

AC Power Meter Design Based on Arduino: Multichannel Single-Phase Approach

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Abstract—Monitoring power consumption of electrical appliances is a step towards energy efficiency and saving management. This paper proposes an Arduino multichannel power meter design with the aim at improving real power accuracy by sampling voltage and current simultaneously. Moreover, it adds the ability for users to choose current sensors for suitable use regarding to appliances. As a consequence, calibration factors must be changed according to a selected sensor. This design, instead of editing the source code by the users, provides configuration files and APIs for remote configuration. This paper presents the hardware design and high-level algorithm for the Arduino firmware. Experiments on multiple workloads with an external reliable power meter are setup for parameter calibrations and the meter design accuracy evaluation.

Keywords—Power Measurement, Power Meter, Arduino, Voltage Sensor, SCT-013-030, ADC

I. INTRODUCTION

Residential and office buildings utilize electrical appliances consuming electricity. Saving the energy reduce the operating cost, and helps decrease greenhouse gas emissions. To come up with an energy saving plan, the energy consumption of each appliance should be accounted. Therefore, an energy meter – e.g., a power meter – comes into play.

It is important to know energy consumption of individual or small groups of appliances rather than the whole building, so that each of them can be controlled towards an energy saving plan properly. Commercial portable meters are suitable for mobile measurement for a few points because they are not designed to stay measuring for a long period of time and the price is needed to be considered. Despite the existence of stationary power meters – e.g., products by EKM [1], Current-Cost [2], Watts up [3], Kill a Watt [4], OpenEnergyMonitor [5] – they have limitation on the number of measured loads and the compatibility with the ranges of current sensors. Although, OpenEnergyMonitor [5] can be coupled with different current sensors but its current products do not allow the user to change the sensors without recompiling the firmware.

For academic related works, [6] and [7] propose power meter designs sensing only current drawn by appliances, ignoring the voltage. They are suitable for measurements for which real power accuracy is compromised, however the measurement error is higher than power meters with voltage sensors when measuring non-resistive loads [8]. Current research work in [9], [10], [11], and [12] introduce power meter designs with both voltage and current sensors, which as a result, render more

accurate real power for all types of load but do not support reconfiguration for variable sensors.

One of the factor addressed by the design in this paper is the sampling time difference between voltage and current. OpenEnergyMonitor [5] and [11] sample voltage and current consecutively, using Analog-to-Digital Converter (ADC) on an Arduino board. Thus, the real power is computed, according to the AC active power formula in [8], from instantaneous voltage and current obtained from different time. To address this problem and to improve our previous work [11], this paper proposes a design with two ADCs responsible for sampling voltage and current separately. Additionally, to support multichannel measurement, a multiplexer is integrated.

In order to support the portability, the ability to couple with different current transformers (CT) as the current sensors is added. This is done by the introduction of configuration files in which each sensor's calibration factors are set. As a result, the user needs not reprogram and recompile the firmware.

The organization of this paper starts with background in Section II, followed by the design in Section III. Then, the evaluation and experimental setup are explained in Section IV and V, respectively. The experimental results are present in Section VI. Lastly, the conclusion and future work are narrated in Section VII.

II. BACKGROUND

A. Home Appliances

Home appliances refer to electrical appliances used in the residential section. They range from small ones such as portable device chargers consuming a fraction of watts to large devices, e.g., thousand-watt air-conditioners [13]. The power consumption figures usually refer to the running watts (averaged watts required when the appliance runs). Still, many appliances consume additional watts referred to as starting watts for a short period of time when the appliances transition themselves from the off to the on state [14]. The additional starting watts are caused by the inrush current when the appliances start. This property of appliances can be a cause of measurement errors if the the starting watts exceed measuring device's limit.

