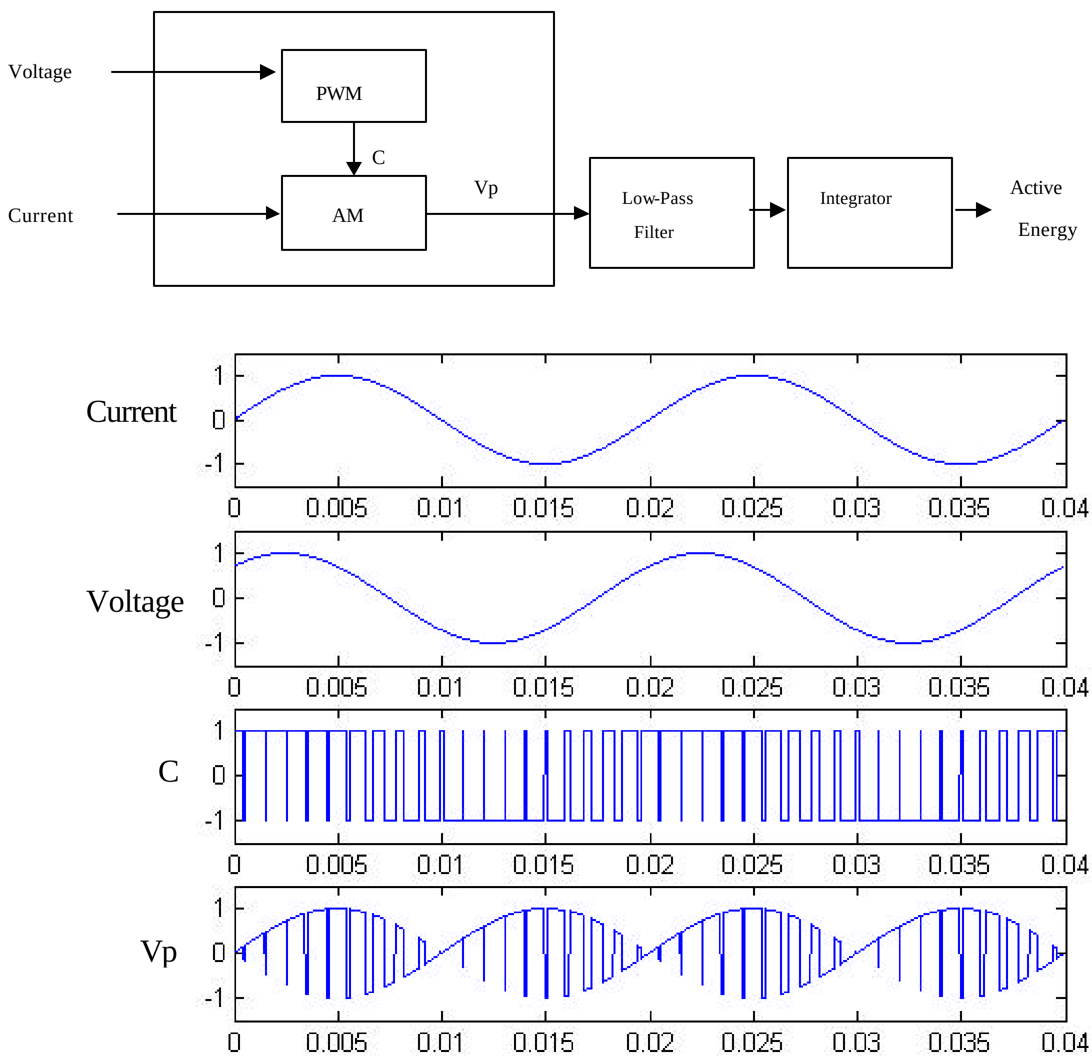

FIGURE 2 – TDM Basic Principle for Measuring Active Energy.

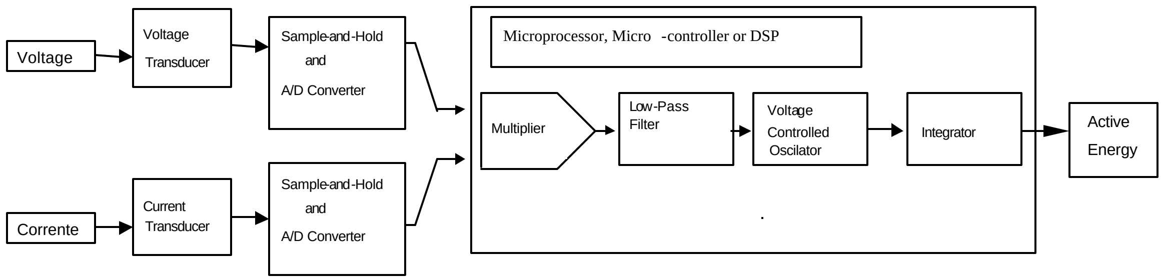

FIGURE 3 – Digital Multiplier Basic Principle for Measuring Active Energy.

