

Development of a low-cost DC measurement circuit for photovoltaic systems using industrial equipment as a reference

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Abstract This paper considers the DC measurement circuit often used in photovoltaic systems and its relatively high cost. The aim of the present work is to highlight the development of a low-cost high accuracy DC measurement arrangement. To achieve this, a circuit comprised of a voltage divider connected to a microcontroller's ADC for voltage measurement, a single board computer for data acquisition and a dedicated current sensor were used. As a result, voltage and current were acquired facilitating the calculation of power for the studied circuit. A correction coefficient was determined and applied by using industrial equipment as a measurement reference. This allowed the development of a measurement system that may be used as an alternative to the conventional industrial solution, with an average accuracy of 99.67 % compared with the considered reference. The proposed system may be used to increase the flexibility of measurement in DC applications through a cost-effective lab solution, and will be improved in further research studies.

Keywords: DC measurement system, photovoltaic systems, ADC, alternative measurement system, voltage divider, data acquisition, low-cost applications, hall-effect current sensor, MQTT, ESP32, Raspberry Pi

I. INTRODUCTION

In the field of energy production, it is important to always know the state of the equipment. To determine the characteristics and the effectiveness of a power generation system, a measurement unit device must be used. This also applies to photovoltaic (PV) systems where DC voltage, current, power and energy are considered the most important parameters [1], [2], [3].

With the passage of time many photovoltaic measurement techniques have been developed. All methods present strengths and weaknesses due to energy loss, measurement accuracy, system complexity and of course the lack in equipment precision. Measuring an electrical value produces a slight aberration to the power system as nothing is completely ideal no matter what the domain. Considering this fact, studies were conducted with different measurement methods for specific power system scenarios.

The most important topics that determine the needs and topologies of a measuring PV system are: power quality, meteorological aspects and geographical localization of consumption points as presented in [4]. Besides those aspects,

cost plays a crucial role in the design of a PV measuring system.

The scale and effectiveness demand of the PV measuring system must be considered and analyzed to improve the cost – quality ration. Cost effectiveness implies that the secondary circuits must be properly scaled while using low-cost equipment for DC measurements. Under those circumstances, a viable solution to meet the industrial grade accuracy and demanded timestamp between measures consists in a side-by-side calibration of the affordable method and an industrial more expensive one as also presented in [4].

Noise in DC measurement is a common and concerning problem that must be considered, especially while using cost-efficient solutions with low filtering capabilities. Consequently, circuits such as voltage dividers, hall effect sensors and microcontrollers may be used.

This paper focuses on the design of a PV measuring circuit that can acquire DC voltage, current and power at a fast data transfer rate using only cost-efficient materials. Filtering and circuit complexity was considered. Measured values were compared to those of an industrial grade inverter.

In the next section the methods and materials used to measure, acquire and process the electrical parameters of a studied photovoltaic system are presented. The 3rd section illustrates a comparison between data obtained in the field using the designed affordable measurement circuit and the industrial grade inverter. The results comprised of the acquired data and the efficiency of the designed measurement system comparing it with the existing work are discussed in the 4th section. The conclusions are highlighted alongside future work in the final section.

II. MATERIALS AND METHODS

For this paper case study, a low-cost circuit was made to acquire proper electrical measurements from a 203.5 V photovoltaic (PV) string. The PV system is comprised of 5 monocrystalline PV panels with an efficiency of 19.5%, an open circuit voltage of 40.7 V and a short-circuit current of 10.74 A as specified in the datasheet [5]. The measuring unit system was designed to acquire DC voltage up to 300 V and

current up to 15.5 A respectively at a data transfer rate of 0.5 measurements / second or 30 measurements / minute.