Another parameter of home appliances to be considered is their type. All appliances, also referred to as loads, can be categorized according to their behavior into either linear loads, or non-linear loads [15]. The impedance of linear loads

is constant and this makes the current drawn by a linear load proportional to the voltage applied to it, and the voltage and current frequencies are equivalent. Resistive (e.g., incandescent light bulbs, water boilers, toasters), inductive (e.g., fans, water pumps, blenders), and capacitive (e.g., capacitor banks) loads are all linear. On the contrary, non-linear loads vary their impedance depending on the voltage applied. Therefore, the current drawn is not proportional to the voltage applied to the load, resulting in distorted current waveform deviated from the fundamental frequency. Most electronic devices such as televisions, computers, radios, mobile phone chargers fall into this load category.

Despite the behavior difference, both load categories use the same formulas to calculate real power, apparent power, and power factor, providing that both instantaneous voltage and current at the same time are known.

III. DESIGN

The design consists of 3 main components as shown in Fig. 1. Most of the work in this design contributes to the transducer shield composed of 3 main modules: the voltage and current transducer module, the real-time clock module, and the voltage regulator module. The voltage regulator provides +5V supply to the whole shield. The real-time clock module shown Fig. 4 provides the timestamp for the measurement data. The core of the voltage and current transducer module consists of the analog-to-digital conversion section and the multiplexer section.

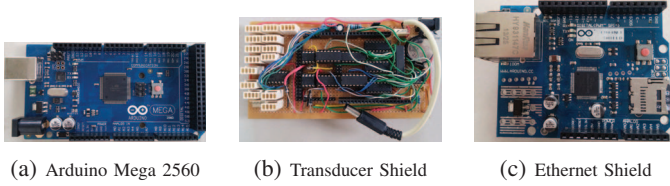


Fig. 1: Proposed Power Meter Design Main Components

A. Multiplexer Section

Fig. 2 is the schematic for this section. All the ICs comprise an analog multiplexer with 15 channels for analog signals from current sensors. Channel selector is done by 4-bit numbers ranging from 0 to 14 at pin 20 - 23 of U10, a 4-to-16 line decoder. The output of this IC is active low; therefore, inverters U7 - U9 are required. The signal from inverters is fed to enable pins (E pins) of analog switches U3 - U6 to close or open the circuit for each current sensor channel. The output of all CT channels (Z pins) are connected together to provide a single input for ADC that converts analog signal from a current sensor to its digital counterpart.

Each analog switch IC (HEF4066B) contains 4 analog switches inside. Thus, four of this IC provides 16 analog switches. Nonetheless, one switch is dedicated for the voltage channel with circuit always closed so as to add the same delay to the voltage signal as the current one.