II.2 Digital Multipliers

Digital multipliers are based on sample-and-hold blocks and analog-to-digital converters units to produce digital words proportional to the input signals of voltage and current. The multiplication, filtering and pulse production are made digitally by a microprocessor, a micro-controller or a digital signal processor. Figure 3 presents a block diagram of the digital multiplier principle. Two important characteristics of this implementation are the sampling rate of the analog-to-digital converters, related to the Nyquist frequency, and the number of bits of resolution, which determines the granularity of the measurement [7,8]. For instance, the sampling rate of the Texas approach MSP340 is 0,000122s and it uses a 14 bit analog-to-digital converter (ADC)[6].

III. SIMULATION OF THE PRINCIPLES INCLUDING HARMONICS

Two methods were used for this investigation:

a) A systematic injection of voltage and current harmonics with the purpose of obtaining parametric results of active power related to each harmonic component. The parametric approach may give a preliminary idea of the influence of each harmonic on the meters.
b) For achieving preliminary results concerning real loads, a rectifier bridge with capacitive load was chosen as it can represent several practical loads. This simulation was done considering non-ideal voltage sources, with impedances in series with them.

III.1 Systematic injection of harmonics

A basic case, using analog multiplication, was created in order to compare with TDM and digital multiplier principles. Figure 4 presents a block diagram of the basic case.
Two basic concepts could be used as comparison parameters: the average power, due to fundamental frequency and all the harmonics of voltage and current and the active power due only to the fundamental frequency of voltage and fundamental frequency of current.
This work will focus only the average power. In this way, if an specific harmonic is responsible for a fraction of the active energy, it will influence the average power.

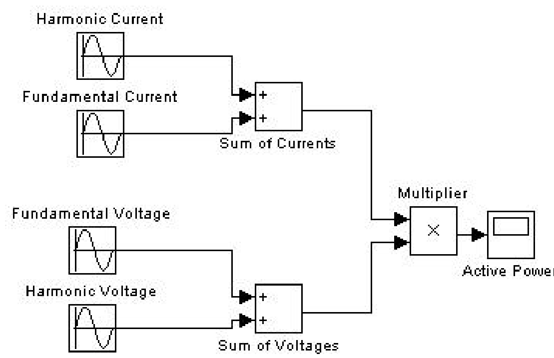

FIGURE 4 –Basic Case.

The signals of voltage and current as well as the output of the multiplier were analyzed using Fourier Transform in order to verify the dc level (proportional to the active power) and also all the harmonics. The voltage and current contributions of all the harmonics to the average power at the output of the multiplier were studied.

III.1.1 Injection of harmonics and TDM principle

a) The frequency of the triangular wave is multiple integer of the fundamental frequency (for example, the frequency of triangular PWM waveform (signal C in Figure 2) is 1000Hz and the fundamental frequency is 50Hz).
b) The frequency of the triangular wave is not multiple integer of the fundamental frequency (for example, the frequency of PWM triangular waveform is 1100Hz and the fundamental frequency is 60Hz). This case is found in power revenue meters [5].

III.1.1.1 Injection of harmonics and TDM principle (triangular wave is multiple integer of the fundamental frequency)

For these simulations the fundamental frequency was 50Hz, the frequency of the triangular wave for PWM was 1000Hz and the amplitude modulation ratio of the PWM is 0,5. Parametric tests were performed injecting only one harmonic at a time varying the amplitude and frequency of it. Table I shows a description of the test. Table II shows the result when the harmonic injected has the same amplitude as the fundamental frequency. The pu (per-unity) system was used to express the signals of voltage, current and power. The expected result of the average power is 1 pu.