Achieving a high level of precision on DC voltage data measurement was done by connecting an in-house voltage divider to a microcontroller's analog digital converter (ADC). Moreover, multiple low value resistors were considered so the dissipated heat would be reduced accordingly with Joule law. As an additional safety measure ½ W resistors and 1 W resistors were used. To determine the corresponding resistors (1) was used alongside a Mathworks Matlab / Simulink simulation.

$$U_{out} = U_{in} \cdot \frac{R2}{R1 + R2} \quad (1)$$

Where: U_{out} is the resulting voltage of the voltage divider; U_{in} is the input voltage of the voltage divider; $R1, R2$ are the voltage divider resistors.

Measuring the actual voltage of the power system was done by applying (2) to the response of the voltage divider. A calibration coefficient of -0.039 was considered to determine the sample sized voltage of the ADC. This value was obtained by trial and error for our specific microcontroller and can be different from model to model. A 64:1 average measure ration was applied to normalize the possible measurement noise.

$$U_{ADC} = U_{out} \cdot \frac{U_{ref}}{4095} - 0.039 \quad (2)$$

Where: U_{ADC} is the sample sized voltage of the ADC; U_{ref} is the reference voltage of the ADC.

Current measurements were made by using a 15.5 A serial ACS711ex Hall-Effect Linear Current Sensor [6] (Allegro microsystems, Manchester, England, UK) preinstalled on a breakout circuit board designed by Pololu (Pololu Corporation, Las Vegas, NV, USA).

The usual occurrence of noise in DC measurement systems was considered. A WI-FI-ready microcontroller was used to send data over the internet in order to obtain proper galvanic isolation between the measurement system and the acquisition device. For filtering a 100 nF and a 1 µF capacitors were installed. Consequently, the waveform noise of the measured voltage signal was attenuated. Although similar work has been done in the field, the noise issues were not considered [1], [2] and [7]. Moreover, instead of using a 10 Bit Arduino Nano like in the cited work the ESP32-C3 (Espressif Systems, Shanghai, China) with its 12-bit processor improved measurement accuracy.

Quality of the data measurement was ensured by designing a Message Queuing Telemetry Transport (MQTT) communication server. To accomplish this a Raspberry Pi400 (Raspberry Pi Foundation, Cambridge, England, UK) was used to work as an open-source Eclipse Mosquitto MQTT data broker. Consequently, the measured data was processed and

published using the ESP32-C3 through MQTT communication protocol to the Raspberry Pi single board computer (SBC) which also plays the role of acquisition device. The necessary knowledge about MQTT protocol and Eclipse Mosquitto service was extracted from OASIS Open MQTT standard V5.0 [8] and other works [9]. A similar MQTT Pub-Broker-Sub communication architecture for a DC measurement unit was designed and presented in [1], [10] and [11].

While functioning, the measurement unit can output faulty results conducting to misleading information about the system as implied in other works [12]. To prevent this a fast transfer rate of 30 measurements / minute that can compensate and offer a good understanding of the system's behavior was prepared.

Correction coefficients were determined by comparing the measured data between the developed system and the acquired data from a Huawei SUN2000-3KTL-L1 inverter. For this paper, the most noticeable characteristics of the considered equipment are: a maximum input voltage of 600 V, a rated input voltage of 360 V, a max input current per MPPT of 12.5 A and a maximum short-circuit current of 18 A as specified in the datasheet [13].

The accuracy of the system was calculated using (3) which is based on absolute and percentual errors determined with (4) and (5).

$$ACC = 100 - \epsilon_{PERCENT} \quad (3)$$

$$\epsilon_{PERCENT} = \frac{\epsilon_{ABS}}{\text{reference value}} * 100 \quad (4)$$

$$\epsilon_{ABS} = \text{measured value} - \text{reference value} \quad (5)$$

Where: ACC is the accuracy of the studied circuit; $\epsilon_{percent}$ is the percentual error; ϵ_{ABS} is the absolute error.