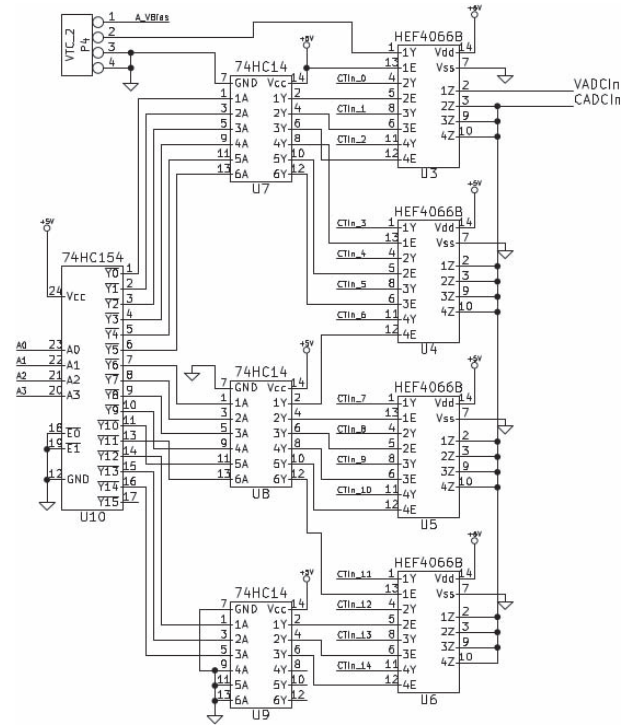


Fig. 2: Multiplexer Section

B. Analog-to-Digital Conversion Section

This section, shown in Fig. 3, is responsible for converting analog signals from voltage and current sensors, provided by the output from the multiplexer section (see labels *VADCIn* and *CADCIn* Fig. 2 and 3), to digital signals for being processed in Arduino. U1 and U2 are 12-bit ADCs. The output digital data comes out of pin 6 serially. They can be communicated with Arduino using SPI. However, Arduino has only one 8-bit buffer register for SPI but the data from these ADCs come out at the same time. Thus, U12, a serial-to-parallel shift register, is added to the schematic for the same purpose of SPI 8-bit buffer register.

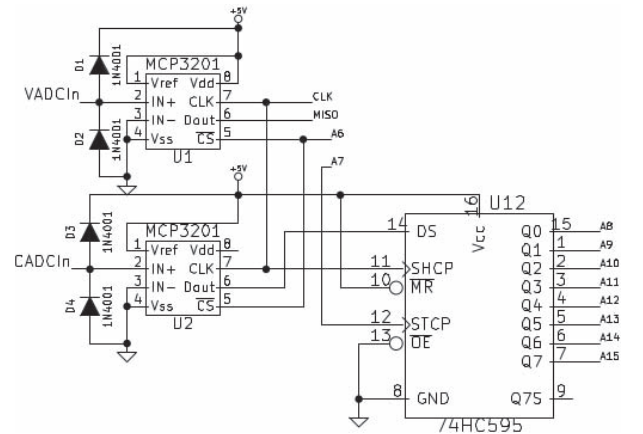


Fig. 3: Analog-to-Digital Conversion Section

C. Real-Time Clock Module

Real-time clock module, shown in Fig. 3 consists of the real-time clock calendar IC MCP7904, the 32.768kHz crystal, a 3V backup battery, two 2K resistors for I2C communication, and a 10K resistor for an interrupt channel.

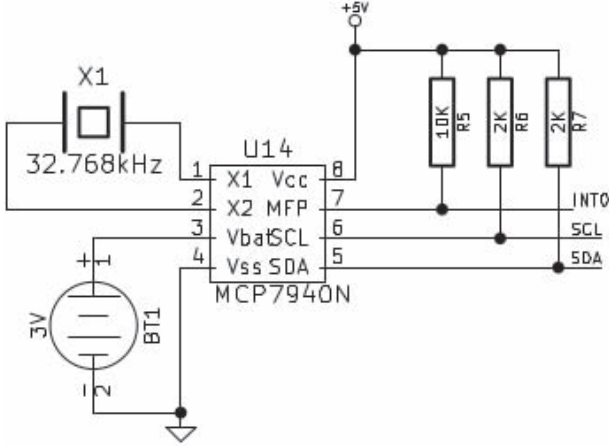


Fig. 4: Real-Time Clock Module

D. Firmware

The overall algorithm of the software is described in Algorithm 1. The algorithm starts with the hardware powered up in line 1. Then, all the configured parameters are retrieved from the configuration files, and temporarily stored in program variables, making them ready for the usage in calculations, as described in lines 2 to 3. Next, at line 5, the variable *curChnl*, used as a counter, representing present current channel number is initialized as zero, pointing to the first current channel. At line 6, the variable *activeChnls* is a list or an array used to store the connected current channel numbers. Accordingly, all 15 current channels, described in Figure 2 as *CTIn_0*–*CTIn_14*, are explored to be examined whether there is a current sensor connected to a specific channel determined by *curChnl* or not, as described in lines 7 to 11. If a current sensor is detected at a channel, the channel number, stored in *curChnl*, is added to the list *activeChnls*.

