AN ARDUINO SHIELD FOR POWER NETWORK VOLTAGE AND CURRENT MEASUREMENT

Daniele Gallo, Carmine Landi and Mario Luiso

Department of Information Engineering, Second University of Naples
Aversa (CE), Italy, mario.luiso@unina2.it

Abstract: The development trends of electrical networks clearly indicate that grids of the future will include more and more smart components. In the new smart grids, smart components fulfill measurement and control tasks: in this scenario, not only the simple energy consumption, but also other parameters have to be measured. Among these parameters certainly there is the quality of energy. Therefore new smart meters have to face the issue to measure energy consumption and energy quality over a wide frequency range. Therefore, in order to make possible the implementation of a smart meter with standard commercial components, in this paper a prototype of voltage and current transducers for the Arduino microcontroller board is presented. Its design, simulation and experimental characterization are shown.

Keywords: voltage transducer, current transducer, smart meter, Arduino microcontroller.

1. INTRODUCTION

The development trends of electrical networks clearly indicate that grids of the future will include more and more smart components. In the new smart grids, smart components fulfill measurement and control tasks: in this scenario, not only the simple energy consumption, but also other parameters have to be measured. Among these parameters certainly there is the quality of energy. Therefore new smart meters have to face the issue to measure energy consumption and energy quality over a wide frequency range. Moreover, in order to make power network more and more smart, it will not be sufficient a single smart meter for each electrical customer, but the trend indicates that every single electrical load in the future will have its own smart meter. In this scenario it is clear that the low cost of a smart meter will be one of the key factors. Therefore this paper aims to propose a way to realize a smart meter with standard commercial components. In particular, a typical smart meter is composed of voltage and current transducers, a microprocessor and eventual actuators. The design of the microprocessor and of actuators is not in the scope of this paper. Instead, in this paper a prototype of voltage and current transducers for the Arduino microcontroller board is presented. As it will be explained in section 2 the realized prototype is an "Arduino shield" ([1]), that is a board that can be plugged on top of the Arduino PCB extending its capabilities. Far from commercial instrument transformers, which are typically usable in the narrow 50-400 Hz frequency range, the realized transducers have both large bandwidth and high accuracy. In section 2 a brief review of Arduino microcontroller board is reported. Section 3 presents the design and the simulation of realized transducers. Section 4 deals with transducer realization. Section 5 show experimental tests on the prototype of the transducers.

2. ARDUINO MICROCONTROLLER REVIEW

Arduino is an open-source single-board microcontroller, descendant of the open-source Wiring platform, ([2], [3]) designed to make the process of using electronics in multidisciplinary projects more accessible. The hardware consists of a simple open hardware design for the Arduino board with an Atmel AVR processor and on-board input/output support. The software consists of a standard programming language compiler and the boot loader that runs on the board ([1]).

Arduino hardware is programmed using a Wiring-based language (syntax and libraries), similar to C++ with some simplifications and modifications, and a Processing-based integrated development environment ([1]).

An Arduino board consists of an 8-bit Atmel AVR microcontroller with complementary components to facilitate programming and incorporation into other circuits. An important aspect of the Arduino is the standard way that connectors are exposed, allowing the CPU board to be connected to a variety of interchangeable add-on modules (known as shields). Official Arduinos have used the megaAVR series of chips, specifically the ATmega8, ATmega168, ATmega328, ATmega1280, and ATmega2560. A handful of other processors have been used by Arduino compatibles. Most boards include a 5 V linear regulator and a 16 MHz crystal oscillator (or ceramic resonator in some variants. An Arduino's microcontroller is also pre-programmed with a boot loader that simplifies uploading of programs to the on-chip flash memory, compared with other devices that typically need an external programmer. Current Arduino boards are programmed via USB, implemented using USB-to-serial adapter chips such as the FTDI FT232. The Arduino IDE is a cross-platform application written in Java, and is derived from the IDE for the Processing programming language and the Wiring

project. It is designed to introduce programming to artists and other newcomers unfamiliar with software development. It includes a code editor with features such as syntax highlighting, brace matching, and automatic indentation, and is also capable of compiling and uploading programs to the board with a single click. There is typically no need to edit makefiles or run programs on a command-line interface.

