AC Power Meter Design for Home Electrical Appliances

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***Abstract*—Monitoring power consumption of portable appliances is a step towards energy saving plans for any electrical equipment. This paper proposes a customizable power meter design employing voltage and current transformers, and Arduino. This meter is to monitor RMS voltage and current, real and apparent power, and power factor in real time. The voltage, the current, and the real power are calibrated with respect to a reference power meter. The resolutions are derived from analytical approach and the accuracies are evaluated from experiments in a variable of appliances and current transformers.**

***Keywords*—Energy Consumption, Energy Saving, Power Monitoring, Power Meter, Embedded Systems**

I. INTRODUCTION

Consuming and saving energy have been gaining more interest for environmental impacts [1]. Online energy and power consumption monitoring of each appliance or department has become more unavoidable procedure for energy saving and planing strategies.

This paper focuses on single phase home appliances consuming power from a few watts (e.g. mobile device chargers) to thousand watts (e.g. air conditioners). Most of these appliances are not pure resistive and introduce different values between real and apparent power, because of non-unity power factor [2], [3], [4].

Power meter is a key element design for accurate power consumption data, which is used for recording and analyzing energy usage. However, currently power meters limit on the measurement settings, e.g. the range of power consumption and data logging maintenance according to the difference and changes of appliances, on the accuracy e.g. some power meters consider only current drawn and ignore voltage levels [5], [6].

Despite those works presenting power meter implementations, they do not address the customizability of the monitoring device measuring different power consumption ranges. This research approaches power meter customizability so that the methodology to find necessary parameters is presented for i.e., transformer turns ratios and calibration factors. The derived approaches will be applied for designing a customizable power meter in the future work.

The paper is organized as follows. Section II starts with the background of energy components built in the power meter. Then, Section III presents the design of power meter and discusses the methodologies to find turns ratios and to calibrate current, voltage, and real power data with referenced meters. Section IV describes evaluation methodlogies and results. Last, Section V provides conclusions and future work.

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II. BACKGROUND

A power meter measuring real power and other parameters needs to acquire voltage and current data. Therefore, voltage and current sensors are required. There are many types of voltage and current sensors based on different working principles [7], [8], [9]. The sensors providing galvanic isolation are selected in this design so that there is no disturbance from the measured circuit to the measuring circuit and vice versa. The isolation also contributes to the safety of operators. The chosen voltage and current sensors are voltage and current transformers.

Signals acquired by the sensors need to be digitized and processed. A processing unit is responsible for this task. Any microcontroller is capable of fitting into this position as long as it meets hardware requirements of the software. Arduino is a highly available and general purposed computing platform chosen for the prototype. The module is popular and a plethora of resources is available from its large community.

The design involves definitions of parameters to be calculated by the software, namely, RMS voltage (V_{RMS}), RMS current (I_{RMS}), real power (P), apparent power (S), power factor (PF). Arduino is also explained in this section as it is used in the prototype of the design.

A. Power Consumption Components

1) Voltage and Current Transformer (VT and CT): Both voltage and current transformers induce the voltage or current at the primary to the secondary. The voltage or current at the primary (V_p/I_p) are usually higher than that at the secondary (V_s/I_s). However, the opposite also exists. The voltage and current has a relationship with primary (N_p) and secondary (N_s) turns as given by (1) and (2). Some current transformers also come with a burden resistor at the secondary as a small dummy load to produce voltage across both ends of CT secondary. The signals at the secondary of these transformers are so small that they are appropriate for the input of a processing module.

$$\frac{N_p}{N_s} = \frac{V_p}{V_s} \tag{1}$$

$$\frac{N_s}{N_p} = \frac{I_p}{I_s} \tag{2}$$

2) Arduino: Arduino is an open-source hardware board that can be applied for various applications. It can be programed by a cross-platform computer, e.g. Windows, OS X, or Linux, and the program is uploaded to it via a USB port. The board is also extensible by hardware modules called "shields", providing additional functionalities such as Ehternet, WiFi, SD card, RF communication. Moreover, it is available in various models rendering different features. The power meter prototype in this paper utilizes Arduino Mega 2560 model providing 16 analog inputs and 54 digital I/O pins. These 16 analog inputs can be used to acquire signals from up to 15 CTs and 1 VT. This model is chosen because its relatively large flash memory (256 KB) and SRAM (8 KB) reduce constraints in software design. Nevertheless, the fact that it has one ADC is a drawback disabling multiple-channel simultaneous signal acquisition.

