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Performance Evaluation of a Multifunctional Energy Metering IC under Sinusoidal and Non-Sinusoidal Conditions

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***Summary*: Low-cost handheld instruments performing a large variety of electrical measurements are recently appeared on the market. Their diffusion is mainly due to the availability of integrated circuits that carry out many measurement functions, thus simplifying the instrument implementation and reducing the costs. In this paper, the accuracy performances of an integrated circuit featuring rms and power measurements are evaluated under both sinusoidal and non-sinusoidal conditions. The implemented measurement bench and the obtained results are presented. The results show that the accuracy of the device under test is satisfactory for active power and current rms values, instead of the voltage channel accuracy is significantly worst.**

1. INTRODUCTION

It is well known that performing correct measurements under non-sinusoidal conditions needs some requirements to be fulfilled: a) application of a proper definition of the parameter to be measured; b) implementation of a measurement hardware having an adequate wide-bandwidth; c) choice of an observation time window that allows avoiding spectral leakage. Many scientific contributions dealing with instruments developed for measuring quantities under steady-state non-sinusoidal conditions can be found in the literature, see, for example, [1–5]. Such instruments satisfy all the above constraints and work well, thus providing a correct estimation of the desired parameter, no matter the measurand has physical meaning or not. However, many of them implement definitions of quantities widely accepted by the scientific community [6].

From the point of view of International Standards, the IEC EN 61000-4-30 [7] and, specially, the IEC EN 61000-4-7 [8], define the parameters to be measured and the general concepts (in terms of accuracy classes, structure and measurement techniques) of the related instruments, respectively. Obviously, the most part of commercial instruments designed for power quality measurements are declared to be in compliance with [7, 8]. However, it must be noted that this fact does not avoid getting wrong measurements in some conditions; by way of example, incorrect estimation of rms value and power occur when a not proper observation time window is taken [9].

Besides desktop instruments, a significant number of low-cost portable instruments performing a large variety of measurements have been recently proposed on the market. Their diffusion is made possible by the development of a generation of integrated devices (ICs) that carry out many measurement functions, thus simplifying the instrument implementation and significantly reducing their cost. Such ICs are often used as core of the new static energy meters that, as it is known, feature many functions.

In this paper, the performances of an IC featuring rms values and power measurements are investigated under both sinusoidal and non-sinusoidal conditions.

Section 2 describes the main features of the considered device and the way it has to be used for achieving measurements. Section 3 deals with the measurement system implemented to evaluate the IC performance; the results are presented and discussed in Section 4. Finally, Section 5 reports some final remarks.

2. THE IC UNDER TEST

The considered IC is the poly phase multifunction energy metering with per phase information ADE7758 made by Analog Devices [10]: it is a high accuracy 3-phase electrical energy measurement IC with a serial interface and two outputs: one for active power measurement and the other one for either reactive or apparent power measurements, depending on a software choice. Such an IC is declared to be in compliance with some IEC EN Standards [11–14] related to energy meters. The ADE7758 incorporates ADCs, reference circuitry, temperature sensor, and all the signal processing required to perform active, reactive, and apparent energy measurement and rms calculations. The device features six analog inputs divided into current and voltage channels. The current channel consists of three pairs of fully differential voltage inputs having maximum differential input voltage equal to ±500 mV. The voltage channel has three single-ended voltage inputs and the maximum input voltage is ±500 mV.

In this paper, the ADE7758 has been tested in its capability to provide current and voltage rms values and active power measurements. The method used by the IC to calculate the rms value is to low-pass filter the square of the input signal and taking the square root of the result; this calculation is simultaneously performed on the six analog input channels. Likewise, the active power information on each phase is obtained by extracting, with a suitable low-pass filter, the dc component of the instantaneous power signal, which is generated by multiplying the current and voltage signals.