Arduino and Arduino-compatible boards make use of shields, which are printed circuit boards that sit atop an Arduino, and plug into the normally supplied pin-headers ([1]). These are expansions to the base Arduino. There are many functions of shields, from motor controls, to breadboarding (prototyping).

The realized voltage and current transducers represent an Arduino shield, in particular a shield to make it a smart meter.

3. DESIGN AND SIMULATION OF THE SHIELD

The electrical scheme of the two transducers is shown in Figure 2. It can be seen that simple electronic components, such as operational amplifiers (op-amps), resistors and capacitors have been used; in fact, one of the main advantages of this circuit is the very low cost of its components. For both the transducers, in Figure 2, three main sections can be found: the first one is the input stage which couples the transducer to the voltage source, having an high input impedance; the second one is the optical insulation stage, which separate low voltage output section from high voltage input section; finally, the third one is the output stage which couples the transducer with the input stage of measuring instruments. In the following subsections there are the descriptions of the transducers stages and the simulations.

A. Input Stages

The two transducers differ among themselves for the input stage. For the voltage transducer the input stage is an active compensated divider; it has been obtained by two op-amps: the first one (U2A) is mounted in current-pump configuration, while the second one (U2B) realizes a transresistance amplifier. The current-pump configuration is used in order to obtain a current differential amplifier with the output node on the non inverting input. Setting:

$$\frac{R1}{R6} = \frac{R2}{R5} \qquad (1)$$

and connecting non inverting input to ground, U2A generates a current proportional to the input voltage; this current is converted in a voltage signal by U2B. The entire input stage exhibits a transduction ratio of 650/200 V/mV, equal to about 3252. This scaling factor is given by the ratio of R1, or R2, and the sum of R4 and R7 and it is tuneable simply changing the value of this ratio. It is important to note that the circuit senses only the input differential voltage and rejects the common mode voltage, since the current pump amplifies the difference between the current in R1 and that in R2. The input stage of the current transducer is composed of a shunt, with resistance equal to 2.5 mΩ and

power equal to 2.25 W, and a differential amplifier with gain equal to 1.8.

B. Insulation Stages

The common mode voltage between inputs of voltage transducers and ground may be very dangerous: not only it can destroy the amplifier and the other instrumentation connected to it (for example: analog to digital converters, data acquisition systems, oscilloscopes, etc.), but it may be unsafe for the operators, too. So it is necessary to insulate the transducer to preserve the safety of workers and the integrity of instrumentations. To this aim, an optical insulation stage has been introduced after the input stage. The two transducers have two identical insulation stages. It consists of a modulator optically coupled to a demodulator. It is the integrated component HCPL7840, produced by Agilent. It guarantees insulation up to 2500 V with an upper bound on usable bandwidth at approximately 100 kHz, high enough for applications on power systems; in fact it is a very large limit compared to those present in the standards. A first order analogical filter R7-C3, has been inserted at the input of the insulator with the aim of avoiding frequency alias. In order to keep the insulation between input and output voltages, i.e. between power line and the measuring equipment, clearly, it is necessary to use two different isolated supplies, which present galvanic separation. The isolated DC sources have been obtained by means of two isolated DC/DC converters.

C. Output Stages

As the insulation stages, also the output stages are identical for the two transducers. The insulation stage receives input signals in the range of ±200 mV and its output is the reproduction of the input but amplified with a scaling factor of 8 and with a common mode voltage of about 2.5 V. In order to eliminate this common mode voltage a differential amplifier has been used. It has a unity gain and adds to the input voltage an offset equal to 1.65 V. So, it's output is in the range of 0÷3.3 V and it is compatible with the range of Arduino analog input.

D. Simulations

The entire transducers have been simulated in Multisim environment, in order to find the right value of resistances and capacitances, using the real models of the active components.

Time domain simulations are shown in Figure 3 and Figure 4. Figure 3 shows input (230 V_{RMS}) and output (1.65 V_{DC} and 2.475 V_{peak}) voltages of voltage transducer. Figure 4 shows input current (30 A_{RMS}) and output voltage (1.65 V_{DC} and 3.3 V_{peak}) of current transducer. For sake of brevity only time domain analysis is reported. In particular it can be observed that: 1) both the output voltages have mean value of 1.65 V, 2) voltage transducer exhibits a ratio of 650/1.65 V_{peak}/V_{peak} and 3) current transducer exhibits a ratio of 45/1.65 V_{peak}/V_{peak}.