B. AC Power Definitions

1) Root-Mean-Square Voltage and Current: The root-mean-square voltage (V_{RMS}) is the representation of the effective value of an AC voltage, normally used as the AC voltage. Such a value is defined as the magnitude equivalent to DC voltage applying to the same load and producing the same power. It can be defined as (3), where V_{pVTj} is the j^{th} instantaneous voltage and N is the number of samples.

Root-mean-square current (I_{RMS}) as defined in (4) uses the same concept as in V_{RMS}.

$$V_{RMS} = \sqrt{\frac{\sum_{j=1}^{N} V_{pVTj}^2}{N}} \tag{3}$$

$$I_{RMS} = \sqrt{\frac{\sum_{j=1}^{N} I_{pCTj}^2}{N}} \tag{4}$$

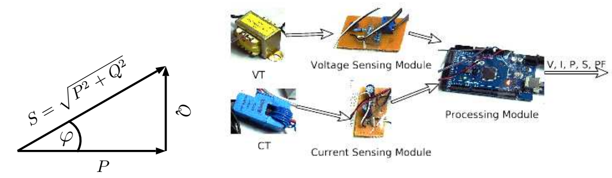
2) Real Power: There are three types of power in AC electricity: real/active power, reactive power, and apparent power. The reactive power does not generate work and is not measured in this power meter design. On the other hand, the real power generates work and is essential in calculating the energy consumption. It is defined as (5) providing that the instantaneous voltage ($V_{pVT}(t)$) and current ($I_{pCT}(t)$) functions with respect to time (t) are continuous signals. However, instantaneous voltage and current in digital power meter are sampled, hence discrete values. Therefore, the approximate real power can be defined as (6), where V_{pVTj} is the j^{th} voltage sample, I_{pCTj} is the j^{th} current sample, and N is the total number of samples.

$$P = \frac{1}{T}\int_{\tau}^{\tau+T} (V_{pVT}(t) \times I_{pCT}(t))dt \tag{5}$$

$$P = \frac{1}{N}\sum_{j=1}^{N} (V_{pVTj} \times I_{pCTj}) \tag{6}$$

3) Apparent Power: The apparent power is the vector summation, when represented in the power triangle as in Fig. 1a, of the real and reactive powers. It can be defined by (7), where S denotes the apparent power.

$$S = V_{RMS} \cdot I_{RMS} \tag{7}$$



(a) Power Triangle (b) Block Diagram

Fig. 1: Power Triangle and Block Diagram

4) Power Factor: The power factor is defined as the cosine of the angle between the real and apparent powers, when the real P, reactive Q, and apparent S powers are illustrated as vectors as in Fig. 1a. φ is the angle between the real and apparent power.

$$PF = \frac{P}{S} \tag{8}$$

III. Power Meter Design

A. Block Diagram

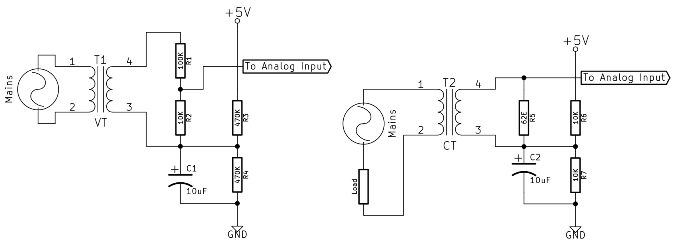
Fig. 1b illustrates the block diagram of the power meter. The processing module receives analog signals from the voltage and current sensing modules and processes them by software to obtain RMS voltage (V), RMS current (I), real power (P), apparent power (S), and power factor (PF).

B. Hardware Design

The principle of this power meter is to sense current and voltage signals and use them to calculate voltage (V), current drawn by appliance(s) (I), real P and apparent power S consumed by appliance(s), and the power factor (PF). Therefore, there are two essential hardware modules responsible for signals sensing: *voltage sensing module* and *current sensing module*.

In this section, *voltage sensing module* and *current sensing module* are presented. The processing module can be of any choice supporting the outputs from these two sensing modules.