All ADE7758 functionalities are accessed via the on-chip registers that allow both configuring the calculation parameters and reading the measurement values. In particular,

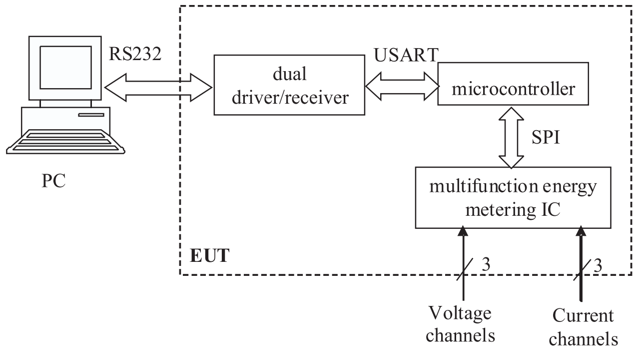

Fig. 1. Block diagram of Equipment Under Test

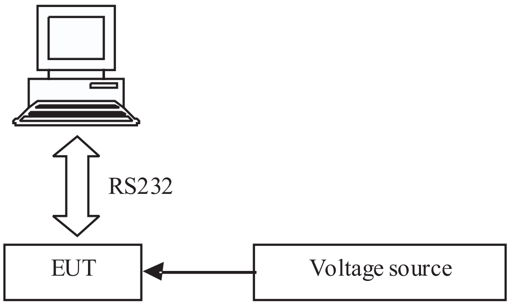

Fig. 2. Test bench for voltage and current measurements

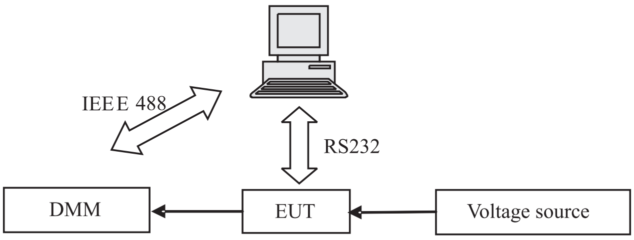

Fig. 3. Test bench for active power measurements

the current and voltage rms information are available in the proper registers, whereas the active power measurement is proportional to the frequency of a pulse output of the device (the phases to be included in the total power calculation is selected by means of an appropriate register). The registers are accessed via the built-in SPI-type serial interface, where the acronym SPI stands for Serial Peripheral Interface, which is a standard synchronous serial data link that operates in full duplex mode.

To be used, the IC must be provided with some simple devices, thus realizing the Equipment Under Test (EUT) schematically shown in Figure 1. It is made of three devices: the ADE7758, an high performance microcontroller PIC18F452 and a dual driver/receiver MAX232 with their own additional circuits. The PIC is a microcontroller featuring two serial I/O modules, the SPI module and the USART (Universal Synchronous Asynchronous Receiver Transmitter) module. Properly programmed, the PIC uses the first one to communicate with the multifunction energy metering and the second one to interface with an external Personal Computer (PC) through MAX232. The PC permits to get a user-friendly interaction with the EUT. The PIC sends to the IC a proper command that specifies the measurement parameters and reads the measurement results. Of course, PIC, MAX232 and PC do not affect the performance of the EUT that are due to ADE7758 only.

3. THE MEASUREMENT SETUP

Voltage, current and active-power measurement performances of the EUT have been evaluated by means of four kinds of tests:

- DC test to find the factor needed to convert the ADE7758's calculations in standard unit;
- AC test to determine the frequency response;
- AC sinusoidal test to characterize the device at the frequency of 50-60 Hz;
- AC test under non-sinusoidal conditions.

The schematic block diagram of the test bench for the DC voltage and current test is shown in Figure 2. The calibrator Wavetek Datron 4800 has been used as voltage source and has been chosen as reference instrument; its nominal accuracy specifications are 6 ppm for DC voltage and 50 ppm for AC voltage. Input signals having amplitude ranging from –1 V to 1 V with steps of 50 mV have been considered. Of course, only signals with amplitude in the interval [–500 mV, 500 mV] have been used to calculate the conversion factor, given that the IC maximum input voltage is ±500 mV.

The schematic block diagram of the test bench for the active power test is shown in Figure 3. The only difference between this bench and the previous one is the presence of a HP3458A multimeter (DMM), which works as a frequency-meter, controlled remotely by the PC via IEEE 488 bus with GPIB-USB interface. The DMM nominal accuracy is 0.01% of reading. The multimeter is necessary to measure the frequency of the ADE7758 pulse output that is proportional to active power. As far as the calibrator and the input signals are concerned, the same considerations of the voltage and current DC test may be applied.