TABLE I
Parametric injection of harmonic

	voltage		current		average power
fundamental	1,0 pu	-90°	1,0 pu	-90°	0,5 pu
harmonic	1,0 pu	-90°	1,0 pu	-90°	0,5 pu
AVERAGE POWER					1,0 pu

TABLE II
Injection of 100% harmonics and TDM principle

Harmonic order	RMS Power Error (TDM)	Harmonic order	RMS Power Error (TDM)
3	0,04%	2	-0,02%
5	-0,02%	4	-0,01%
7	0,03%	6	-0,02%
9	0,05%	8	0,02%
11	-0,08%	**10**	**1,02%**
13	**8,77%**	12	-0,04%
15	-0,58%	14	-0,34%
17	-0,82%	16	-0,08%
19	**13,69%**	**18**	**1,44%**
21	**12,81%**	**20**	**1,80%**
23	**2,56%**	22	0,94%
25	**-5,89%**	**24**	**1,64%**
27	**-2,43%**	**26**	**1,18%**

As can be seen in Table II, the error of TDM approach compared to the basic case (analog multiplication) is greater than 1% at 10°, 13°, 18°, 19°, 20°, 21°, 23°, 24°, 25°, 26° and 27° harmonic. This is related to the PWM principle used in TDM method. The spectrum of the signal C (Figure 2) is presented in Figure 5. In this Figure it can be seen sidebands centered around the triangular wave frequency (in this case, 1000 Hz) and its multiples, that is, 2000Hz, 3000Hz and so on [10]. Theoretically, the frequencies at which harmonics occur are given by the following expression:

$$fh = (j * mf \pm k) * fundamental.frequency \tag{2}$$

where:

$$mf = \frac{triangular\ \ wave\ \ frequency}{fundamenta\ \ l\ \ frequency} \tag{3}$$

and k and j are integer values. For odd values of j, the harmonics exist only for even values of k. For even values of j, the harmonics exist only for odd values of k. It is important to note that these harmonics are created by the PWM modulation and are not physically present at the voltage signal.

The voltage harmonics interact with the current signal in the multiplication block . Theoretically, only harmonics of the same frequency at voltage signal and current signal may contribute to the average power. As in the TDM case the input of the multiplier block is the current signal and the PWM signal (signal C in Figure 2), the non physical PWM voltage harmonics may interact with the eventual current harmonics of the same frequency producing non physical power.

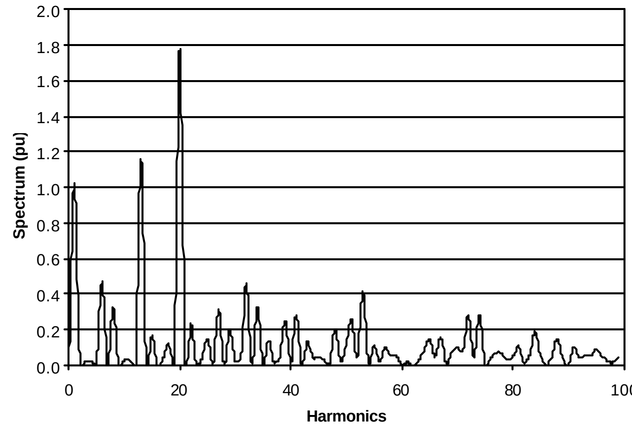

FIGURE 5 –Spectrum of signal C.

As an example, there were injected the 13° harmonic in the voltage and 13° harmonic in the current. Using analog multiplication, the results were already presented in Table I.

The fundamental contributes with 0.5pu to the average power and the 13° harmonic also contributes with 0.5pu resulting in a net average power of 1.0 pu.

The same situation was simulated using TDM approach with 1000 Hz of triangular frequency and 50 Hz fundamental frequency. In this case, the value of the fundamental is 2% greater than the analog case and the value of the 13° harmonic is 16% greater than the analog case. , producing 8,8% average final error as depicted in Tables III.

TABLE III
Injection of 13° harmonic and TDM multiplication

	voltage		current		average power
fundamental	**1.019 pu**	-90°	1 pu	-90°	0.509 pu
13° harmonic	**1.156 pu**	-90°	1 pu	-90°	0.578 pu
TOTAL					**1.088 pu**

Total harmonic distortion (THD) of a signal Z is defined by [9]:

$$THD = \frac{\sqrt{\ \ (Z_H)^2}}{Z_F} \tag{4}$$

where the subscript “F” is relative to the fundamental and “H” is the harmonic order.

The THD in all the situations depicted above is the same, equal to 100%. It is greater than the IEEE Standard 519 [9] for voltage harmonics limits (maximum of 3% for any individual harmonic voltage and THD of 5%) and also greater than harmonic current limits (maximum of 15% for any individual harmonic current and THD of 20%, for small loads). In fact if the voltage and current injected were smaller, the influence of TDM on the average power would be reduced. As an example, Table IV shows the situation when the injected harmonic is 10% of fundamental frequency. In this case, the THD is 10%.