Frequency domain simulations are shown in Figure 5 (voltage transducer) and Figure 6 (current transducer). A very low distortion can be observed from both the figures.
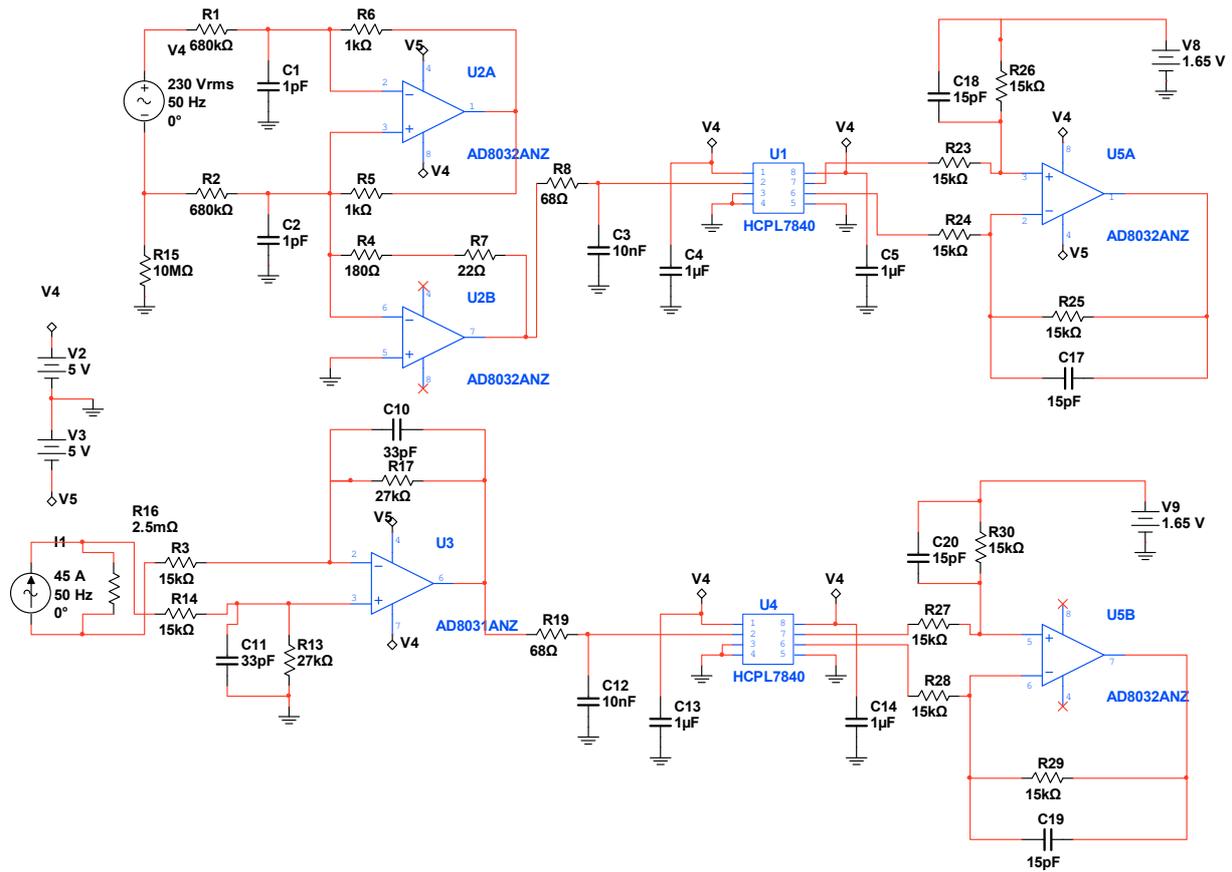
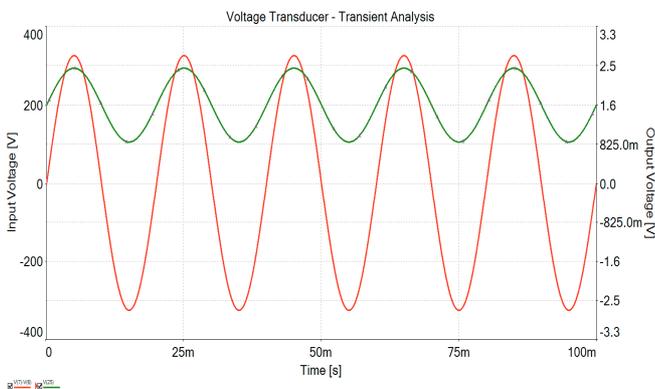Figure 2. Circuital scheme of the voltage and current transducers.
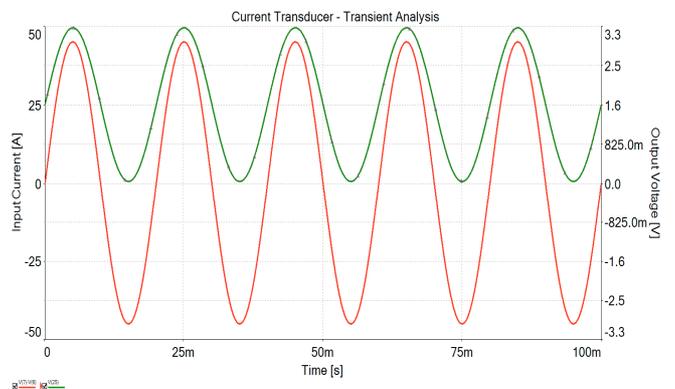