1) Voltage and Current Sensing Module: The schematic for voltage sensing module is shown in Fig. 2a. T_1 is the voltage transformer (VT) the specification of which is 220 to 9 volts. R_1 and R_2 comprises a voltage divider with the dividing factor of 11. If the root-mean-square (RMS) value of V_{sVT} is 9V according to the specification and the voltage signal is the perfect sine wave, $V_{sVT} = 9 \times \sqrt{2}$, which is 12.728V. Hence, $V_{sdVT} = 1.1571$. However, each VT's characteristic normally deviates from the specification. Therefore, the values of these parameters can be different, usually higher. C_1 is used to filter out high-frequency noises. Finally R_3 and R_4 are incorporated into the circuit to bias the voltage signal by a DC voltage of 2.5V. This results in that the voltage signal V_{inVT} is lifted up by 2.5V. This bias is necessary because the analog input of the Arduino board accepts only positive voltage values. Since the voltage reference of analog-to-digital converter (ADC) of Arduino is set to be 5V, V_{inCT} swings from $2.5 - 1.1571 = 1.3429$V to $2.5 + 1.1571 = 3.6571$V.



(a) Voltage

(b) Current

Fig. 2: Voltage and Current Sensing Modules Schematic

This guarantees a safe range of voltage not to be distorted by 5V limit, and not to damage the ADC. The upper and lower gaps from the maximum value to 5V and the minimum value to 0V are treated as the spare for higher voltage fluctuation at some point in time.

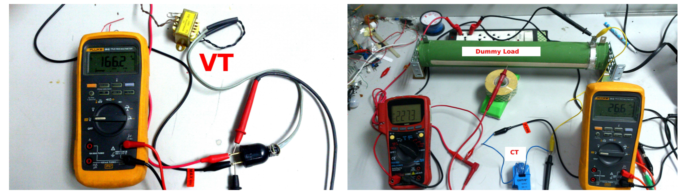
The schematic for current sensing module is shown in Fig. 2b. The bias voltage of 2.5V is supplied by R_6 and R_7. The CT used in this prototype is SCT-013-030 with built-in burden resistor R_5.

C. Software Design

Software design described in this section is not specific to programming languages and algorithms. It assumes the processing module has only one ADC, normal for most microcontrollers. The software reads voltage and current values from ADC channels connected to VT and CT consecutively. Then it takes read values into calculation for actual voltage and current values. The calculated values need to be calibrated with correspondent values from a reference meter. Then the real power, apparent power, and power factor are calculated from the calibrated values.

The software consists of 5 main modules: *voltage measuring module*, *current measuring module*, *real power measuring module*, *apparent power measuring module*, and *power factor measuring module*. Finally, this section discusses about *calibration* done in the software.

1) Voltage and Current Measuring Module: Thess module obtains the ADC output values corresponding to the channels connected to the voltage and current sensing module. 10-bit ADC is used in this implementation. Therefore, its output value lies between 0 and 1023 inclusively. This value ($ADCLevel_{VT}$ for voltage or $ADCLevel_{CT}$ for current) must be converted to a corresponding voltage at the input of ADC (V_{inVT} or V_{inCT}). The conversion is done by multiplying $ADCLevel_{VT}$ or $ADCLevel_{CT}$ with the voltage change for the change of least significant bit of ADC value (LSB_{ADC}). V_{inVT}/V_{inCT} must be converted back to secondary voltage V_{sVT}/V_{sCT}. The value is subtracted by the bias voltage (2.5V) to obtain V_{sdVT}/V_{sCT}. For voltage, $V_{sVT} = V_{sdVT} \times [(R_1 + R_2)/R_2]$. For current, secondary current I_{sCT} is derived from V_{sCT} by Ohm's law. Finally, to obtain the primary values, $V_{pVT} = V_{sVT} \times R_{p-to-sVT}$ for the voltage and $I_{pCT} = I_{sCT} \times R_{s-to-pVT}$ for the current. These are described in (9) and (10).



(a) VT

(b) CT

Fig. 3: Experimental Testbed to Find CT and VT Turns Ratio

The root-mean-square voltage and current calculations are defined in (3) and (4) respectively, where N denotes the number of samples within n cycles.