TABLE IV
Injection of 10% harmonics and TDM principle

Harmonic order	RMS Power Error (TDM)	Harmonic order	RMS Power Error (TDM)
3	0,04%	2	-0,03%
5	0,02%	4	0,03%
7	-0,07%	6	-0,04%
9	-0,05%	8	0,02%
11	0,07%	10	0,04%
13	0,08%	12	-0,02%
15	0,08%	14	0,04%
17	-0,02%	16	0,04%
19	**0,40%**	18	0,00%
21	**0,41%**	20	-0,01%
23	0,02%	22	0,02%
25	0,03%	24	-0,05%
27	0,00%	26	-0,02%

III.1.1.2 Injection of harmonics and TDM principle (triangular wave is not multiple of the fundamental frequency)

For these simulations the fundamental frequency was 60Hz, the frequency of the triangular wave for PWM was 1100Hz and the amplitude modulation ratio of the PWM is 0,5. As can be seen in Table 4, the errors are smaller compared with the errors of the previous case. However, they remain important if the accuracy class required is smaller than 1%.

TABLE V
Injection of 100% harmonics with TDM principle, fundamental frequency: 60Hz, frequency of the triangular wave for PWM: 1100Hz,.

Harmonic order	RMS Power Error (TDM)	Harmonic order	RMS Power Error (TDM)
3	0,00%	2	0,00%
5	-0,00%	4	-0,00%
7	0,00%	6	-0,05%
9	0,02%	8	-0,00%
11	-0,01%	10	-0,02%
13	0,11%	12	-0,05%
15	0,60%	14	-0,06%
17	0,13%	16	-0,12%
19	**1,52%**	**18**	**-1,03%**
21	**2,75%**	**20**	**-0,34%**
23	**-3,35%**	**22**	**0,99%**
25	**-1,79%**	**24**	**1,09%**
27	**-3,85%**	**26**	**1,71%**

III.1.2 Injection of harmonics and digital multiplier principle

The frequency of sampling and the number of bits have great influence on the response of the multiplier. Several tests were performed. For these simulations the fundamental frequency was 50Hz. The simulations were performed in a parametric approach using the sampling rate of the analog-to-digital converters and the number of bits of resolution.
It can be seen that near the sampling rate (1000Hz) or half of it (500Hz) there are significative errors between the digital multiplier and the basic case as depicted in Table VI. They are due to the aliasing (or frequency folding) effect [8]. This result shows that the frequency of the harmonics in the voltage and current signals can not be closer or equal to half of the sampling frequency or any multiple integer of this frequency. Otherwise, the digital multiplication method may produce high errors in the average power.

TABLE VI
Comparison between basic case and the digital multiplier

Harmonic order	RMS Power Error (TDM)	Harmonic order	RMS Power Error (TDM)
3	0.00%	2	0.00%
5	0.00%	4	0.00%
7	0.00%	6	0.00%
9	0.00%	8	0.00%
11	0.00%	10	-50.00%
13	0.00%	12	0.00%
15	0.00%	14	0.00%
17	0.00%	16	0.00%
19	-100.00%	18	0.00%
21	100.00%	20	-50,00%
		22	0.00%

III. 2 Simulation of a capacitive load rectifier

Figure 6 depicts the circuit used for simulation of a single-phase bridge rectifier with resistive plus capacitive load, used for comparison with TDM and digital multiplier principles. The values of C_eq and R_eq used are 100 ohms and 100 F respectively. The values of Rs_eq used are in the range between 0 and 2 ohms.

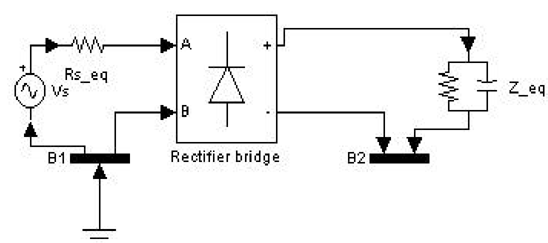

FIGURE 6 –Rectifier Bridge.