Figure 3. Time domain simulation of voltage transducer

Figure 4. Time domain simulation of current transducer

4. SHIELD REALIZATION

The first prototype of the transducers has been realized on a prototyping board and it has been preliminarily tested with a 230 V, 2 kW linear load.

Since the output voltages complied with the specifications, a new prototype has been realized with a printed circuit. The layout of circuit has been obtained through the Eagle CAD software: this software offers Arduino libraries which allow to design a shield for Arduino. In Figure 6 circuit layout on a double sided board is shown. The layout has been printed on a presensitized board and then the components has been soldered above. The final prototype, mounted on an Arduino UNO board, is shown in Figure 7.

5. EXPERIMENTAL RESULTS

The experimental setup for the characterization of the transducers ([4]) consists of a multifunction calibrator, Fluke 5500A, and a reference multimeter HP 3458A.
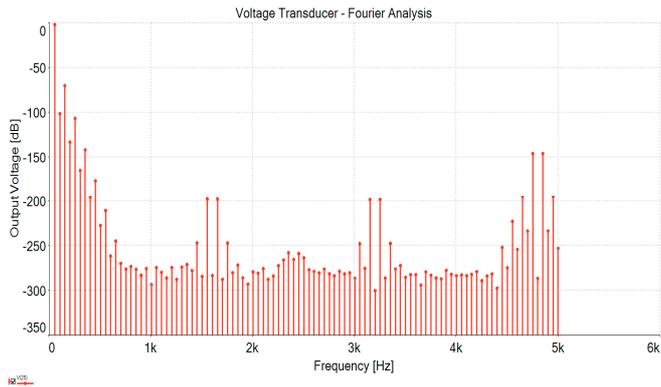
Figure 5. Frequency domain simulation of voltage transducer
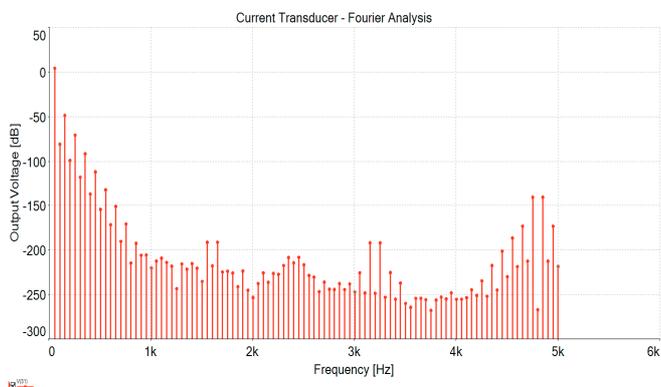

