Experimental Performance Assessment of a low-cost single-phase Arduino-based Power Meter

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Abstract: ***A single-phase, low-cost, plug and play, portable and wireless meter has been implemented to measure the electrical parameters of typical household electrical loads ranging from a few watts to a few kilowatts. ADE7753 smart measuring IC was employed to acquire load current and voltage information through sensors. The Arduino Mega 2560 board, alongside the Arduino Wi-Fi shield were used for wireless communication and for logging of information on an external memory card. Measurements performed on eight typical office loads using the proposed meter and a calibrated Fluke 345 power quality clamp meter revealed an acceptable performance for most of the considered electrical appliances. The absolute percentage error in measured active power and cumulative energy consumption were less than 5 % for most of the considered appliances. The total cost of the system was 139 USD, which makes it affordable to measure the power consumption of different typical domestic loads.***

Keywords: Power meter, Arduino, Fluke 345, Single-phase, ADE7753

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1. Introduction

The built environment consumes a significant 40 % of the total energy demand worldwide. Intelligent buildings are becoming more popular as they have the capability to monitor, manage and control many aspects to improve their energy performance. Moreover, as the electricity infrastructure migrates towards smart grids, conventional electromagnetic based energy meters are being replaced by state of the art electronic systems with advanced functionalities in order to extract more useful information about the energy consumption than merely numerical data. For instance, most conventional meters have no ability to provide detailed consumption information for specific hours, days or weeks, given that only accumulated energy use data is available. Moreover, the absence of communication option leads to the tedious, expensive and time consuming task of manual meter reading which can be erroneous and can involve corruption. Traditional metering techniques consisted of measuring the energy consumption of an entire building. Nowadays, it can be more advantageous to monitor the energy performance of individual devices or a group of devices for a more effective energy management.

Several state-of-the art electronic meters have been proposed in literature. A Wi-Fi smart plug for monitoring the energy consumption of remote electrical appliances via Web, as well as switching them ON/OFF via consumer interaction was developed using the ESP-WROOM02 microcontroller and STPM01 chip [1]. A smart plug to provide power reduction without turning off the load was investigated in [2]. A power meter based on Arduino, current and voltage transformers was proposed in [3] and [4]. A low-energy consuming electric energy meter reader based on MSP430FG4618 controller and comprising a module for communication through SMS was proposed by [5]. An Arduino and Ethernet-based smart plug which provides real time update of the energy consumption at the device level is proposed in [6]. An electronic energy meter using the ADE7751 metering IC and having the capability of automated progression of measurement through wireless communication was proposed in [7]. The authors of [8] presented a low-cost wireless GSM energy meter and a web interface for automatic billing and management of collected data. The MCP3905A metering IC, an 8-bit PIC16F877A Microcontroller, a GSM modem and the EEPROM Atmel 24C256 external memory were used. An Arduino-based power factor metering system was proposed in [9], whereby it was concluded that the system does not perform well with predominantly inductive loads made up of lamps. A wireless current sensor node was proposed in [10] and [11], but the issue is that voltage was not measured and therefore, devices' performances could not be fully described. An Arduino-based smart meter employing ADE7753 metering IC, and having information storage and wireless transfer capabilities was proposed in [12], but limited investigation was carried out on the performances of the device.

Many of the cited works tested the developed meters on simple loads such as bulbs, but other common loads in a typical domestic context have been disregarded. Moreover, very few studies exist whereby the performance of the proposed meter has been compared against a calibrated industry-grade meter. Furthermore, for cases where the limited results have been cross checked with other reliable measurements, no investigation was carried out to identify causes of the errors so that improvements can be carried out. As per the authors' knowledge, so study so far has critically assessed the performance of a designed wireless low cost meter based on ADE7753 IC and Arduino with appliances having different power ratings, power factors and involving switch-mode power supplies. The contribution of this paper is to address the above knowledge gap.

2. Methodology

The block diagram of the developed system is shown inFigure 1. The domestic utility supply voltage of the island of Mauritius is 230 V ± 6 % at a frequency of 50 Hz and the earthing system is of T-T type.

