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Development and Prototyping of an Accurate and Cost-efficient Digital Sampling Multi-Meter Using Instantaneous Power Calculation Algorithm

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ABSTRACT

The parameters of an electrical power system have wide variations during the operation of electrical devices; these changes are required to be measured using an accurate meter. A cost-effective Digital Sampling Multi-meter (DSMM) using a microcontroller and two sensors was proposed to overcome the complexity of traditional power meters. Voltage and current signals from sensors were discretely time-sampled and then analysed based on the Instantaneous Power Calculation Algorithm (IPCA) using an Arduino to measure six of the electrical quantities. It Root Mean Square (RMS) terminal voltage and load current, real, reactive, and apparent power, and finally Power Factor (PF), then these were displayed on both the LCD and the PC serial monitor. Also, the instantaneous waveforms of the voltage, current, and power are easily analysed and plotted with any type of load. The IPCA algorithm was adopted because of its real-time measurement, high accuracy, ease of implementation, and low cost. Measurements are performed for linear loads (resistive, inductive, and capacitive) and non-linear loads (rectifier circuits). The proposed meter's accuracy was found to have acceptable relative percentage errors for most measured parameters, especially at linear loads (maximum relative error for V_{rms} 0.7% at inductive load, 5% for I_{rms} at capacitive load, and 5% for PF at capacitive load), calculated based on the FLUKE Power Quality Meter, which was considered a high-quality measurement instrument.

1. INTRODUCTION

Electric power measurements are crucial for research, industrial, and consumer applications, primarily for testing, monitoring, and maintaining energy supply networks and equipment, and are economically the most important electric measurement. Accurate measurements of voltage and current are crucial for efficient electrical load monitoring, ensuring energy management and sustainability in the power system. As the world becomes more automated, accurate measurements are essential for energy efficiency and future power system success [1]. The RMS values of voltage and current are fundamental metrics supplied by a power meter. However, not all meters collect RMS values uniformly. They use a variety of procedures for calculating the RMS value of the voltage and current quantities and storing the data. Key aspects include the sample rate and the nature of the data acquired. Most inexpensive handheld meters do not compute the RMS using the peak detection approach. They quantify the maximum value and divide it by the square root of two, as in [2, 3], which also required an external electrical component as a precision rectifier for peak detection. This method is precise if the waveform is absolutely sinusoidal. Other meters referred as "true RMS" meters compute the RMS value via sampling the waveform many times per cycle, square the values, average the square values, and then compute the square root [4-7]. On the other hand, currently most of the loads are non-linear,

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and the voltage or current waveform is not perfectly sinusoidal. In this issue, true RMS measurement is most appropriate for distorted and non-distorted waveform measurements.

The displacement PF is the cosine of the phase angle between the voltage and current waveforms, focusing solely on the fundamental frequency component. It can also be calculated as the ratio between real and apparent power [8-10]. The PF, which is calculated in this form, is called the total PF. It includes all harmonic components in addition to the fundamental frequency, and it is critical for assessing the true efficiency of power usage in systems with non-linear loads. In addition to the total PF does not require external electrical components as zero crossing detectors for both the current and voltage signals as in displacement PF as in [11-12] see Figure 1.

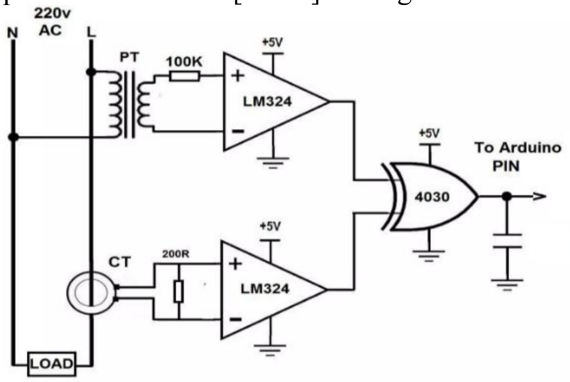


Figure 1. Circuit diagram of displacement PF determination.

Thus, this work introduces a comprehensive Arduino-based metering system that fully integrates the IPCA algorithm to measure six essential electrical quantities. In addition to real-time display on both LCD and PC, the system provides oscilloscope-like monitoring by capturing instantaneous waveforms of voltage, current, and power under different load conditions. Unlike many existing designs, it achieves accurate true RMS and PF measurements without the need for external rectifier, peak-detector, or zero-crossing circuits, thereby improving accuracy while reducing hardware complexity and cost.

The proposed Arduino-based DSMM using the IPCA improves existing measurement designs by enabling the meter to plot waveforms of voltage, current, and power over time after transmitting the data to a serial monitor; this helps in studying and analyzing these waveforms for variable load types (resistive, inductive, capacitive, etc.).

2. INSTANTANEOUS POWER CALCULATION ALGORITHM

The instantaneous power $P_{(t)}$ is generally a time-varying quantity, in an AC circuit it is defined as the product of the instantaneous voltage $V_{(t)}$ and current $i_{(t)}$ as shown in Figure 2 [13].