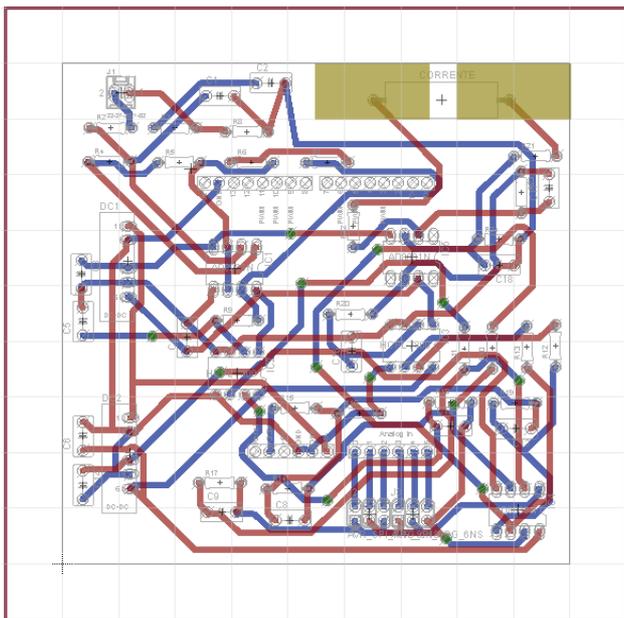Figure 6. Frequency domain simulation of current transducer
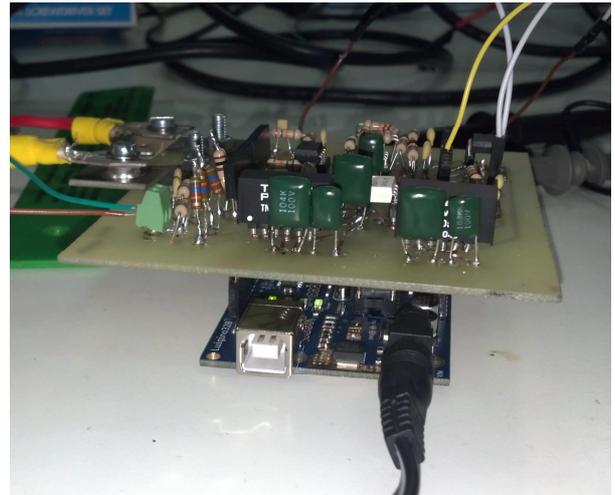

Figure 7. Layout of the circuit

Figure 8. Final prototype of the transducers on Arduino board.

The results have been obtained in certified laboratory for voltage and current measurement. The measurement uncertainties stated in the following are estimated at the level of twice the standard deviation (corresponding, in the case of normal distribution, to a confidence level of about 95%).

As reference standards, those reported in [5]-[9]have been considered.

The calibration procedure is the same for the two transducer and it is divided in two steps. In the first step, the transducer under test is supplied with a sinusoidal signal at frequency of 50 Hz and increasing amplitude: this step aims to verify the variability of the transduction ratio with the amplitude of the input. In the second step the transducer under test is supplied with a sinusoidal signal with fixed amplitude and increasing frequency: in such a way the frequency bandwidth of the transducer is tested.

The estimation of the uncertainty has been evaluated through the application of the uncertainty propagation law, as recommended by [7], considering the contributions associated with the reference samples and those attributable to the instrument in question, including among them also those related to the repeatability and resolution of the instrument under test.

The environmental conditions were:
- Temperature: (23 ± 5) °C
- Relative humidity (55 ± 5) %

In Table 1 the values involved in the first step of calibration procedure for current transducer are shown, while in Table 2 the values involved in the second step are reported. Figure 7 and Figure 8 show the transfer function of current transducer versus, respectively, input current amplitude and frequency.

In Table 3 the values involved in the first step of calibration procedure for voltage transducer are shown, while in Table 4 the values involved in the second step are reported. Figure 9 and Figure 10 show the transfer function of voltage transducer versus, respectively, input voltage amplitude and frequency.