The possibility of a primary system malfunction that would cause damage to the microcontroller was considered. In this manner a high voltage protection of the microcontroller was made by reverse connecting a 3.6 V Zenner diode between the I / O port and the voltage divider as presented in Fig. 1. Consequently, if a faulty voltage appears endangering the microcontroller, the diode will close and redirect it to the common ground. According to the ESP32-C3 datasheet the ADC reference voltage is 1.1V [14] but it can sustain values up to 3V.

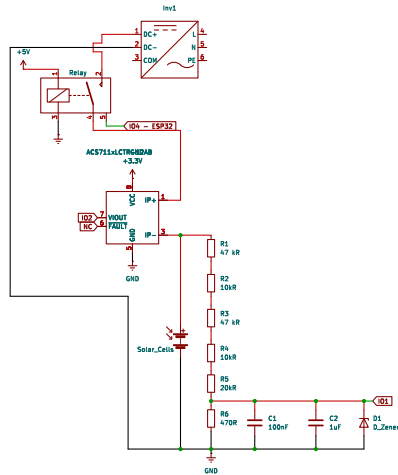


Fig. 1 - Schematic diagram of the developed measuring system

III. RESULTS

To determine the right parametrization of the DC measuring system, various analyses were made. Voltage divider complexity, heat dissipation, output voltage to the microcontroller ADC and response time were considered.

The development of DC measuring unit was done in 2 phases. In the beginning a reference calculation was conducted to determine data for the first parameterization scenario. After that, an iterative simulation in Matlab / Simulink software was directed.

To determine the proper resistors for the voltage divider, 5 possible simulation scenarios were carried out. Different values for resistors were chosen accordingly with (1). In the first case a 6-resistor architecture was simulated with the following amounts and values: 2 resistors of 47 k Ω , 2 resistors of 10 k Ω , a 22 k Ω resistor and a 470 Ω resistor. A 1.033 V value was determined for the voltage divider output and 2.198 mA current running through the circuit. Corresponding measurement tools were used in Matlab / Simulink to display the resulted values as presented in Fig. 2.

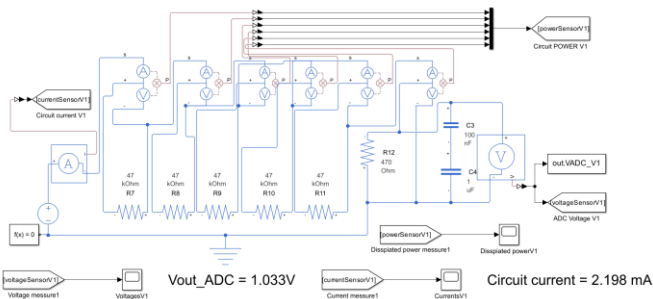


Fig. 2 – Initial context of the voltage divider simulation using Matlab / Simulink, Case 1 / 2

The second scenario analyzed was also developed with 6 resistors, the only difference being the change of the 22 k Ω

resistor into a 20 k Ω resistor. Resulted values of the simulation consisted of a 1.049 V DC voltage and a 2.231 mA circuit current.

Third case, which is presented in Fig. 3 consisted of a more compact and cleaner approach with only 4 resistors. The chosen amounts and values were: 2 resistors of 56 k Ω , a resistor of 22 k Ω and a resistor of 470 Ω . The resulting voltage and circuit current are the same as in the second case because of the same equivalent series resistance in the circuit.

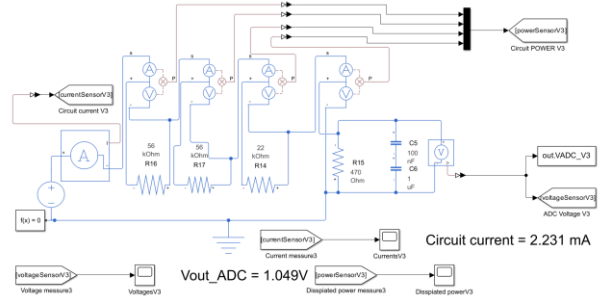


Fig. 3 – More compact approach of the simulated voltage divider using Matlab / Simulink, Case 3