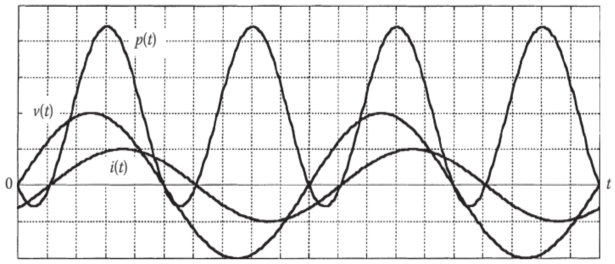


Figure 2. Waveform of instantaneous voltage, current, and power.

The average power (*P*) for such a periodic waveform over one complete period (*T*) is defined as:

$$P = \frac{1}{T}\int_0^T P_{(t)}dt = V_{rms} * I_{rms} * PF \tag{1}$$

Instantaneous power theory accurately determines total real power used by loads, ensuring accuracy for all types of loads, including linear and harmonic-rich nonlinear DC loads. [14]. The true RMS value of a continuous voltage waveform is a measure of the effective or equivalent DC voltage that delivers the same power to a load. Mathematically for a continuous voltage and current functions $V_{(t)}$ and $I_{(t)}$ over a time period (T), are calculated as follows [15-17]:

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T V_{(t)}{}^2 dt} \tag{2}$$

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T I_{(t)}{}^2 dt} \tag{3}$$

Now the discrete time-equivalent of equations (1, 2, and 3) are:

$$V_{rms} = \sqrt{\frac{\sum_{i=1}^{n} V_{(i)}{}^2}{n}} \tag{4}$$

$$I_{rms} = \sqrt{\frac{\sum_{i=1}^{n} I_{(i)}{}^2}{n}} \tag{5}$$

$$P = \frac{1}{n}\sum_{i=1}^{n} V_{(i)} * I_{(i)} \tag{6}$$

where n is the maximum number of samples, and $V_{(i)}$, $I_{(i)}$ is the instantaneous values of the voltage and current of the i^{th} sample. As the number of measurements is necessarily finite, the integral is replaced by a summation and the time interval T by n. Continuous equations typically require analytical solutions involving systematic mathematical techniques they are executed by solving equations "by hand". Discrete equations can often be solved by hand

but are usually implemented by computers for efficiency [17-18].
Apparent power (S) is the product of RMS of voltage and RMS of current magnitudes, as shown in equations (7) [7].

$$S = V_{rms} * I_{rms} \tag{7}$$

The PF can be calculated as the ratio between real and apparent power [8].

$$PF = \frac{Real\ power\ (P)}{Apparent\ Power\ (S)} \tag{8}$$

Reactive power (Q) represents the power that oscillates between the supply and reactive elements (inductors and capacitors) in the circuit without performing any real effect. It is measured in Volt-Amperes Reactive (VAR), and it can be calculated using the following formula:

$$Q = \sqrt{S^2 - P^2} \tag{9}$$

The calculations of the employed algorithm are dependent on the instantaneous values for both of the terminal voltage $V_{(i)}$ and the instantaneous values load current $I_{(i)}$, so this method is known as the IPCA. The IPCA has several advantages over other methods of power measurement as real-time measurement, high accuracy as it takes into account the instantaneous values of voltage and current at any given moment, easy to implement and low cost as it requires only a few components, such as a voltage and current sensors. This makes it an attractive option for developing measuring instruments such as digital multi-meters and power analyzers.

3. DEVICE DESCRIPTION

The main components that were used for this work are the Arduino Mega, a current sensor, an AC voltage sensor, and a 20x4 LCD display. Figure 3 presents the functional block diagram of the developed DSMM.

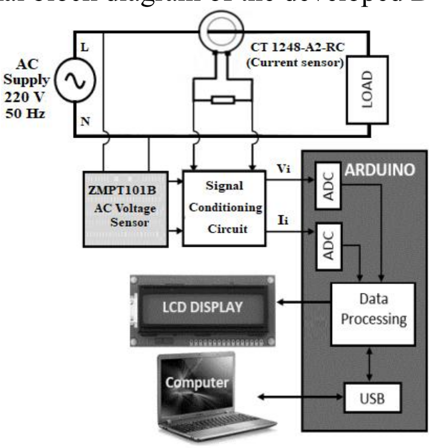


Figure 3. Block diagram of the proposed measuring system

Arduino is gaining popularity in measurement instruments and monitoring systems due to its flexible features, robustness, low-cost, and open-source [19-22], compared to the other types of controllers as FPGA [21].

So, Arduino Mega 2560 was employed in the work. It has 54 digital inputs and outputs, 16 analogue inputs, and 256 kB flash memory operating at 16 MHz. and is fed via USB to a computer [22]. It has a 10-bit Analogue-to-Digital Converter (ADC). Thus, the values read from 0 to 5 V in the analogue inputs are converted from 0 to 1023 bits, resulting in a resolution of 5 V/1024 bits.

3.1 Voltage Measurement

The ZMPT101B sensor was used as voltage sensor. It a step-down voltage transformer module commonly used for AC voltage sensing applications in the range of 0-250V. It often used in conjunction with microcontrollers or other measurement circuits [23-25]. The output is typically centered around a reference voltage, often half the supply voltage (DC offset equal to VCC/2), with positive and negative swings corresponding to the input voltage waveform as shown in Figure 4.