Table 1. Current transducer: verification of the variability of the transduction ratio with the amplitude of input current

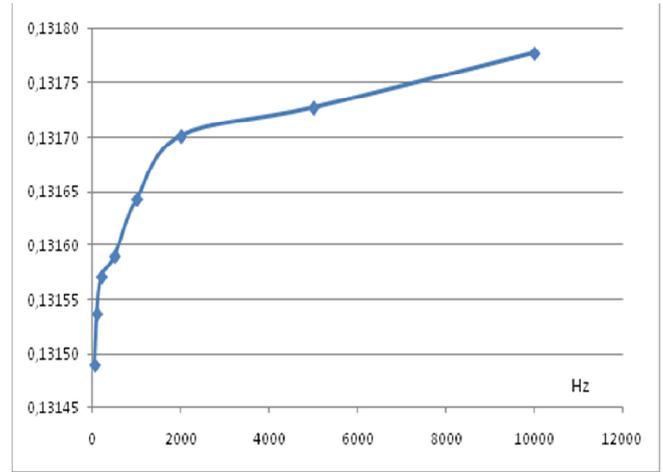| Verification of transduction ratio				
Input current	Frequency	Output voltage	Transfer function	Extended uncertainty
100 [mA]	50 [Hz]	17,4557 [mV]	0,17456	1,6E-02
200 [mA]	50 [Hz]	28,580 [mV]	0,14290	1,3E-02
500 [mA]	50 [Hz]	66,528 [mV]	0,13306	1,3E-02
1 [A]	50 [Hz]	0,131504 [V]	0,13150	1,3E-02
2 [A]	50 [Hz]	0,262222 [V]	0,13111	7,9E-03
5 [A]	50 [Hz]	0,655164 [V]	0,13103	7,9E-03
10 [A]	50 [Hz]	1,310990 [V]	0,13110	1,6E-02

Figure 10. Transfer function of current transducer vs. input current frequency

Table 2. Current transducer: verification of the variability of the transduction ratio with the amplitude of input current

Verification of frequency bandwidth				
Input current	Frequency	Output voltage	Transfer function	Extended uncertainty
1 [A]	50 [Hz]	0,131490 [V]	0,13149	9,0E-02
1 [A]	100 [Hz]	0,131537 [V]	0,13154	9,0E-02
1 [A]	200 [Hz]	0,131571 [V]	0,13157	9,0E-02
1 [A]	500 [Hz]	0,131590 [V]	0,13159	9,0E-02
1 [A]	1 [kHz]	0,131643 [V]	0,13164	9,0E-02
1 [A]	2 [kHz]	0,131701 [V]	0,13170	2,0E-01
1 [A]	5 [kHz]	0,131727 [V]	0,13173	2,0E-01
1 [A]	10 [kHz]	0,131777 [V]	0,13178	6,0E-01

Table 3. Voltage transducer: verification of the variability of the transduction ratio with the amplitude of input current

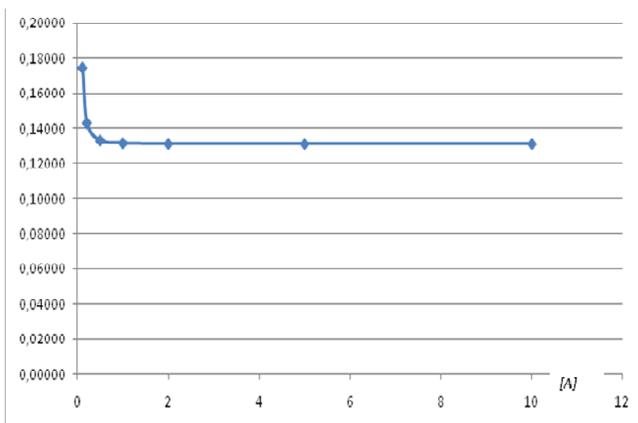| Verification of transduction ratio				
Input voltage	Frequency	Output voltage	Transfer function	Extended uncertainty
10 [V]	50 [Hz]	56,88922 [mV]	0,00569	2,3E-04
20 [V]	50 [Hz]	103,81813 [mV]	0,00519	2,1E-04
50 [V]	50 [Hz]	0,2520443 [V]	0,00504	2,0E-04
100 [V]	50 [Hz]	0,5018812 [V]	0,00502	2,0E-04
200 [V]	50 [Hz]	1,0031967 [V]	0,00502	2,0E-04
500 [V]	50 [Hz]	2,506256 [V]	0,00501	2,0E-04
700 [V]	50 [Hz]	3,457382 [V]	0,00494	2,0E-04