2) Real Power Measuring Module: The real power (P) can be derived from the average of the summation of the products of instantaneous voltage ($V_{pVT}(t)$, V_{pVTj}) and current ($I_{pCT(t)}$, I_{pCTj}) at the same time, over a period of time (T), as described in (5). In this implementation, voltage and current values are discrete because of the ADC sampling nature. Therefore, the average is calculated over the number of samples (N) as shown in (6).

$$V_{pVT} = \left\{ [(ADCLevel_{VT} \times LSB_{ADC}) - 2.5] \times \frac{R_1 + R_2}{R_2} \right\} \times R_{p-to-sVT} \quad (9)$$

$$I_{pCT} = \frac{[(ADCLevel_{CT} \times LSB_{ADC}) - 2.5]}{R_5} \times R_{s-to-pCT} \quad (10)$$

3) Apparent Power Measuring Module: After the RMS values of voltage and current (V_{RMS} and I_{RMS} respectively) are calculated, the apparent power (S) can be derived from (7).

4) Power Factor Measuring Module: Power factor (PF) is the cosine of the angle between real and apparent powers. Therefore, it can be calculated by using (8).

D. Finding Turns Ratios

1) Finding VT Turns Ratio: VT turns ratio complies with (1). The numbers of turns at the primary and secondary are sometimes unknown and difficult to find. The voltages at both sides can be found easily by applying a known voltage to the primary and observing the secondary voltage. Hence the turns ratio can be derived. This is the approach used to find VT turns ratio with different voltage values applied to the primary. The turns ratio used in this implementation is the average of all turns ratios derived from each time different voltage values are applied to the primary as defined in (11).

$$R_{p-to-sVT} = \frac{\sum_{j=1}^{N} \left(\frac{V_{pVTj}}{V_{sVTj}} \right)}{N} \quad (11)$$

Fig.3a shows the testbed to find VT turns ratio. After the experiment, the resulting averaged turns ration $R_{p-to-sVT}$ is 23.923.

2) Finding CT Turns Ratio: CT turns ratio can also be found with (2) and the empirical results with burden resistor (R_5) value equal to 62.

$$R_{s-to-pCT} = \frac{\sum_{j=1}^{N}\left(\frac{I_{pCTj}}{I_{sCTj}}\right)}{N} \quad (12)$$

Table **??** shows the results from the CT with primary of 15 turns. The turn ratio ($R_{s-to-pCT}$) can be calculated according to (12). Fig.3b shows a testbed for finding CT turns ratio. An adjustable power resistor is used as a variable dummy load. The experiment together with (12) yields the averaged turns ratio $R_{s-to-pCT}$ of 123.9503.

E. Calibration

The calibration is an approach to adjust a measuring device of unknown accuracy with respect to a reference measuring device [10]. The reference meter, e.g. a power meter with known accuracy, should have higher accuracy than the unknown device. Voltage, current, and power calculated by the software using (9), (10), and (6) may not be as accurate as the reference power meter (AXE MMX-P1). To obtain the values close to the reference meter, calibration factors are required and included into the equations. Voltage and current calibrations share the same approach, while phase shifted compensation is utilized in real power calibration.

1) Voltage Measuring Module Calibration: The voltage value computed by Arduino (V_{pVT}) is multiplied with the voltage calibration factor (CF_{VT}), yielding the calibrated voltage (V_{pVTcal}) as given by (13). This constant can be found from a linear transfer function from the voltage value of reference meter to V_{pVT} of the implemented power meter, the x-intercept of which is zero. Such a function can be derived from fitting a set of data points, which can be generated from a set of measurements of different voltage values. The function is defined as (14), where m denotes the slope, V_{RMSmn} denotes the RMS voltage given by the "measurement node", refering to the implemented power meter under calibration. The RMS voltage given by the reference power meter is denoted by V_{RMSpm}.

$$V_{pVTcal} = CF_{VT} \times V_{pVT} \quad (13)$$

$$\begin{aligned} f(x) &= mx \\ V_{RMSmn} &= mV_{RMSpm} \end{aligned} \quad (14)$$

Although CF_{VT} is derived from the inverse of the slope of the function ($1/m$) as mentioned previously, the inverse is still not shown it is CF_{VT} as it is the constant value for RMS voltage. However, CF_{VT} is the constant for instantaneous voltage. Thus, to obtain CF_{VT}, (3) and (14) are needed to be taken into consideration, resulting in (15). Therefore, $CF_{VT} = 1/m$.

$$V_{RMSpm} = \sqrt{\frac{1}{N}\sum_{j=1}^{N}(CF_{VT} \times V_{pVT})^2} \quad (15)$$

Fig.4 shows data points from different measurements and their fitted linear transfer function with $m = 1.0303$. Therefore, CF_{VT} in (13) can now be replaced with 0.97.