In the 4th case heat dissipation was considered as a primary parameter so the picked resistors could be much more easily chosen with a power of only 0.25 W. To do so, 10 resistors had to be used. The chosen amounts and values were: 4 resistors of 20 k Ω , 2 resistors of 10 k Ω , 2 resistors of 6.8 k Ω , a resistor of 22 k Ω and a resistor of 470 Ω as being presented in Fig. 4. The output voltage at the microcontroller analog digital converter (ADC) was 1.036 V and the circuit current was 2.205 mA. Consequently, a maximum of 104 mW power dissipation was obtained when the capacitors were fully charged.

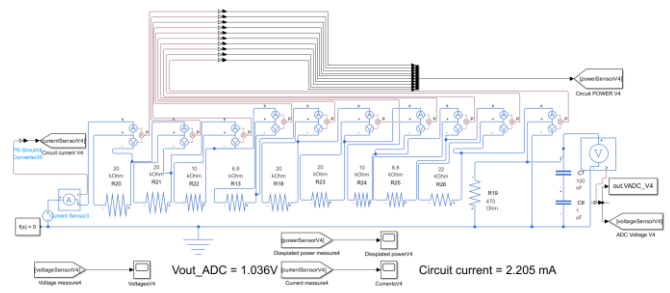


Fig. 4 – Heat dissipation improvement of the voltage divider simulation in Matlab / Simulink, Case 4

For the 5th case energy losses and system complexity were considered as the most important characteristics. As so 2 resistors were used: 1 resistor of 1 M Ω and 1 resistor of 3.3 k Ω , as being presented in Fig. 5.

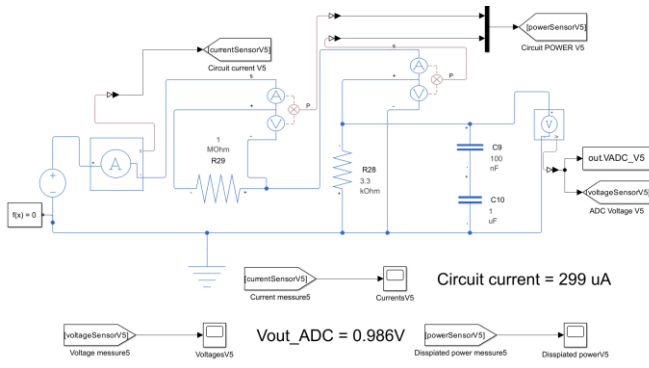


Fig. 5 - Energy losses and circuit complexity improvement of the voltage divider simulation in Matlab / Simulink, Case 5

To determine the best scenario for this paper case study, an analysis of the output voltages at microcontroller ADC was carried out. The resulted voltages were plotted in Fig. 6.

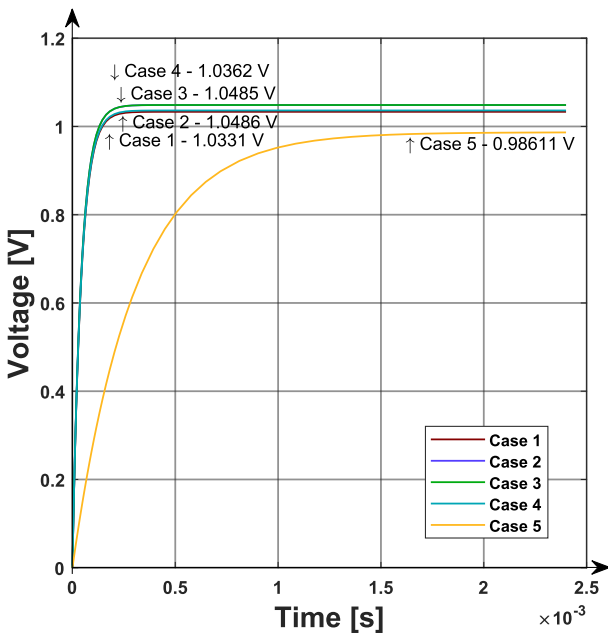


Fig. 6 - Results of the simulation on voltage divider output

Based on the simulated scenarios, the second solution was selected for this paper's voltage divider architecture. The discussion section provides a detailed explanation of the simulated results.