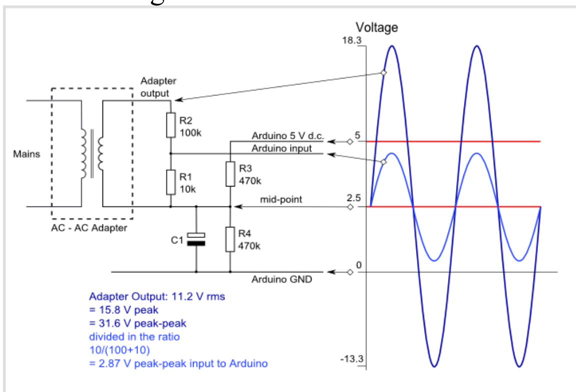


Figure 4. Offset circuit of the voltage sensor

3.2 Current Measurement

The current sensor employed in this work was Current Transformer CT1248-A2-RC with a turn ratio equal to 1:1500. Its high-accuracy AC whole current transformer, low amplitude error & phase error, high linearity, and temperature coefficient, and secondary burden resistance equal to 217 ohms make the meter capable of measuring a current of up to 12 amps. A DC offset circuit was used with the CT for biasing the signal by shifting the AC waveform up along the voltage axis, as the ADC of the Arduino required a purely positive signal.
The ZMPT101B voltage sensor and CT1248 current sensor were selected for their suitability in low-cost AC measurement systems. It is also suitable for different linear load cases (resistive, inductive, and capacitive). However, these sensors have certain limitations: reduced accuracy at nonlinear loads, especially the current sensor due to iron core saturation. This problem can be solved by using high-precision Hall effect sensors, which provide better performance under nonlinear load conditions.

4. SOFTWARE IMPLEMENTATION

The code was created using Arduino IDE programming environment and a flow chart was created for software design, as illustrated in Figure 5. Both of the instantaneous analogue signals from current and voltage sensors were converted to digital by ADC in the Arduino Mega. After the data was processed, the results were displayed on the LCD and the serial monitor on the PC.

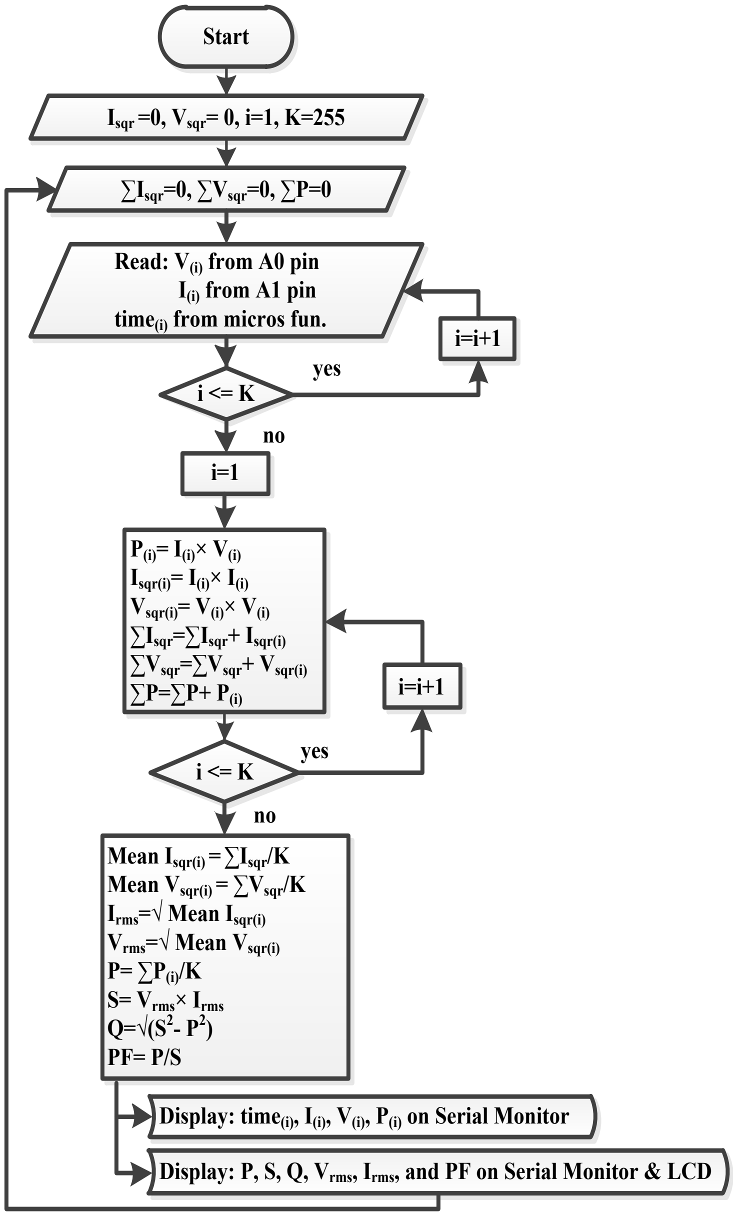


Figure 5. Flowchart of programming the proposed digital multi-meter

The proposed algorithm samples the instantaneous voltage $V_{(i)}$ and current $I_{(i)}$ signals of the sensors to 85 samples for each one for one cycle in addition to samples of the measured instantaneous time (time(i)) using the micros() function. A memory buffer of 255 samples for each of the three samples (voltage, current, and time) is allowed to be stored in the RAM of the Arduino Mega microcontroller using the proposed algorithm. Multiplying the instantaneous voltage by the instantaneous current yields the instantaneous power $P_{(i)}$.