To determine the frequency response, the same test benches as in Figure 2 (for voltage and current) and Figure 3 (for active power) have been used. In these tests, the rms value of the sinusoidal input has been kept constant at 350 mV (approximately the full-scale rms-value), whereas the signal frequency has been varied in the interval [50 Hz, 1050 Hz] for voltage and [50 Hz, 2 kHz] for current and active power. The determination of the frequency response is important to predict the performance of the IC in non-sinusoidal conditions, so the maximum values of the signal frequency used in this test depends on the maximum order of the harmonic considered in [15] and [16]; however, according to the ADE7758 specifications, the cut-off frequency of the voltage channel is 260 Hz, so it is useless the investigation of high frequencies.

The test benches in Figures 2 and 3 have been used also to characterize the ADE7758 under power-frequency sinusoidal conditions. The rms value of the input was varied from 35 mV to 490 mV with steps of 35 mV; the signals with rms value in the interval [35 mV, 350 mV] have been used for the characterization according to the specifications of the IC and the other ones have been used to investigate the performance of the device over the maximum signal levels in respect with the absolute maximum ratings. As in DC tests, the calibrator Wavetek Datron 4800 has been used as both voltage source and reference instrument.

As for the active power, a different test has been implemented to evaluate the performance of the EUT in presence of input signals having a non-zero phase shift. The relevant measurement setup is shown in Figure 4, where the data acquisition board (DAQmx) is a NI 9215 with four simultaneous-sampled input channels and 16-bit resolution. Two signal generators HP33120A, synchronized with a nominal accuracy of 25 ns, feed both the voltage and the current channels of the EUT and DAQmx. Thanks to the good accuracy (0.02% of reading, 0.014% of range) of the DAQmx with respect to the one expected from the EUT, the samples acquired (3000 Sa at 30 kSa/s) have been used to compute the reference active power value. The peak-to-peak value and the frequency of the sinusoidal signals have been kept constant at 500 mV and 50 (60) Hz, respectively, whereas the phase between the two input signals has been varied from 0 to 90 degrees.

The purpose of the last test is to evaluate the performance of the EUT under non-sinusoidal conditions. The schematic block diagram of the test bench is shown in Figure 5. A power source Agilent 6313B has been used as voltage source and a HP3458A multimeter, whose nominal accuracy is 0.007% of reading and 0.002% of range when used as voltmeter, has been chosen as reference instrument. Both the instruments work in remote way, controlled by the PC via an IEEE 488 bus with GPIB-USB interface. U-U refers to 100:1 voltage-to-voltage transducer. It is aimed at reducing the output voltage of the power source, which cannot provide the required voltage in the order of some hundred of millivolts. However, it must be noted that U-U accuracy does not affect the results, given that both the EUT and reference measurements are taken at its secondary side. As for the input signals, the values of the harmonic voltages have been chosen according to [15] while the values of the harmonic current according to [16]; only the odd harmonics have been implemented. Nevertheless, it should be kept in mind that the choice of a proper waveform for testing devices under non-sinusoidal conditions is a debated topic [17].

4. RESULTS AND DISCUSSIONS

The ADE7758 is a poly-phase multifunction energy metering IC, but all the tests have been executed for the phase A only; it is possible to do this, without loss of generality, because the performances of the three phases are very similar. Table 1 reports, for different inputs rms-values and for both voltage and current channels, the ratios of channels B and C measurements with respect to channel A measurement; given that these ratios are substantially unitary, it can be concluded that no significant difference in the channels performance occurs.

In all the above-described tests, 100 measurements have been performed and the mean and standard deviation values have been considered. The ratio between standard deviation and the corresponding mean value is less than $1\cdot10^{-3}$ for voltage measurements and less than $3\cdot10^{-4}$ for both current and active power measurements.