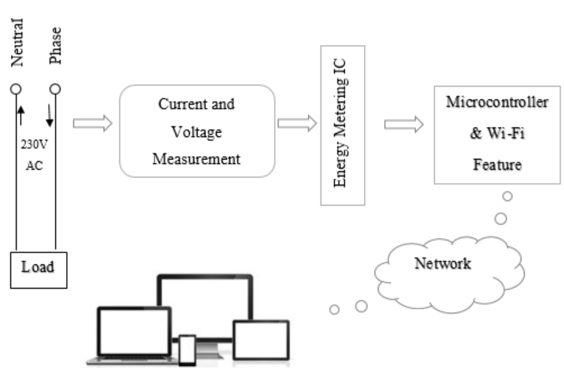

Figure 1. Block diagram of proposed meter

2.1. Current and Voltage Measurement

The ZMCT116A [13]CT having a turns ratio of 2500:1 was selected for this application as it is relatively cheap, it is ideal for noisy environment, it provides galvanic isolation and it requires no external power supply. Based on the maximum current to be measured by the system, the calculated burden resistance RB to be connected to the CT was found to be 200 Ω. A low-pass filter was included to reduce the noise on the secondary of the CT. A 240 V AC to 12 V AC voltage transformer (VT) was used to measure the supply voltage and to provide galvanic isolation between the high voltage on the supply side and the low voltage side of the electronic circuitry.

2.2. Current and Voltage Measurement

The ADE7753single-phase multifunction metering IC was used in this work.The chip has 2 input channels; one for the current and one for the voltage. Each channel is equipped with a 16-bit Σ-Δ analogue to digital converter (ADC). The IC incorporates RMS calculation for the voltage and current. Channel 1 is used to measure current and channel 2 is used to measure voltage. Given that the maximum differential voltage supported by the voltage channel was ± 0.5 V and that the output voltage of the VT was 12 V, a suitable voltage divider circuit was designed to maintain the voltage within the required range. A low pass filter was added to reduce noise.

2.3. Microprocessor

To be able to extract the processed information from the ADE7753 through Serial Peripheral Interface (SPI) and to provide wireless communication function, Arduino Mega 2560 was selected. This microprocessor is known to be cheap, reliable and has many well-known applications such as power system substation monitoring and control [14]. The Arduino Wi-Fi shield was used as add-on board to allow the Arduino Mega to connect to the internet wirelessly using the 802.11 protocol. An on-board microSD card reader allows storage of information on an external memory. Arduino Mega communicates with both the Wi-Fi shield's processor and the SD card using the SPI bus. The shield is powered by the Arduino Mega, which is itself powered by an independent 5 V power supply.

2.4. Circuit Implementation

After simulations on Proteus software, sections of the entire circuit were practically tested to confirm adequate operation. Figure 2 and Figure 3 show the connections to the voltage and current channels of the ADE 7753 respectively. Figure 4 shows how the different components were assembled excluding the microprocessor, and Figure 5 shows the portable meter.