5. SIMULATION RESULTS

For more verification, the proposed DMM system was developed and simulated via the Proteus software environment (vision 7 Professional (ISIS) program) is presented as shown in Figure 6 (for inductive load at R=220-ohm, L = 1000 mH, Vs = 220 V). Proteus is a software package for industrial and educational use, enabling collaborative modeling of microcontroller-based designs using circuit simulation, animated components, and microprocessor models [26]. It allows for the development, testing, and verification of the proposed Arduino code before creating a physical prototype.The simulated circuit of the proposed measuring system in Proteus displayed six calculated parameters as shown in Figure 7 for different types of loads.

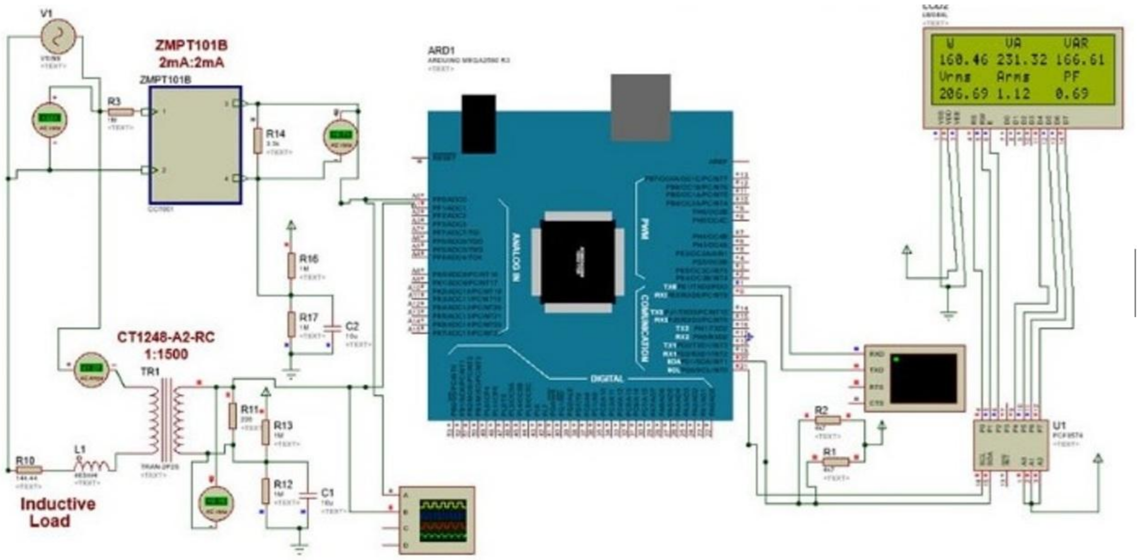
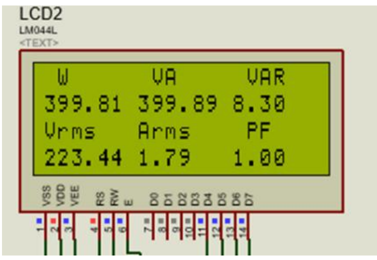
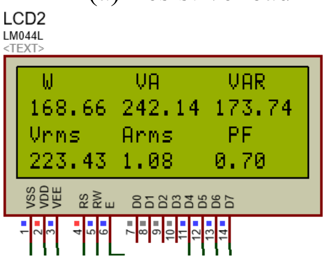


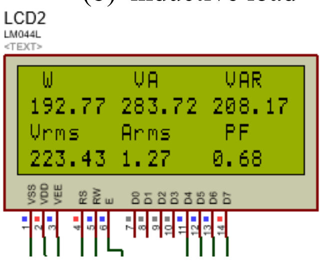
Figure 6. Simulation circuit diagram of the proposed DSMM



(a) resistive load



(b) inductive load



(c) capacitive load

Figure 7. Measured data on the LCD of the simulation model with variable load.

The serial monitor of the Proteus software program also displays the instantaneous value of voltage, current, and power in addition to the six calculated parameters as shown in Figure 8.

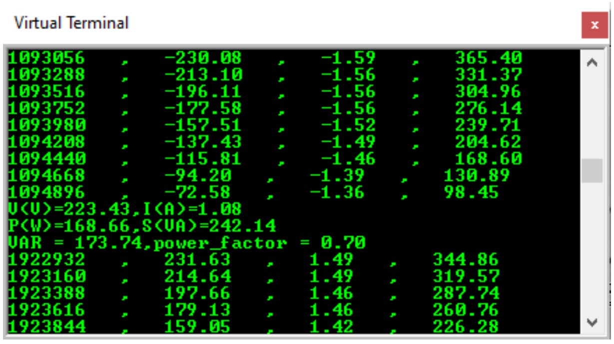


Figure 8. Serial monitor of Proteus software program.