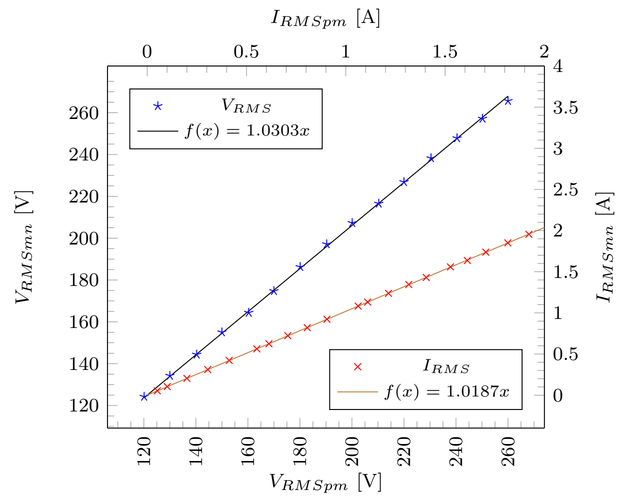


Fig. 4: V_{RMS}, I_{RMS} and Fitted Transfer Function

2) Current Measuring Module Calibration: The current calibration is also necessary because of the same reason as voltage. A transfer function is obtained. Then the current calibration factor (CF_{CT}) is derived. The calibrated current value (I_{pCTcal}) can be calculated by (16). The inverse of slope of the transfer function (17) is the starting value on the way to derive CF_{CT}.

$$I_{pCTcal} = CF_{CT} \times CF_{CT2} \times I_{pCT} \quad (16)$$

$$\begin{aligned} f(x) &= mx \\ I_{RMSmn} &= mI_{RMSpm} \end{aligned} \quad (17)$$

To obtain CF_{CT}, (4) and (17) are needed to derive (18) and therefore, $CF_{CT} = 1/m$.

$$I_{RMSpm} = \sqrt{\frac{1}{N}\sum_{j=1}^{N}(CF_{CT} \times V_{pVT})^2} \quad (18)$$

Fig.4 shows data points from different measurements and their fitted function with $m = 1.0187$. Therefore, CF_{CT} in (16) can be substituted by 0.98. CF_{CT2} is an additional factor that can be used to adjust CF_{CT} in case the result I_{pCTcal} is still not satisfied.

3) Real Power Measuring Module Calibration: In this implementation, only one ADC is used. Thus the voltage and current signals are sampled alternately. The prototyped algorithm is designed to sample the voltage before the current. Therefore, the phase of the sampled voltage value lags the voltage phase at the time the current is sampled. The lag is described in (19). $\theta_{lag}(ADCLevel_{VT})$ denotes the phase lag of $ADCLevel_{VT}$ with respect to the phase of the voltage at the time $ADCLevel_{CT}$ is sampled. The parameter f denotes the frequency of the voltage signal, e.g., 50Hz. The function $t(x)$ maps an instantaneous ADC sampled value x to the time it is sampled.

$$\begin{aligned} \theta_{lag}(ADCLevel_{VT}) = 2\pi f[t(ADCLevel_{CT}) - \\ t(ADCLevel_{VT})] \end{aligned} \quad (19)$$

Ideally, an instantaneous power at time t ($P(t)$) can be defined as (20).

$$P(t) = V_{pVT}[t(ADCLevel_{CT})] \times I_{pCT}[t(ADCLevel_{CT})] \tag{20}$$

Nonetheless, $V_{pVT}[t(ADCLevel_{CT})]$ is unknown due to the single-ADC reason. Thus, this value has to be estimated. The estimation is done by applying the *Phasecal* method[1], which basically employs the linear extrapolation method. The method is described by (21), where $PHASECAL$ is a chosen constant for the extrapolation, and $ADCLevel_{VTlast}$ denotes the previous $ADCLevel_{VT}$. The calibration of real power measurement is done by adjusting $PHASECAL$. The resulting real power after applying certain $PHASECAL$ values is compared to the real power read from the reference power meter.

$$\begin{aligned} V_{pVT}[t(ADCLevel_{CT})] = V_{pVT}[t(ADCLevel_{VTlast})] + \\ PHASECAL \times \{V_{pVT}[t(ADCLevel_{VT})] - \\ V_{pVT}[t(ADCLevel_{VTlast})]\} \end{aligned} \tag{21}$$

4) Apparent Power and Power Factor: As apparent power and power factor are derived from the V_{RMS}, I_{RMS}, and P according to (7) and (8) respectively. There is no need to further calibrate these two parameters.