Lines 12 to 15 check whether there are no current sensors connected. If there are not, the program is terminated. Otherwise, in line 20, the program obtains voltage and current digital data from two ADCs depicted in Figure 3. Then, the real power, RMS voltage, and RMS current are calculated, as described in lines 21 to 24. The timestamp is obtained and a measured data entry is written to the file *MEASDAT.DAT* in binary form, as shown in lines 25 to 26. These data acquisitions and measured data calculations are done for every connected current channels defined in the list *activeChnls*, and only 20 times as a whole in order not to flood the SD card with plenty amount of data. Lastly, the data entries are retrieved from file *MEASDAT.DAT* to be displayed and they are deleted.

IV. METHODOLOGIES

The evaluation approach was done by comparing the experimental results from the design in [11] and the design proposed

Algorithm 1 High-Level Firmware Algorithm

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1: Power up.
2: Read configured parameters from the file.
3: Store the parameters in variables.
4: Set numberOfDataSets to be a value
5: curChnl ← 0.                                ▷ Channel of each current sensor
6: activeChnls ← empty list                      ▷ A list to hold active
   channels
7: while curChnl < 14 do                        ▷ There are 15 channels.
8:   if curChnl has sensor connected then
9:     Add curChnl to activeChnls.
10:  end if
11: end while
12: if size(activeChnls) = 0 then
13:   status ← “no-sensors-connected”
14:   goto ending
15: end if
16: i ← 0.
17: while i < numberOfDataSets do
18:   curChnl ← 0.
19:   while curChnl < size(activeChnls) do
20:     Obtain digital voltage and current signals from
       voltage sensor and current sensor activeChnls[curChnl]
       simultaneously.
21:     Compensate the voltage and current data with
       the configured voltage and current calibration factors for
       activeChnls[curChnl].
22:     Calculate real power [W].
23:     Calculate RMS voltage [V].
24:     Calculate RMS current [A].
25:     Obtain timestamp from RTC.
26:     Append to file “MEASDAT.DAT”
       activeChnls[curChnl], RealPower, VRMS, IRMS,
       Timestamp.
27:     curChnl ← curChnl + 1.
28:   end while
29:   i ← i + 1.
30: end while
31: Read contents from file “MEASDAT.DAT”.
32: Display the read contents.
33: Delete all contents from file “MEASDAT.DAT”.
34: ending:

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in this paper. The power accuracy from both designs, obtained from the experiments, was shown and compared.

The accuracy is measured as the RMS error and percentage RMS error shown in Equation 1. Therefore, the smaller the RMS error is, the better the accuracy exhibits.

$$RMSE_x = \sqrt{\frac{\sum_{i=1}^{20} (x - x_i)^2}{20}} \quad (1)$$

$$PRMSE_x = \frac{RMSE_x}{x} \times 100 \quad (2)$$

where

$RMSE_x$ is RMS error of the reference value x ;

$PRMSE_x$ is percentage RMS error of the reference value

reference value x and

x_i is the i^{th} observed value from the implemented meter.

V. EXPERIMENTAL SETUP

From now on, the design in [11] is referred to as Consecutive Sampling Design (CSD), and the design proposed in this paper will be called Simultaneous Sampling Design (SSD).

The components in the setup were categorized into three categories: 1) the power meters under tested, 2) the reference power meter, and 3) electric loads. There are two power meters under tested: the implementation of the design in [11] and the one presented in this paper. The reference power meter is AXE MMX-P1 [16]. There were two types of electric loads in the experiments, namely, linear loads and non-linear loads. The linear loads were divided into two types, i.e., resistive loads and inductive loads.

The schematic for power accuracy experimental setup was illustrated in Fig. 5, which corresponded to the actual setup in Fig. 6. In Fig. 5, The power meter in this paper is referred to as *METER-V2* and the other proposed in [11] was denoted *METER-V1*. The computer was used as the monitor of the measurement results. *T1* and *T2* were current transformers SCT-013-030 [17] with 10 turns at the primary. *T3* was used as the voltage transformers. The varied component is only *RLoad* or the electric loads for each time of the experiment. In Fig. 6, Approach 1 denotes the design in [11] and Approach 2 means the design in this paper.