After determining the right equipment, a 1-week field measurement was conducted. The acquired results were processed and illustrated in Fig. 7 (magenta curve) alongside the inverter data (blue curve). To achieve a better understanding of the resulted waveform, only 1 day was extracted in the graph. A 1.085 correction coefficient was implemented to increase the accuracy of the DC measurement unit and presented in Fig. 7 (yellow curve). Applying (3), (4) and (5) to measured data between 11:00 AM and 03:00 PM conducted to a precision of 99.67% of the inverter data. The

motive for this specific timeframe is defined and described in the discussion section.

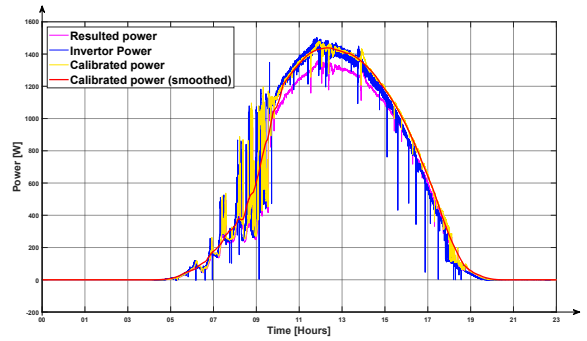


Fig. 7 - Measured data of the developed circuit alongside the inverter and corrected data

The equipment used in this study was bought from the same international marketplace. Consequently, a real perspective of the prices for this domain was created. The overall price of the developed system was considered and presented in TABLE I.

TABLE I
CIRCUIT COMPONENT COSTS

Pts.	Equipment	Price (€)
1	470 Ω metal film resistor 0.25W - TME.EU	0.0303
2	47 k Ω metal film resistor 1W - TME.EU	0.094
2	10 k Ω metal film resistor 0.5W - TME.EU	0.0609
1	20 k Ω metal film resistor 0.25W - TME.EU	0.0375
1	100 nF ceramic capacitor - TME.EU	0.1854
1	1 μ F tantalum capacitor - TME.EU	0.172
1	POLOLU ACS711lex - TME.EU	4.86
1	2pt PCB terminal block - TME.EU	0.232
1	double sided prototyping board - TME.EU	0.63
1	DFROBOT Beetle ESP32-C3 - TME.EU	7.05
1	3.6V, 0.5W. Zener diode - TME.EU	0.0303
1	400V / 24A terminal block - TME.EU	0.637
1	1m wire with 0.25 mm ² wire section - TME.EU	0.122
1	Raspberry pi400 - TME.EU	82.86
Total		97.0014

IV. DISCUSSION

Conducted simulation on voltage divider solutions pointed to key aspects of each scenario that could indicate a better solution of the studied circuit. For the first case where a 6-resistors architecture was considered although the obtained voltage was in the safe working area of the ADC, a higher value could've increased the overall accuracy of the measurement system. Second scenario turned out to be a better approach considering the increased value of the analog digital converter (ADC) voltage. The precision measurement increased while the complexity of the system remained the

same. To reduce the overall complexity of the voltage divider circuit, 3rd scenario with only 4 resistors was studied. Although the system complexity has been reduced as presented in Fig. 3, the corresponding resistor values are harder to find and conduct to a higher level of heat that must be dissipated. An improve heat dissipation was considered for the 4th case. Unfortunately, too many resistors had to be installed for this to happen conducting to a high complexity of the voltage divider system and a lower value of the ADC voltage. To achieve a more efficient circuit, 5th scenario had been studied. Even though the current flowing through the circuit has been drastically reduced to only 299 μ A, the total resistance in series with the microcontroller ADC was too big compared to its impedance which is around 100 k Ω . Consequently, the DC voltage measurement with this configuration would develop faulty results. Simulations outcome suggested that the second scenario will produce satisfactory results for the studied photovoltaic (PV) system.