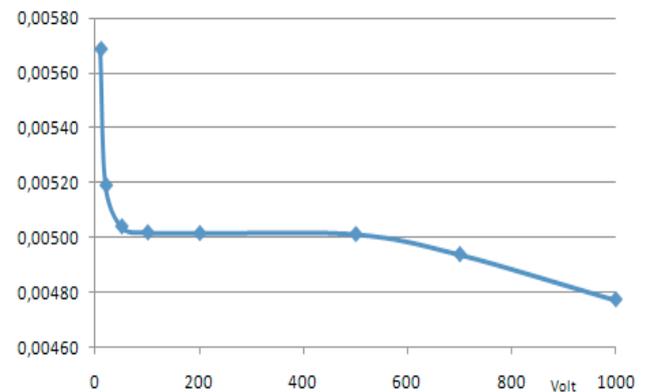Figure 9. Transfer function of current transducer vs. input current amplitude

Figure 11. Transfer function of voltage transducer vs. input voltage amplitude

Table 4. Voltage transducer: verification of the variability of the transduction ratio with the amplitude of input current

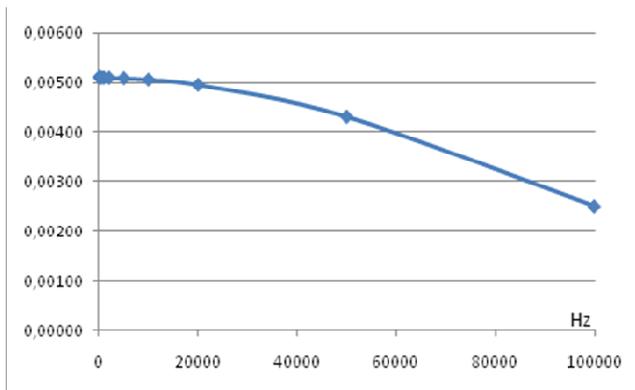| Verification of frequency bandwidth				
Input voltage	Frequency	Output voltage	Transfer function	Extended uncertainty
30 [V]	50 [Hz]	0,153201 [V]	0,00511	2,1E-04
30 [V]	100 [Hz]	0,153011 [V]	0,00510	2,1E-04
30 [V]	200 [Hz]	0,152895 [V]	0,00510	2,1E-04
30 [V]	500 [Hz]	0,152845 [V]	0,00510	2,1E-04
30 [V]	1 [kHz]	0,152781 [V]	0,00509	2,1E-04
30 [V]	2 [kHz]	0,152726 [V]	0,00509	2,1E-04
30 [V]	5 [kHz]	0,152433 [V]	0,00508	2,1E-04
30 [V]	10 [kHz]	0,151545 [V]	0,00505	2,1E-04
30 [V]	20 [kHz]	0,148339 [V]	0,00494	4,0E-04
30 [V]	50 [kHz]	0,129199 [V]	0,00431	8,2E-04
30 [V]	100 [kHz]	0,0753595 [V]	0,00251	6,1E-04

Figure 12. Transfer function of voltage transducer vs. input voltage frequency

For current transducer, the results show low variability of transduction ratio in the range 100 mA- 10 A and a -3 dB frequency bandwidth close to 100 kHz.

For current transducer, the results show low variability of transduction ratio in the range 10 V- 1000 V and a -3 dB frequency bandwidth close to 100 kHz.

6. CONCLUSIONS

In this paper a prototype of voltage and current transducers, compatible with Arduino microcontroller boards, for power network measurements has been presented. This prototype constitutes an "Arduino shield", since it can be plugged on the top of an Arduino board and give it the capability to measure voltage and current of power networks. The design, the simulations and the calibration have been presented. Experimental results show that the realized transducers have good performance, from both the point of views of frequency bandwidth and accuracy. They have also another important feature, the low cost: this makes the shield, together with an Arduino board, a powerful demo kit, attractive for both electrical engineering teaching electrical energy industry.

7. REFERENCES

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