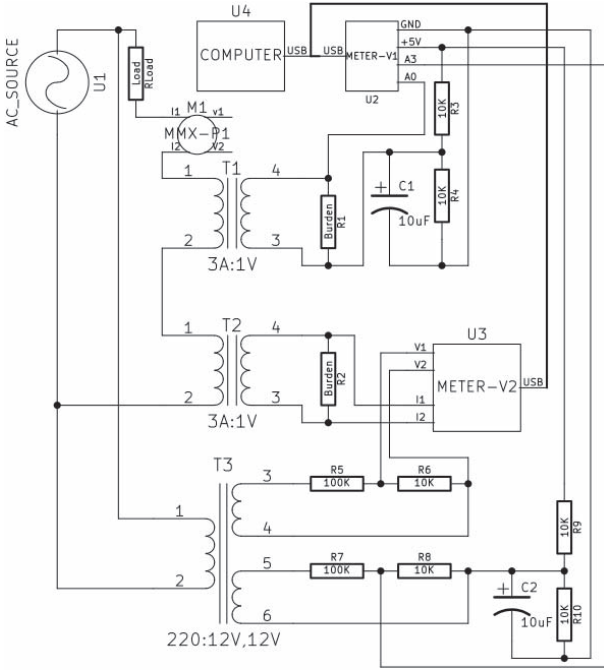


Fig. 5: Experimental Setup Schematic

VI. EXPERIMENTAL RESULTS

The resistive loads' power RMS errors from both designs were comparable to CSD slightly higher, depicted in Fig. 7. However, the errors from measuring inductive loads and non-linear loads were substantially different with CSD significantly higher than SSD, as shown in Fig. 8 and Fig. 9, respectively.

The errors from non-resistive loads in CSD was pretty high compared to SSD because the former design sampled

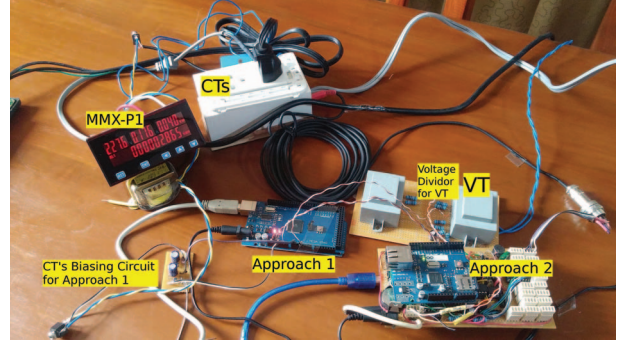


Fig. 6: Experimental Setup

the voltage and current consecutively, inducing phase shift difference between the two parameters. Even though the phase shift was compensated as described in [11], SSD was better than CSD since the actual signals were obtained from voltage and current channels.

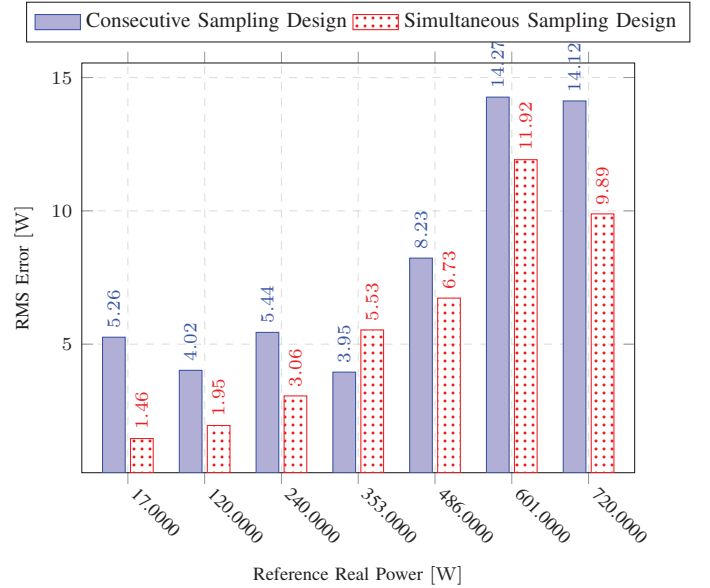


Fig. 7: RMS Power Errors (Resistive Loads)