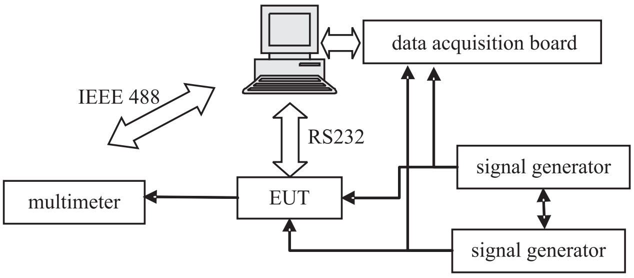

Fig. 4. Test bench for active power measurements with shifted-phase signals

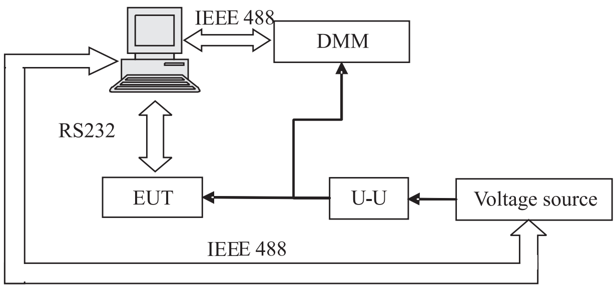

Fig. 5. Test bench for current and voltage test under non-sinusoidal conditions

Figures 6 and 7 show, for voltage and current, respectively, the relationship obtained, under DC conditions, between the input signal and the EUT output expressed as value read in register of the IC. Figure 8 shows the relationship between the active power and the frequency of the pulse produced by the IC. The voltage and current rms measurements are read in a register that provides the output of the ADE7758 internal analog-to-digital converter, while the active power is proportional to the frequency of the pulse output of a dedicated pin of the IC. To convert these measurements in standard unit (volt for voltage and current and watt for active power) it is necessary to determine the conversion factor (*cf*) for the voltage channel, the current channel and the active power measurement. To this purpose the curves of Figures 6–8 have been linearized by applying a regression technique; the following values have been computed:

Table 1. Ratios of channels B and C rms-measurements with respect to channel A rms measurement (60 Hz).

Reference rms value [mV]	Voltage channel		Current channel	
	B/A	C/A	B/A	C/A
70	0.9994	0.9989	0.9974	1.001
140	1.001	1.001	0.9973	1.000
210	1.001	1.001	0.9970	0.9998
280	1.002	1.001	0.9974	0.9999
350	1.001	1.001	0.9973	0.9996