Increasing the accuracy of the proposed solution was done by applying a correction to the measured output of the system. To determine the desired coefficient, raw measured data of the case study circuit were compared with measurements done by an industrial grade inverter. The comparison was presented in Fig. 7 alongside the plot of the corrected measurements. This meaner was also applied in [4] to achieve satisfactory data measurement for a 500 V system.

Because of the clouded sky multiple spikes in energy production graph appeared. As a result, a normalized characteristic was developed using a moving average filter. The new plot visually describes the improvement added by the correction coefficient.

One of our objectives for this paper was to develop a cost-effective measurement system that can provide good results for a normal-scale photovoltaic system. For that the total investment in designing and developing of the proposed circuit was only around 100 € as presented in *TABLE I*. Considering the industrial equipment and also other works [1], [4] where total price is at least double, it can be said that the experimental circuit studied in this paper is affordable.

To overcome the lack in redundancy for this work case study, the overall system was designed to be completely local with no limitations for data storage and no unannounced maintenance sessions. Those particular situations are often found in open-source free services or software and can interfere with the measuring process as presented in [15].

A high fluctuation in accuracy of the power readings was observed for a 24-hour measurement period. The corrected data (yellow curve) describes high deviation from the inverter data (blue curve), as seen in Fig. 7. This happened due to non-linearity and scaling errors inherent to the microcontroller's ADC. It seems that the data outside the median region is affecting the overall performance. However, if we only consider a particular timeframe between 11:00 AM and 03.00 PM, the effect is attenuated. Consequently applying (3), (4) and (5) to the mentioned reading period, a 99.67% accuracy was obtained. When calculating performance, we focused on

the appropriate timeframe to get the relevant system accuracy. In future works multiple correction coefficients could be used for different periods and voltages to compensate for the ADC limitations.

V. CONCLUSIONS

This paper presents an open source, low-cost data acquisition unit architecture for DC measurements on photovoltaic systems. An experimental solution for the developed circuit was illustrated and explained. To verify the obtained results an industry grade inverter was used as reference in a side-by-side comparison.

Considering the results and functionality, a system similar to one developed in this paper can be used for precise DC measuring at a fast refresh rate of data acquisition. Furthermore, measuring systems like one researched and presented in our study comes at a fraction of an industrial inverter price which improves the attractiveness in terms of economic investment. More than that, such systems can be installed in DC applications other than PV systems where measuring is not meant to be done by an inverter.

To achieve an affordable circuit, different methods were considered and applied. Voltage measurements have been conducted by connecting an in-house voltage divider to an inexpensive ESP-32 C3 microcontroller ADC. Extra fees were avoided including subscription payments of services like storage or system maintenance by developing a set of proprietary algorithms based on C++ programming language and MQTT communication protocol.

A Mathworks Matlab / Simulink iterative simulation was carried out in order to determine the right values for the voltage divider resistors. Multiple scenarios were considered where energy loss, heat dissipation and circuit complexity parameters were debated. In the end a 6-resistor architecture based on 1/4 W resistor and 0.5 W resistor was chosen and experimented with.

Because of the full-scale irregularities of the ESP-32 C3 ADC, a particular time range was considered to measure the electrical parameters. Consequently, the measurement precision was promising with an average accuracy of 99.67% of the inverter data.

Based on this paper, future studies can be done in order to obtain better measurements accuracy, filtering and time-frame coverage. With an initial investment of just 100 € this paper represents a promising start for future low-cost measurement unit prototypes with more capabilities and improvements.

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