6. Experimental Results

The prototype of the proposed DSMM shown in Figure 9 consisted of four major components: an Arduino, a voltage and current sensor, and an LCD. The prototype was tested for two types of loads: linear loads (resistive, inductive, and capacitive) and non-linear loads (rectifier circuits). Figure 10 shows all types of loads that are employed experimentally for testing the developed DSMM prototype.

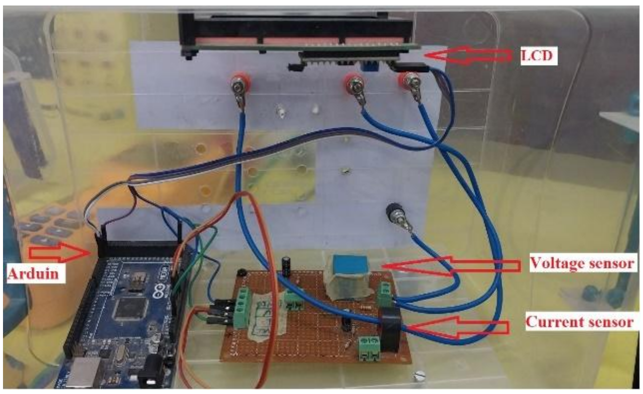


Figure 9. Prototype of the meter.

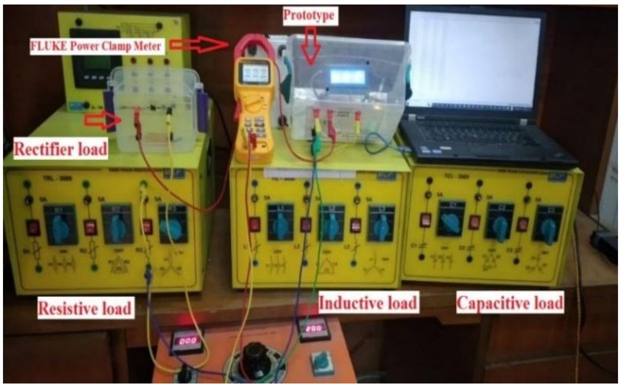


Figure 10. Prototype and loads.

Calibration procedures were conducted to ensure accuracy and reliability of the measurements. By comparing the DSMM readings with known reference values (taken by a Fluke meter), as shown in Figure 11, offsets and scaling errors are adjusted.

For estimation of the percentage error of the readings of the proposed DSMM, accuracy verification tests are required. These tests involve measuring the electrical parameters in both of the proposed designs and the reference precise meter (Fluke 345 Power Quality Clamp Meter) as presented in Table 1.

Figure 11. Matching the measurements parameter read by proposed DSMM and Fluke meter for Resistive load.

Table 2 presents the percentage error of three basic quantities (V_{rms}, I_{rms} , and PF) for different types of loads.

Table 1. Comparison of the measurement results for four types of loads

Load type	Prototype						Fluke Meter					
	V_{rms}	I_{rms}	W	VA	VAR	PF	V_{rms}	I_{rms}	W	VA	VAR	PF
Resistive	220.85	1.79	395.21	396.05	25.87	1	219.9	1.76	385	386	27	0.997
Inductive	219.74	1.07	165.37	234.58	166.58	0.7	221.3	1.08	163	239	174	0.682
Capacitive	222.91	1.27	193.26	283.22	207.04	0.68	222.9	1.20	192	266	-184	0.721
Rectifier	222.54	0.5	54.70	111.80	97.50	0.49	221.1	1.22	187	269	193	0.695

Table 2. Percentage error of measurement results

Load type	%Error= ((measured value -ref. value) / ref. value) * 100 %		
	%Error of V_{rms}	%Error of I_{rms}	%Error of PF
Resistive	0.432	1.705	0.301
Inductive	0.704	0.926	2.639
Capacitive	0.004	5.833	5.687
Rectifier	0.651	59.016	29.496