IV. Evaluation

In this section, the correctness of the implemented power meter's measured values are evaluated. The evaluation results are given in terms of resolution and accuracy of the following parameters: V_{RMS}, I_{RMS}, and P.

A. Methodology

To find the resolution for each parameter, analytical approaches are used. For the accuracy, a series of experiments were conducted and the resulting values were analyzed. All experiments use the same VT, CT, implemented power meter, and reference power meter. The implemented power meter is a calibrated one. Values from both implemented and reference power meters were recorded. The percentage error of each measurement value from the implemented power meter was calculated based on its corresponding value from the reference power meter. Finally, the full-scale non-linearity for each parameter is derived.

1) RMS Voltage (V_{RMS}): The resolution of the RMS voltage can be calculated from the resolution of ADC used. Therefore, the voltage resolution is the voltage difference between two values of ADC's least significant bit change. In this implementation 10-bit ADC (1024 different values) is used and its analog reference is 5V. Hence, each value's least significant bit change is corresponding to 0.0049V or 4.9mV (LSB_{ADC}). The voltage resolution (ΔV_{pVTmin}) is defined in (22), using the definition of V_{pVT} from (9).

$\Delta ADCLevel_{VTmin}$ denotes the minimum ADC level difference, which is 1. This value can be used as the voltage resolution.

$$\begin{aligned} \Delta V_{pVTmin} &= V_{pVT1} - V_{pVT2} \\ &= LSB_{ADC} \times \frac{R_1 + R_2}{R_2} \times R_{p-to-sVT} \end{aligned} \tag{22}$$

In this implementation, R_1 and R_2 are 10KΩ and 100KΩ respectively. Thus, $(R_1 + R_2)/R_2$ is 11. The VT used in this implementation has $R_{p-to-sVT}$ of 23.923. Therefore, the instantaneous voltage resolution in this implementation is $0.0049 \times 11 \times 23.923 = 1.29$V. The tests to find RMS voltage accuracy were conducted under the range 120 - 260V. The voltage measured by the reference power meter and the implemented power meter were read and recorded. The values and percentage errors are represented as a graph in Fig.5. The average of such errors is 0.62%. The maximum absolute error is 2.05V at the point of 160.2V. Thus, the full-scale non-linearity of the RMS voltage measurement is $(2.05 \times 100)/260 = 0.79\%$.

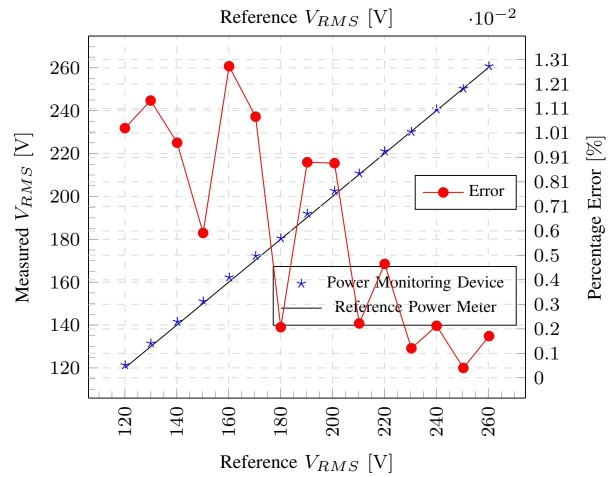


Fig. 5: Resulting V_{RMS} and Percentage Errors

2) RMS Current (I_{RMS}): The resolution of RMS current also depends on ADC resolution. Like the approach to find RMS voltage, RMS current resolution (ΔI_{pCTmin}) can be defined by (23), which is adapted from (10).

$$\begin{aligned} \Delta I_{pCTmin} &= I_{pCT1} - I_{pCT2} \\ &= \frac{R_{s-to-pCT} \times LSB_{ADC}}{R_5} \end{aligned} \tag{23}$$

$\Delta ADCLevel_{CTmin}$ denotes the minimum ADC level difference which is 1. In this implementation, R_5 is 62Ω. The secondary to primary ratio of CT ($R_{s-to-pCT}$) is 123.95, and the voltage corresponding to the ADC least-significant-bit change (LSB_{ADC}) is 0.0049V. Therefore, the instantaneous current resolution is 0.0098A or approximately 10mA. The experiment for current accuracy was conducted under the range 500mA to 2A. The current measured by the reference power meter and the implemented power meter were read and recorded. The values and percentage errors are represented as a graph in Fig.6. The average of such errors is 0.75%. The maximum absolute error at the point of 1.9A is 0.014A. Thus, the full-scale non-linearity of the RMS current measurement is $(0.014 \times 100)/2 = 0.7\%$.