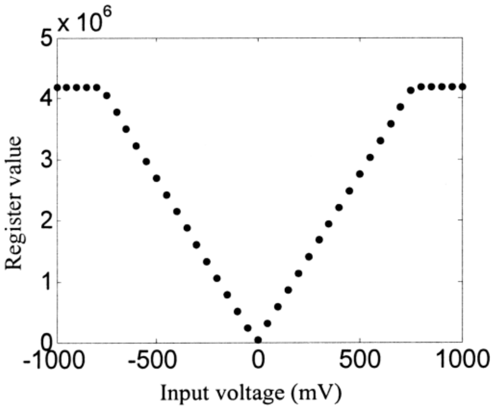

Fig. 6. Evaluation of conversion factor of the voltage channel

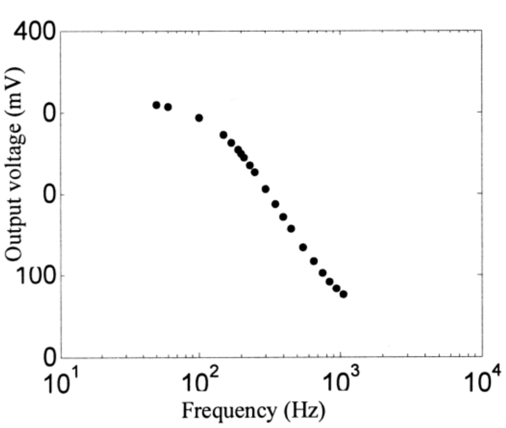

Fig. 9. Frequency response of the voltage channel

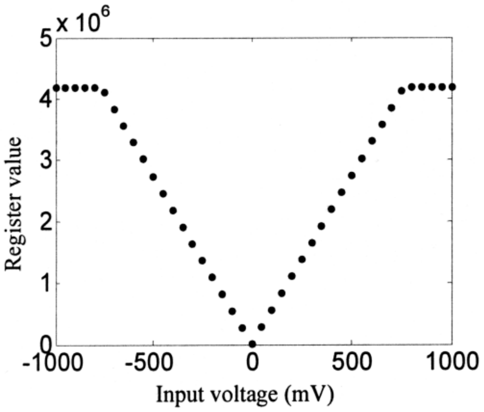

Fig. 7. Evaluation of conversion factor of the current channel

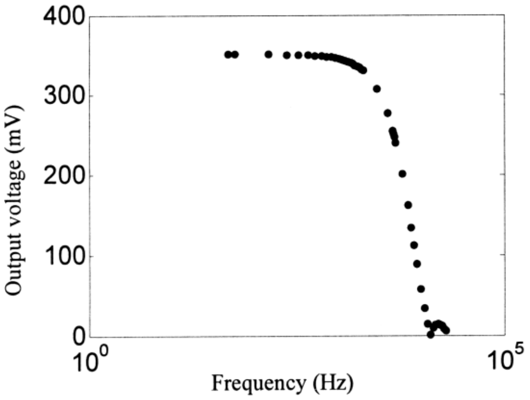

Fig. 10. Frequency response of the current channel

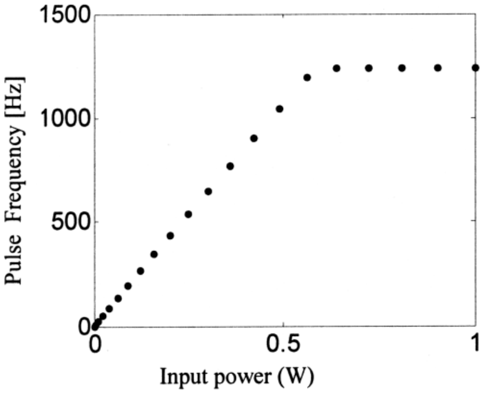

Fig. 8. Evaluation of conversion factor of the active power channel

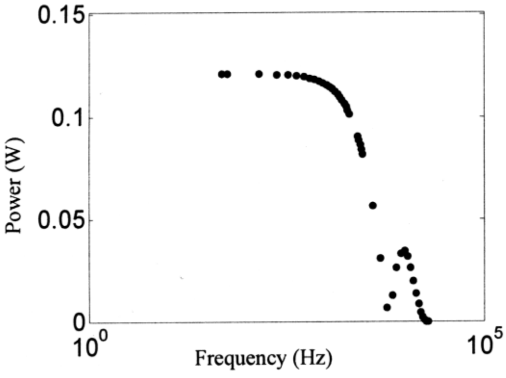

Fig. 11. Frequency response of the active power channel

— $cf = 1.833 \cdot 10^{-4}$ mV^{-1} (voltage channel),
— $cf = 1.823 \cdot 10^{-4}$ mV^{-1} (current channel)
— $cf = 4.683 \cdot 10^{-4}$ Hz/W (active power).

It can be observed that over a certain value the device reaches the saturation in all three cases.

As far as the bandwidth is concerned, the frequency responses related to the three kind of measurements are shown in Figures from 9 to 11 (in Figure 11 the frequency is referred to the voltage and current signals frequency). The cut-off frequency is approximately 200 Hz for the voltage channel, 4.8 kHz for the current channel and 2.7 kHz for the active power channel.

As mentioned in the previous Section, tests under sinusoidal conditions were performed at both 50 Hz and 60 Hz. Table 2 shows, for both voltage and current channels, the difference (in percentage of the reference values) between the measured rms values and the reference ones. Table 3 provides the same information about the active power measurement in the case of unitary power factor. They show that the current channel performs significantly better than the other ones.

Starting from these outcomes, a calibration curve can be drawn, thus allowing to summarize the EUT performance in a practical way. In particular, the reference measurements and the measurements provided by the EUT are the x-domain and y-domain of the calibration curve, respectively.

The calibration curve is then linearized by applying a regression technique, which provides a straight line crossing the axes origin, so it is possible to define the deviation of the calibration curve from the ideal characteristic by means of the well-known following indexes:

$$k = \frac{g - g_n}{g} \qquad (1)$$

$$\delta = \frac{max\left\{\left|y_i - g \cdot x_i\right|\right\}}{y_{FS}} \qquad (2)$$

In (1), g is the angular coefficient of the line, which linearizes the calibration curve, whereas g_n is the slope (which is unitary if the computed *cf* values are used) of the ideal characteristic. In (2), y_i is the generic measurement of the EUT, whereas x_i denotes the reference measurement. Finally, y_{FS} refers to the maximum of y_i. Let us refer to k and δ as gain error and the non-linearity error, respectively. With reference to Tables 2 and 3, the following values of k and δ were computed:

- $k = -12\cdot10^{-2}$ and $\delta = 0.30\cdot10^{-2}$ for voltage channel at 50 Hz
- $k = -13\cdot10^{-2}$ and $\delta = 0.40\cdot10^{-2}$ for voltage channel at 60 Hz
- $k = 0.038\cdot10^{-2}$ and $\delta = 0.042\cdot10^{-2}$ for current channel at 50 Hz
- $k = 0.037\cdot10^{-2}$ and $\delta = 0.035\cdot10^{-2}$ for current channel at 60 Hz
- $k = -1.5\cdot10^{-2}$ and $\delta = 0.22\cdot10^{-2}$ for active power at 50 Hz
- $k = -1.5\cdot10^{-2}$ and $\delta = 0.22\cdot10^{-2}$ for active power at 60 Hz

They show that the performances at 50 Hz and 60 Hz are quite similar for all the measured parameters. Moreover, the voltage channel behaves significantly worst than the current one, which, on the contrary, has a full-scale accuracy of about 10^{-3}. Tables 4 and 5 show, for 50 Hz and 60 Hz, respectively, how a phase shift φ between voltage and current influence the active power measurement (input signals amplitude 500 mV).

It can be observed that when the phase shift increases the performance in active power measurements gets significantly worse: the difference between measured and reference active power goes from 3% for low angle to about 20% when the angle is close to 90°. At 90° the measurement becomes unreliable.

Table 2. Voltage and current measurement errors under sinusoidal conditions.

Reference Voltage [mV]	Measured errors			
	Voltage channel [%]		Current channel [%]	
	50 Hz	60 Hz	50 Hz	60 Hz
35	-13	-14	$2.6\cdot10^{-2}$	$2.6\cdot10^{-2}$
70	-14	-15	$6.0\cdot10^{-2}$	$6.0\cdot10^{-2}$
105	-14	-15	$7.6\cdot10^{-2}$	$7.6\cdot10^{-2}$
140	-14	-15	$5.5\cdot10^{-2}$	$5.5\cdot10^{-2}$
175	-14	-15	$8.6\cdot10^{-2}$	$8.6\cdot10^{-2}$
210	-12	-12	$9.9\cdot10^{-2}$	$9.9\cdot10^{-2}$
245	-12	-12	$-0.8\cdot10^{-2}$	$-4.9\cdot10^{-2}$
280	-12	-12	$-1.2\cdot10^{-2}$	$2.4\cdot10^{-2}$
315	-12	-12	$3.5\cdot10^{-2}$	$3.5\cdot10^{-2}$
350	-12	-12	$5.3\cdot10^{-2}$	$5.3\cdot10^{-2}$
385	-12	-12	$4.4\cdot10^{-2}$	$4.4\cdot10^{-2}$
420	-12	-12	$8.3\cdot10^{-2}$	$8.3\cdot10^{-2}$
455	-12	-12	$9.3\cdot10^{-2}$	$9.3\cdot10^{-2}$
490	-10	-10	$-5.9\cdot10^{-2}$	$-5.9\cdot10^{-2}$

Table 3. Active power errors under sinusoidal conditions (unitary power factor).

Reference Active Power [μW]	Errors [%]	
	50 Hz	60 Hz
1225	-6.6	-6.6
4900	-6.9	830
11025	-7.0	-7.0
19600	-7.0	-7.0
30625	-7.0	-7.0
44100	-1.3	-1.3
60025	-1.3	-1.3
78400	-1.3	-1.3
99225	-1.3	-1.3
122500	-1.3	-1.3
148225	-1.3	-1.3
176400	-1.3	-1.3
207025	-1.3	-1.3
240100	-5.3	-1.3

Finally, the results under non-sinusoidal conditions are shown in Table 6 and Table 7 for voltage and current channels, respectively. In the first column of the Tables, the harmonic order of the component applied in addition to the 50-Hz one, is indicated, and in the second column its relative voltage is shown. The results relevant to the 60-Hz harmonics are quite similar.