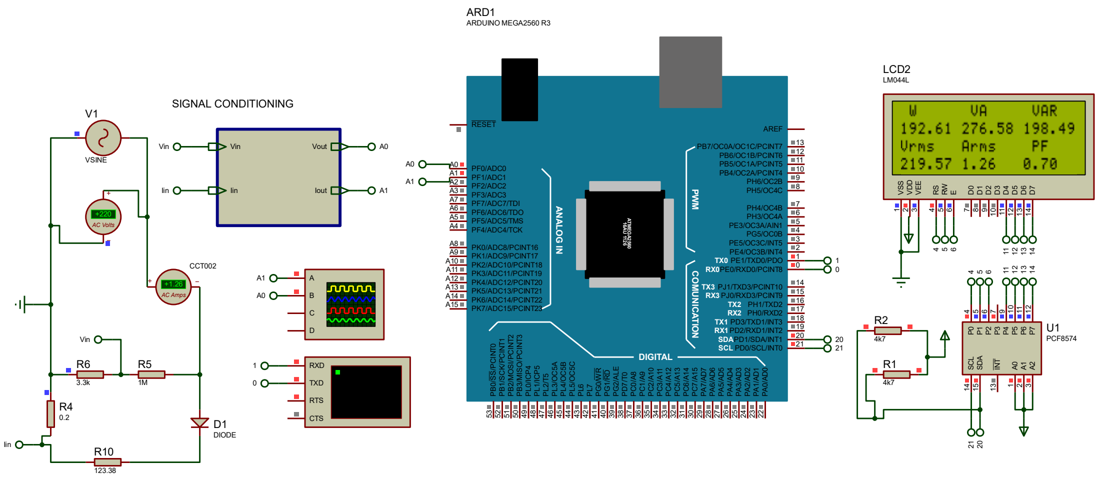


Figure 12. Simulation circuit diagram of the proposed DSMM with Nonlinear load.

The comparison of parameters shows that the values obtained by the designed prototype closely match those measured by high-quality measurement instruments (Fluke Meter) especially with linear load. To overcome the accuracy issues in tables 1 and 2, especially with nonlinear load, this case was analyzed deeply as follows:

Case study: the proposed work with Nonlinear load (Single-phase half-wave rectifier with a purely resistive load 123.38 ohm) was simulated with Proteus software environment as shown in Figure 12. The I_{rms} equal to 1.26 A, are consistent with the results of the mathematical analysis using equation (10)

$$I_{rms} = \frac{V_{rms}}{R} = \frac{0.5V_m}{R} = \frac{0.5*\sqrt{2}\times 220}{123.38} = 1.26 \text{ A} \qquad (10)$$

And thus, the percentage error of the I_{rms} was about 0% relative to the AC ammeter of the software, as it also measured the current at 1.26 A.

The obtained value of the PF is 0.7 is not due to displacement between voltage and current but rather to distortion in the current signal, as the load is resistive; it is compatible with the results of the power factor in example 3.1 of [27]. It should be noticed that the waveforms of the current and voltage are clear and aren't distorted as shown in Figure 13; thus, all the measuring data are accurate as above in the results.

Figure 14 shows the instantaneous values of time, voltage, current, and power at the start of operation on the serial monitor window for a practical test of the measuring system.

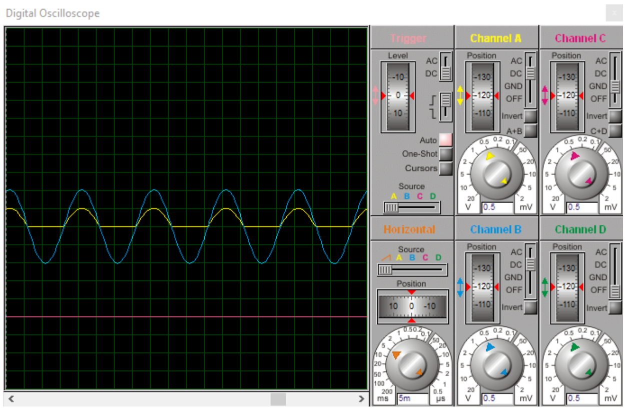
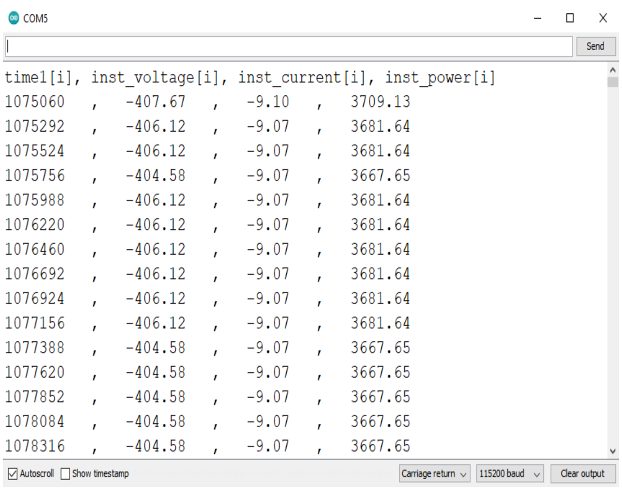


Figure 13. Waveforms of the voltage and current signals entering the Arduino


COM5

time1[i],	inst_voltage[i],	inst_current[i],	inst_power[i]
1075060	-407.67	-9.10	3709.13
1075292	-406.12	-9.07	3681.64
1075524	-406.12	-9.07	3681.64
1075756	-404.58	-9.07	3667.65
1075988	-406.12	-9.07	3681.64
1076220	-406.12	-9.07	3681.64
1076460	-406.12	-9.07	3681.64
1076692	-406.12	-9.07	3681.64
1076924	-406.12	-9.07	3681.64
1077156	-406.12	-9.07	3681.64
1077388	-404.58	-9.07	3667.65
1077620	-404.58	-9.07	3667.65
1077852	-404.58	-9.07	3667.65
1078084	-404.58	-9.07	3667.65
1078316	-404.58	-9.07	3667.65

Autoscroll Show timestamp Carriage return 115200 baud Clear output

Figure 14. Instantaneous values of time, voltage, current, and power on serial monitor window

In this research, the waveform of instantaneous voltage, current, and power was plotted versus time from the experimental values that were sent to the serial monitor, which is shown in Figure 14, at the testing of the proposed work with different types of loads, as shown in Figure 15.