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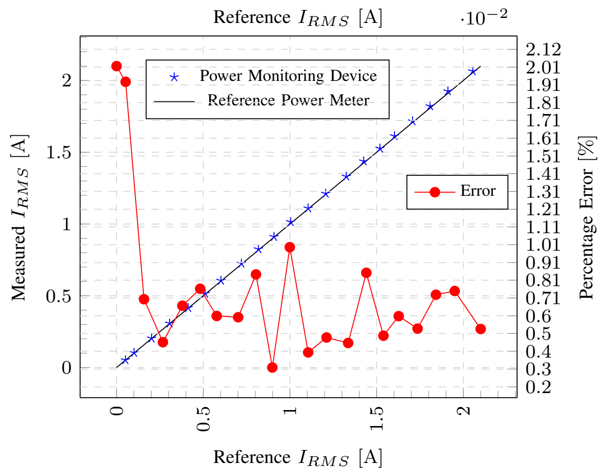

Fig. 6: Resulting I_{RMS} and Percentage Errors

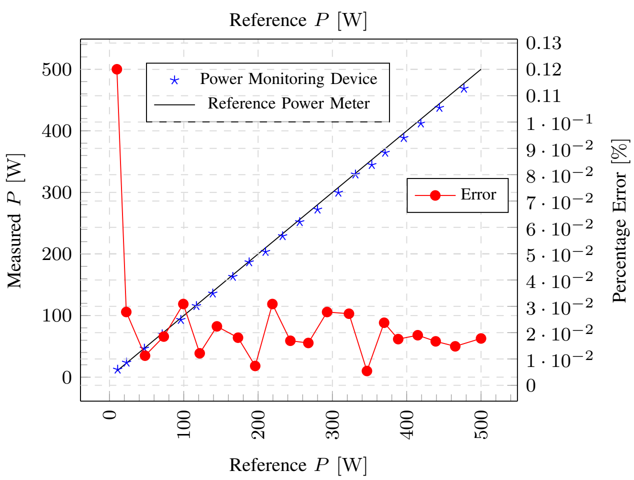

Fig. 7: Resulting P and Percentage Errors

3) Real Power (P): The real power is derived from the instantaneous voltage and current. Therefore, its resolution depends on them. Its least changed value at any time is not constant like those of voltage and current as shown in (24). A special case with voltage fixed at 230V can be assumed to obtain the resolution of $230 \times 0.01 = 2.3$W.

$$\begin{aligned} \Delta P_{min} &= P_1 - P_2 \\ &= V_{pVT1} I_{pCT1} - (V_{pVT1} - \Delta V_{pVT})(I_{pCT1} - \Delta I_{pCT}) \end{aligned} \quad (24)$$

The accuracy for real power was assessed under the range 10W to 480W. The current measured by the reference power meter and the implemented power meter were read and recorded. The values and percentage errors are represented as a graph in Fig.7. The average of such errors is 2.39%. The maximum absolute error is 8.48W at the point of 477W. Thus, the full-scale non-linearity of the real power measurement under this experiment is $(8.48 \times 100)/480 = 1.77\%$.

V. Conclusions and Future Work

In this paper, we present a customizable power meter design by using voltage and current transformer and Arduino computing platform. In order to measure the voltage, the current, and the real power of a variable range of portable appliances, a set of voltage and current transformers are set up for preliminary testbeds to find the accordant turn ratios and the parameters (V_{RMS}, I_{RMS}, PF) calibrated with a reference power meter AXE MMX-P1. The proposed prototype shows the accuracies of the voltage, the current and the real power are 0.62

However, one ADC integrated in Arduino has some flaws for phase shifting. The techniques in the future work are to add more ADC components for current and voltage sensors so that the accuracy of the real power will be improved. A multiplexer will also be added to provide multiple channels. A remote configuration scheme allowing adjusting calibration factors from a distant human-machine interface will be designed and embraced for more portability.

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