The number of harmonics considered for the voltage channel is lower than one used for the current channel due to corresponding lower value of the cut-off frequency. The provided results shown that current channel behaves significantly better than the voltage one and the performances are not affected by the order of the harmonic injected. As for current channel, the maximum difference between reference

Table 4. Active power measurements errors at 50 Hz with varying phase shift φ between voltage and current.

φ (degree)	Reference active power [μW]	Measured active power errors [%]
0.2	119601	-1.8
5	119153	-2.1
10	117877	-3.6
15	115620	-3.6
20	112486	-3.7
25	108491	-3.8
30	103671	-3.9
35	98069	-4.0
40	91719	-4.2
45	84671	-4.4
50	76976	-4.6
55	68701	-4.9
60	59903	-5.3
65	50648	-5.8
70	41003	-6.6
75	31051	-7.8
80	20872	-10
85	10526	-17
90	96	1361

Table 5. Active power measurements errors at 60 Hz with varying phase shift φ between voltage and current.

φ (degree)	Reference active power [μW]	Measured active power errors [%]
0.3	119917	-2.9
5	119377	-3.0
10	117964	-3.1
15	115671	-3.2
20	112502	-3.3
25	108488	-3.5
30	103648	-3.6
35	98030	-3.9
40	91645	-3.7
45	84583	-4.0
50	76880	-4.3
55	68594	-4.6
60	59787	-5.1
65	50525	-5.7
70	40882	-6.6
75	30928	-8.1
80	20736	-11
85	10393	-19
90	41	4334

Table 6. Voltage channel errors under non-sinusoidal conditions.

Harmonics	Relative amplitude	Reference values [mV]	Errors [%]
3	5%	350.6	-10
5	6%	350.3	-11
7	5%	350.9	-11
3-5	5% - 6%	350.7	-9.7

Table 7. Current channel errors under non-sinusoidal conditions.

Harmonics	Relative amplitude	Reference values [mV]	Measured values [%]
3	4%	350.1	$-3.7\cdot10^{-2}$
5	4%	350.0	$-1.4\cdot10^{-2}$
7	4%	350.2	$-4.0\cdot10^{-2}$
9	4%	350.1	$-8.6\cdot10^{-2}$
11	2%	350.5	$-14\cdot10^{-2}$
13	2%	350.0	$-2.9\cdot10^{-2}$
15	2%	350.3	$-8.6\cdot10^{-2}$
17	1.5%	350.1	$-2.9\cdot10^{-2}$
19	1.5%	350.8	$-5.7\cdot10^{-2}$
21	1.5%	350.1	$-2.9\cdot10^{-2}$
23	0.6%	350.6	$-5.7\cdot10^{-2}$
25	0.6%	350.7	$2.9\cdot10^{-2}$
27	0.6%	350.0	$2.9\cdot10^{-2}$
29	0.6%	350.7	$2.9\cdot10^{-2}$
31	0.6%	350.5	$2.9\cdot10^{-2}$
33	0.6%	350.6	$5.7\cdot10^{-2}$
35	0.3%	350.4	$5.7\cdot10^{-2}$
all	all	350.39	$-37\cdot10^{-2}$

and measurement values is about 0.1%, except when all the harmonics are injected in, where the error becomes about 5 times greater. On the contrary, as for the voltage channel, the above maximum difference is about 10%. Of course, the obtained performances are quite similar to the ones gauged under sinusoidal conditions, given that the considered harmonic amplitudes (which corresponds to the limits endorsed by [15, 16]) are lower than a few percents of the rms value of the power-frequency component.

5. CONCLUSIONS

The accuracy performances of an integrated circuit have been investigated under both sinusoidal and non-sinusoidal conditions. The IC allows measuring the rms value of its input voltage and current channels and the associated active power.

In particular, frequency response, non-linearity and gain errors have been determined, under sinusoidal conditions, for the three measurement functions. In the case of non-sinusoidal conditions, the IC has been tested by applying, in addition to the power-frequency component, harmonics having amplitude equal to the limits endorsed by the International Standards.

The results have shown that the accuracy of the device under test can be considered satisfactorily as for active power and, specially, current rms values. On the other hand, the voltage channel accuracy is significantly worst.

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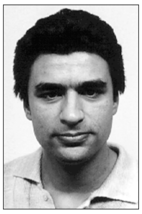

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