In Figure 15 (a), in the case of a resistive load, it's obvious that the voltage and current waveform are in phase and the power is positive, while the reactive power is very small. In Figure 15 (b), in the case of the inductive load, it is clear that the current was lacking from the voltage waveform in addition to being distorted. Finally, in Figure 15 (c), in the case of the capacitive load, it is clear that the current is leading to the voltage waveform, and there's a lot of negative reactive power. This result demonstrates the strength and accuracy of the proposed software algorithm, and such a result wasn't found in the related articles.

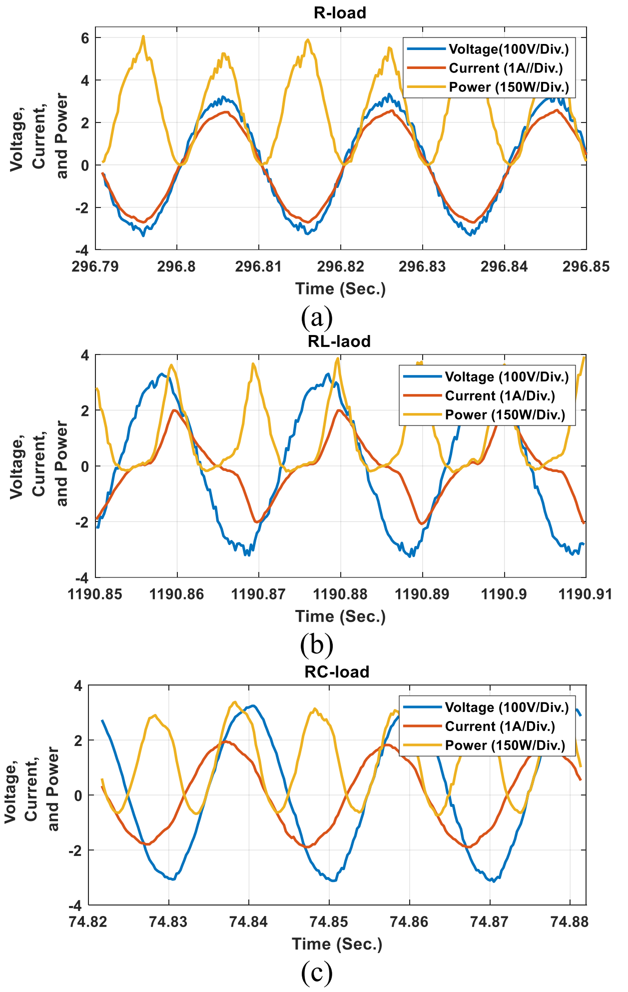


Figure 15. Waveform of voltage, current, and power for three types of loads

Figure16 shows the calculated values for the six parameters presented on the serial monitor window of the Arduino IDE software platform.

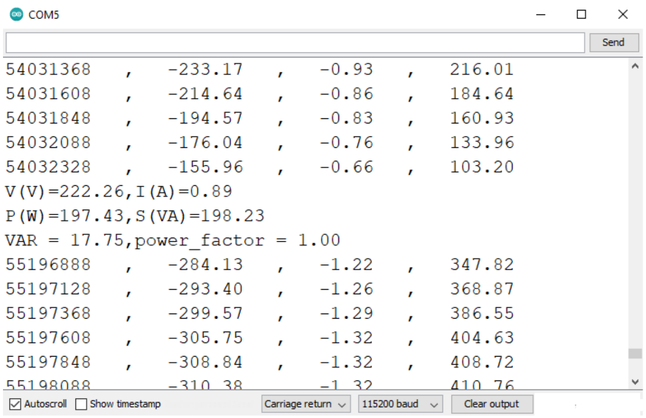


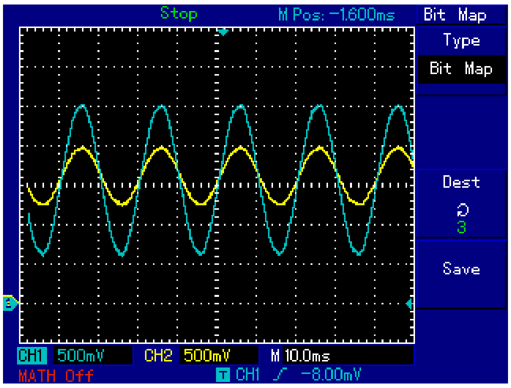
Figure 16. Six parameters of the proposed DSMM (V_{rms}, I_{rms}, P, S, Q, and PF) shown on the serial monitor

It shows the last part of the previous reading samples, which ends with sample 254 at a time of 54032328 microseconds. The figure also shows part of the beginning of the samples for the subsequent reading, which begins with the time (55,196,888 microseconds). The difference between the time of the first sample of the subsequent reading and the time of the last sample of the previous reading is equal to 1.16456 seconds. This time represents the time it takes for the proposed algorithm to implement its flowchart. Thus, the measured values are updated every time (1.16456 seconds). This updated time for the measured values can be divided into three parts:

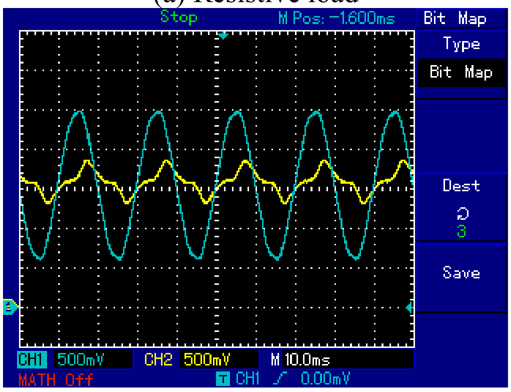
1. The time required to take samples (85 samples per cycle) and store the samples.
2. The time required to perform calculations.
3. The time required to send the instantaneous values (current, voltage, and power over time) to the serial monitor.

The time (1.16456 seconds) can be reduced in several ways, including adding a condition to the algorithm that the instantaneous values (current, voltage, and power) are not sent to the serial monitor unless requested by the user; using a faster Arduino microcontroller, such as the Arduino Due, which is approximately 5 times faster than the current microcontroller; or reducing the number of samples from 85 samples per 20 milliseconds to 40 samples per cycle, increasing the sampling time.

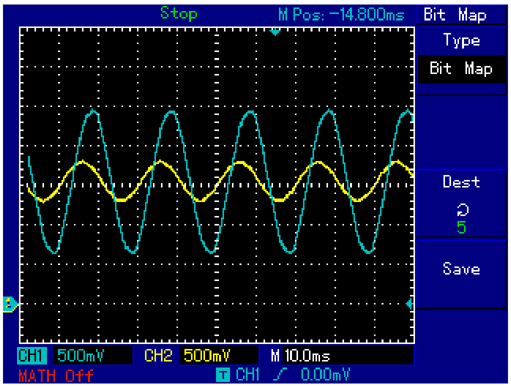
Figure 17 presents the oscilloscope-captured waveforms of the sensed current and voltage signals under various load conditions, with the current waveform shown in yellow.



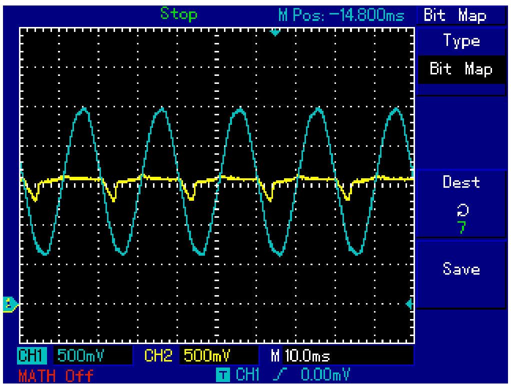
(a) Resistive load



(b) Inductive load



(c) Capacitive load



(d) Non-linear load

Figure 17. Waveforms of the sensed current and voltage signals

It can be concluded that, If the sensed signals of the current and voltage are clear and not distorted, as in the first three figures (a, b, and c) of Figure 17 in the case of the linear load, the measured parameters were accurate. While at the non-linear load, the shape of the voltage signal is correct, but the current signal was distorted**,** which is affected by the saturation of the iron core in the case of non-linear loads, so the current signal does not appear as a pure half-wave signal, as in Figure 17-d, and so the measuring values of the load current and the power factor are inaccurate. Therefore, the proposed software design was absolutely accurate, especially for power factor and the RMS load current, as it was verified and tested via the Proteus software environment for rectifier load, and it provides accurate results.

The distortion on the sensed current signal, causing a rise in the percentage error of current and especially that the CTs may exhibit non-linearity and reduced accuracy, especially at lower currents, which can lead to inaccurate measurements. CTs are designed for specific frequency ranges. Their performance can degrade outside of these ranges, making them unsuitable for certain applications.

This issue can be addressed by employing alternative current-sensing technologies, such as Hall-effect sensors, that offer improved performance for nonlinear load conditions, as they are less affected by core saturation and can handle distorted waveforms better.

7. CONCLUSIONS

This paper presents the design of a single-phase DSMM based on an IPCA using Arduino, as laboratory samples of voltage and current signals were taken from the sensors. This data was stored in the memory of the Arduino microcontroller. Then these instantaneous values were used for calculations of six parameters according to the IPCA. The proposed prototype is very useful for educational issues as it allows for monitoring many parameters in many ways (LCD, oscilloscope, and serial monitor), and the data can be saved and plotted for further analysis. The proposed design is considered a low-cost, reliable, accessible, and flexible solution for an accurate tool for measuring electrical parameters in various applications. In this work, the true RMS value for voltage and current was measured with high accuracy without the need for the external rectifier circuits of the peak-detector for voltage and current signals. Also, the total PF was measured with high accuracy without needing the external circuits of the zero-crossing detector for voltage and current signals. In future work, the proposed design can be integrated with a communication system and IoT platform to produce a smart metering system capable of real-time monitoring, remote data transmission, and improved energy management. The proposed work can also be extended to function as a portable oscilloscope by monitoring the instantaneous values of voltage, current, and power, and plotting these signals on an appropriate LCD display.

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