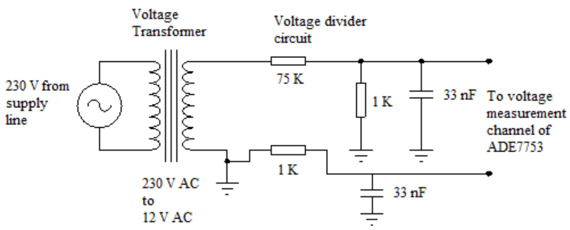

Figure 2. Connection to voltage channel

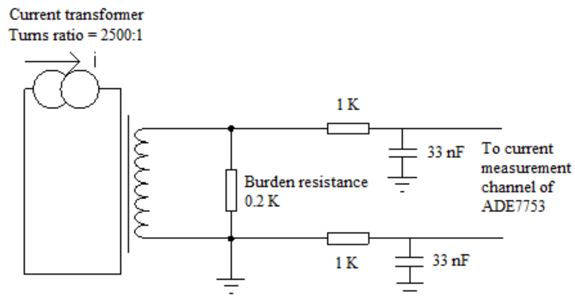

Figure 3. Connection to current channel

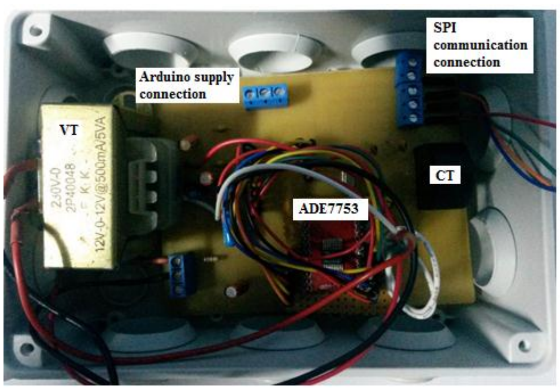

Figure 4. Circuit implementation

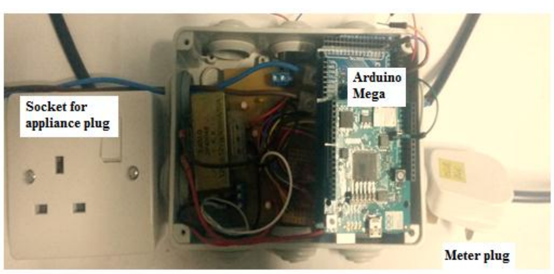

Figure 5. Completed circuit

2.5. Software design

The software design comprised 3 parts: establishing the SPI communication for the microprocessor to fetch the different parameters from the ADE7753; setting up the connection between the Wi-Fi shield and the network; and finally logging the data to an excel file on the SD card. Logged parameters were RMS voltage, RSM current, active power, apparent power, power factor, and cumulative active energy consumption. Though the sampling mode of the ADE7753 was 14 kHz, data was obtained by the Arduino Mega from the ADE7753 at a frequency of 100 Hz as per the Nyquist-Shannon sampling theorem [12] and then averaged to get the parameter value for 1 s for the RMS voltage, RSM current, active power and apparent power. The average power factor for 1 was then calculated by the ratio of average active power to the average of apparent power, given that the ADE7753 does not have special registers for the power factor. The energy for each time period was finally obtained by the product of the active power and the time period.

2.6. Testing

The developed meter was tested on some commonly available electrical appliances: Light bulb, kettle, fan, laptop, soldering iron, refrigerator, computer (PC) power supply, and LED PC screen. The appliances are essentially different types of electrical loads. For instance, the bulb was an incandescent lamp, which is basically a resistive load. The refrigerator contains an induction motor, which is predominantly inductive. Most of the laptops and PC screens make use of switch mode power supplies. The duration of the test for each load varied depending on the availability of the equipment. Moreover, using the 1 s data, averaging over different time periods were obtained as shown in TABLE1.

TABLE1. Measurement scenarios

Electrical Load	Testing duration (s)	Measurement averaging period (s)
Light Bulb	720	45; 90
Fan	540	45
Kettle	420	30; 60
Refrigerator	720	45; 90
Soldering Iron	16	1
Laptop	720	45; 90
PC power supply	720	45; 90
PC screen	720	45; 90

Measurement results were compared to those provided by a calibrated Fluke 345 Power Quality clamp meter, which has a sampling frequency of 15.625 kHz. An averaging time of 1 s was selected to match the averaging time period of the developed meter. Figure 6 shows how measurements were performed on the PC screen using both the developed and the Fluke meters. The measurement from the Fluke 345 meter was taken to be the true value and the percentage measurement error of the proposed meter was calculated as per equation (1).

$$\% \text{ Error} = \frac{\text{DMM} - \text{FMM}}{\text{FMM}} \text{X } 100 \ \% \quad (1)$$

Where DMM is the Developed Meter Measurement and FMM is the Fluke Meter Measurement.

Figure 6. Testing on LED PC screen

The average error for each parameter is the mean of all the measurement errors for that corresponding parameter over the considered testing duration. The Wi-Fi transmission of the meter over a university network was eventually tested through a laptop and a mobile phone to verify the connection. The system was assigned a special IP address of 192.168.100.8 and it was verified if a web browser can display load measurement information.

3. Results and Discussion

The average percentage measurement error for each parameter is shown in Figure 7 to Figure 12 and each figure shows the error for all the measurement scenarios as per TABLE1.