VII. CONCLUSION AND FUTURE WORK

This power meter design is aimed at obtaining more real power accuracy than the previous work [11] by employing 2 ADCs for sampling voltage and current concurrently. This eliminates the problem of time difference between certain instantaneous voltage and current which is a factor contributing to the error in the real power. A multiplexer is added to support multichannel measurement. To facilitate the user so as not to engage with the source code, configuration files are served for storing configuration variables. Moreover, the firmware provides configuration API for external computing node to be able to update the configuration files remotely.

The experimental results from both CSD and SSD show that the power accuracy of the latter design is significantly better, especially under inductive and non-linear measurement

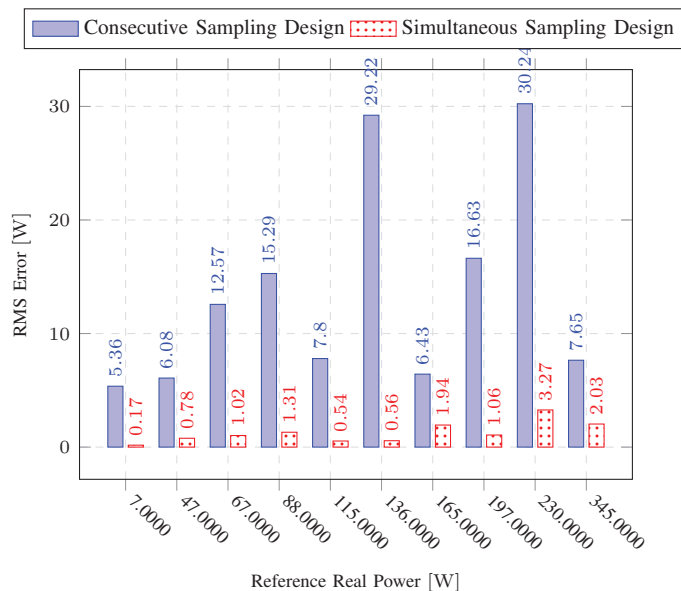


Fig. 8: RMS Power Errors (Inductive Loads)

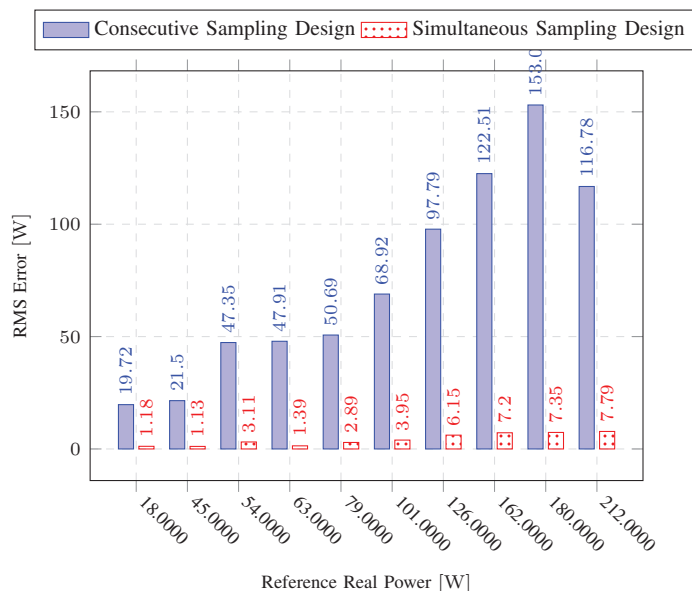


Fig. 9: RMS Power Errors (Nonlinear Loads)

conditions. The reason is that the SSD obtains the voltage and current data without phase shift, while the other design does not.

The work will be extended by integrating a communication interface in order to allow remote configuration and support online power monitoring.

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