At first it was used TDM approach and the frequency of the triangular wave (1000 Hz) was chosen to be a multiple of the fundamental frequency (50Hz). The average power delivered by the source is 197,2W using 2 ohms for Rs_eq. Nevertheless, the TDM arrangement produces a response of 193,9W giving an error of -1,7%. This is due to the spectrum of the voltage PWM waveform (signal C, Figure 2), depicted below in Figure 7. It is verified an harmonic spectrum containing significant harmonics due to PWM. This harmonics interact with the current harmonics, presented in Figure 8 (in a simple analog multiplication, as depicted in Figure 1, this doesn't occurs, as the voltage doesn't have PWM harmonics). For example, in this case, without harmonics, the RMS voltage of the 39° harmonic is 0,066V (-156,6°) and in the TDM case, the same harmonic is 128,8V (-89,6°). If the current doesn't contain harmonics, there is no interaction. However, in this case, the 39° current harmonic is not null and its value is 0,033A (23,4°). Consequently, there will be produced power due to this harmonic of value -0,84W (-0,4%). This component is not physical and only related to TDM method. Even the source is ideal, this situation continues to happen because in spite of the sinusoidal signal of voltage, there will be harmonics produced due to the PWM triangular wave.

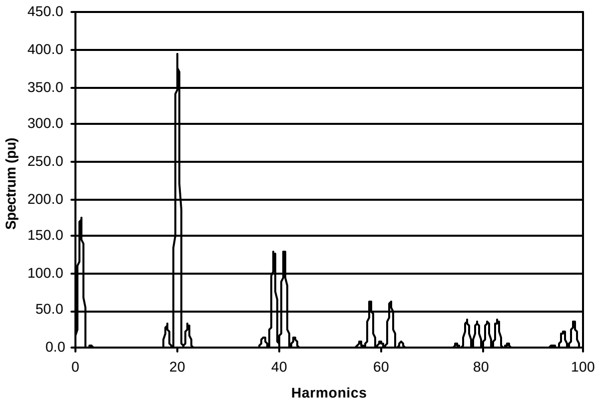

FIGURE 7 –Spectrum of signal C.

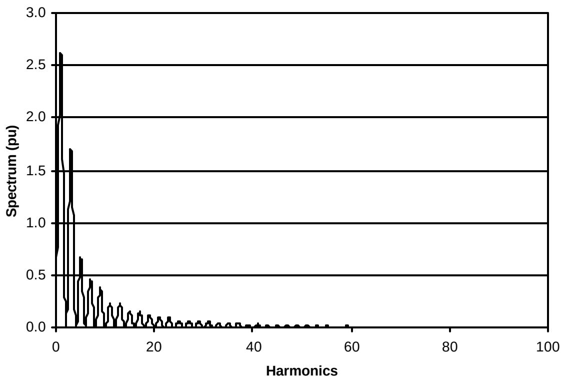

FIGURE 8 –Spectrum of Current.

If TDM approach uses a 1100Hz for triangular wave and a 60Hz fundamental frequency, the error is much smaller, 0.05%, because in this case there is no coincidence between the harmonics produced by TDM and the current harmonics. Therefore, the chosen of the TDM frequency is important regarding the harmonic behaviour of the power TDM meter.

IV. PRELIMINARY EXPERIENCES WITH COMMERCIAL METERS

Preliminary experiences using electromechanical and electronic meters were performed and Table VII shows the first results. The third harmonic was injected in voltage and current of the meters and the result was compared with a 0,05% standard (average power meter). The first commercial solid-state meter investigated measure harmonic power. Nevertheless, the electromechanical has been influenced by the injection of harmonics. In spite of that, this error (1%) is smaller than its accuracy class (2%). This result indicates that the solid-state meters investigated works as true rms meters. On the other hand, the electromechanical meter doens't consider entirely the contribution of the third harmonic to the average power as the electronic meters do.

TABLE VII
Initial experiences with commercial meters

RMS Power Error (TDM)	RMS Power Error (TDM)
TDM meter	0.037%
Digital multiplier meter	-0.011%
Electromechanical meter	-1.002%

V. CONCLUSIONS

More and more non-linear loads are connected to distribution lines causing harmonic voltages and currents, which may affect power revenue meters. This works presents a preliminary analysis of methods used for measurement of active energy including time-division-multiplier (TDM) principle and digital multipliers. Several exhaustive tests were made injecting harmonics in the voltage and current waveforms and some preliminary results are presented. Some considerations about how to project the meters are also considered. Finally some initial results of state-of-the-art meters are described.

This subject is extensive and several aspects should be studied, including three phase-harmonics and unbalanced three-phase networks. How the revenue meters handle reactive energy in a presence of harmonics is another important aspect to investigate.

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