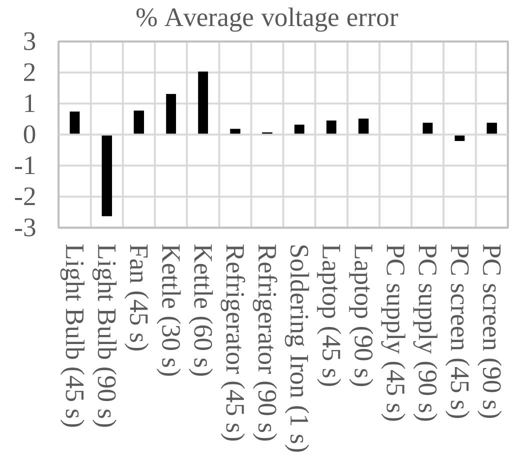

Figure 7. % Voltage Error

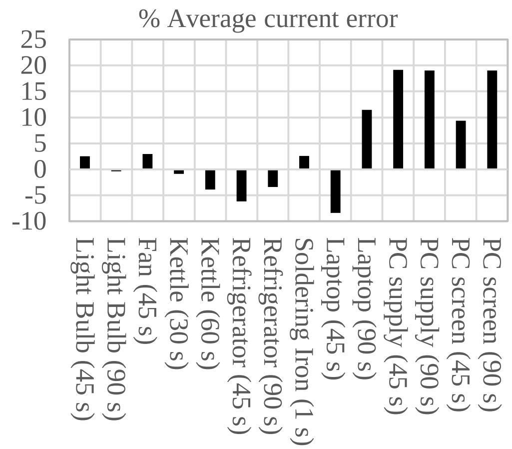

Figure 8. % Current Error

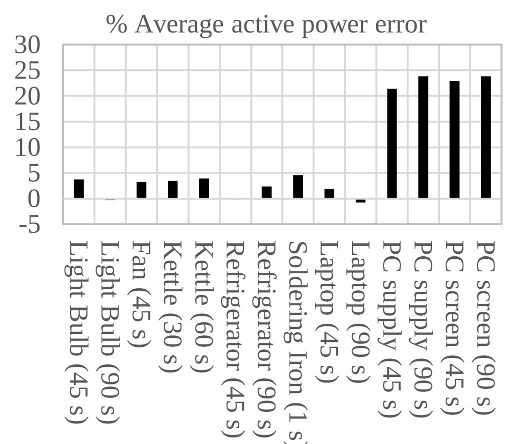

Figure 9. % Active Power Error

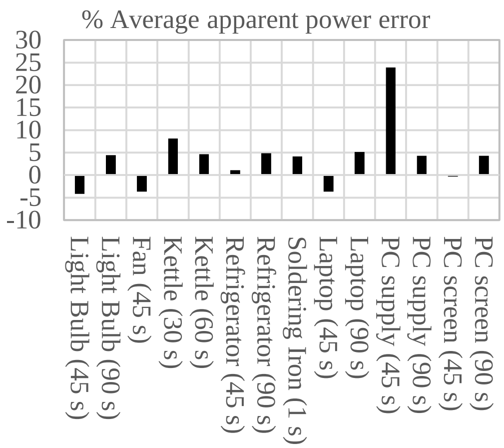

Figure 10. % Apparent Power Error

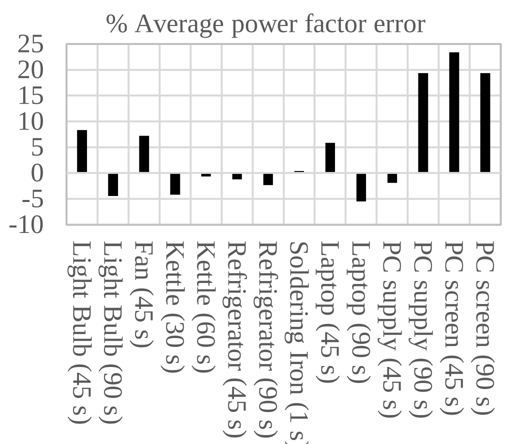

Figure 11. % Power Factor Error

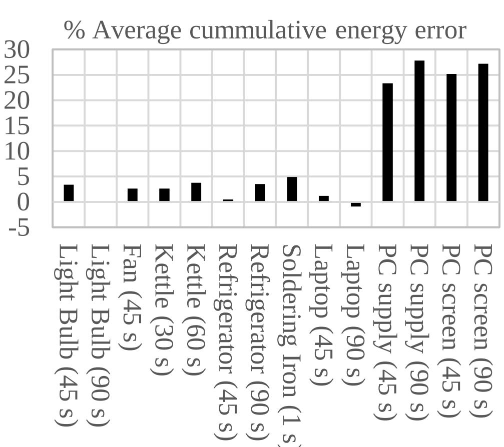

Figure 12. % Energy Error

The percentage absolute average error (PAAE) varied in the ranges of 0.1 % to 2.6 % for voltage measurement, 0. % to 19.2 % for current measurement, 0.2 % to 23.9 % for active power measurement, 0.3 % to 23.9 % for apparent power measurement, 0.4 % to 23.4 % for power factor values, and 0.1 % to 27.8 % for cumulative energy. The voltage measurements were relatively close for the Fluke and the developed meter, with positive and negative errors. Similarly, currents were measured with a decent level of accuracy for most of the loads. The measured current, voltage, powers and power factor by the developed meter tended to vary frequently and by larger amounts compared to the measurements by the Fluke meter. Errors in current and voltage caused error propagation when combined to get the apparent power. Significant errors (> 5 %) were obtained in the cumulative energy consumption for the PC screen and PC power supply, due to large errors in the current and power factor measurements. When considering the different measuring time periods for the same test appliance, no definite conclusion can be drawn. The errors in active power and cumulative energy being less than 5 % suggest that the developed meter is providing sufficient accuracy for most of the considered loads. The average error for all the scenarios, all the parameters and all the appliances was 5.0 %. Figure 13shows the screen shot of a mobile phone accessing the measurement information from its browser. Figure 14 shows a screenshot of the Wi-Fi transmission on a laptop screen. Detailed electrical parameters for the light bulb connected to the metering system were displayed and the page would refresh every 10 seconds so as to get new data accordingly.

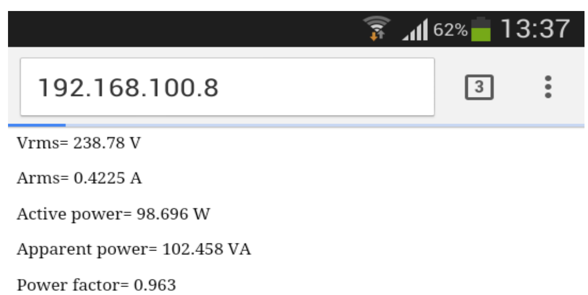

Figure 13. Viewing measured parameters through Wi-Fi on a mobile phone browser

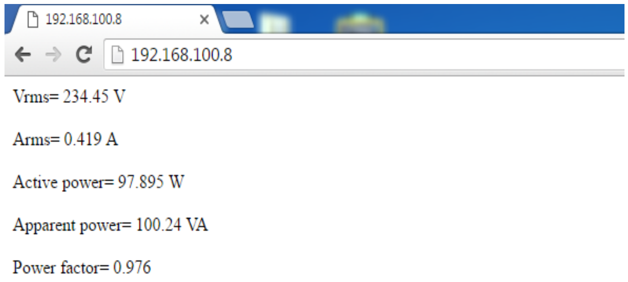

Figure 14. Viewing measured parameters through Wi-Fi on a web browser

4. Conclusion

A single-phase, low-cost, and plug and play, portable and wireless power meter has been developed in this work. The meter has the ability to measure, log and transmit via Wi-Fi essential electrical parameters of an electrical load such as RMS voltage, RMS current, active power, apparent power, power factor and cumulative energy consumption. It has been tested with different types of commonly available electrical loads and the results were compared to measurements provided by a calibrated Fluke 345 meter. For most considered test loads, the obtained errors in average power measurement and the cumulative energy are less than 5 %. It is important to note that the Fluke meter has accuracy values associated with all its measured parameters as per its datasheet[15]. Therefore, the actual parameter values can be lower or higher than those measured by the Fluke meter. In the near future, the meter will be compared to a much more accurate measurement system based on LabVIEW, better current and voltage sensors and more sophisticated energy metering IC. Moreover, a three-phase metering system will be developed. On overall, it can be deduced that the developed meter, being cheap and sufficiently accurate, can be applied in the efficient building electrical loads management and control.

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