Development of an IoT power management system for photovoltaic power plants

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Abstract — **This study describes the development of a power management system for photovoltaic systems (PVS). A web application was developed, receiving data from a hardware interface, installed in each photovoltaic array allowing online power monitoring, fault detection, and configuration of remote power plant installations. The designed system is based on open-source / hardware technologies. Reports for variable periods of time of power generation at PV array, PV string, and at PV cell level are available to the system operator. The benefits, and drawbacks of the developed system are compared along with other systems presented in the literature using criteria in order to evaluate the performance of the designed system. The developed system was tested and compared to the other implementations provides many advantages, such as fault detection per PV cell, power monitoring on all components of the PV array (PV array, string and cell), and the use of open-source / hardware that significantly reduces costs, making the system ideal for small and medium enterprises.**

Keywords— Photovoltaic systems, Power management, Photovoltaic fault detection algorithms, IoT

I. Introduction

The use of photovoltaic systems in the production of electricity has an ever-increasing dynamic [1]. This is because they have zero carbon footprint and are easy to install [2], [3]. Despite their advantages it should be noted that still, the profit margin from such an investment is considered small [4]. For this reason, their operation must be permanently monitored, in order to avoid errors in these systems, thus maintaining energy production at the optimum level. In addition, statistical monitoring of production can help draw conclusions and modifications to improve energy production [5].

The Industry 4.0 plan focuses on communication, connectivity, and visibility across the whole supply chain [6]. The Supervisory Control And Data Acquisition (SCADA), is the mainstream system used for monitoring, controlling, and coordinating work procedures across all industry devices. Multiple sensors exchange telemetry data using Remote Terminal Units (RTU) in a SCADA system. Human Machine Interfaces (HMI) are also included, allowing human actions to be added into the system based on production and safety requirements, providing process oversight [7]. SCADA systems are typically closed systems that are too expensive for small businesses. On the other hand, Martikkala et al. [8] suggests that Internet of Things (IoT) platforms would assist small and medium enterprises (SME) due to their licensing methods and the vast availability of the tools quality.

This paper provides a quick overview of common approaches to power monitoring in photovoltaic power plants. The development of a new system capable of monitoring power generation while detecting faults on PV cell level is then described in depth. Both the literature-found systems and the newly developed system have been compared using a set of criteria to determine their reliability and performance. We discuss the advantages, and disadvantages of the systems. Finally, the conclusions of this paper will be presented.

II. Power Management Systems

Photovoltaic power management systems allow the user to observe information about the monitored photovoltaic system such as, performance, production values, consumption, and faults. The installation of such a system is necessary not only for monitoring the operational status of the PVS, but also to assess the return on investment of the PVS.

Fernandez et al. [7] suggested an IoT system for monitoring solar plants, totally based on open source software. Their system consists of a hardware layer of sensors and digitizers that communicate with an IoT gateway over TCP. The Message Queue Telemetry Transport (MQTT) protocol was used to collect data and send it to an IoT platform. Tina and Grasso [5] investigated the creation of a data collecting platform for remote monitoring of the operation of a stand-alone PV appliance. The suggested system is based on a web-based application that allows data to be distributed to remote users through the Internet and on a data acquisition board. Control, monitoring, alerting, reporting, and data export are the key services supplied to the user. Jiju et al. [9] proposed developing an online renewable energy monitoring and control system based on Android and a custom hardware based on PIC184550. The Bluetooth interface of an Android tablet or phone is used as a data communication module with the hardware of the power monitoring device. PIC184550 is also used in the work of Kabalci et al. [10], where the microcontroller transmits current and voltage measurements to a monitoring tool developed in visual studio. It has to be noted that this monitoring tool can operate for both PVS and wind turbines. The work of Rani et al. [11] on the other hand, uses open source software and hardware tools to develop a system that transmits current and voltage measurements directly from the PV array to the Thing Speak server. Dabou et al. [12] presented a monitoring application based on LabView that receives data from commercial dataloggers. Pereira et al. [13], developed an IoT-based power monitoring system in Python, PHP, and JavaScript. The Graphical User Interface (GUI) is a web application that end-users employ to process data locally or remotely. Harrou et al. [14], used LabVIEW, Simulink, PSIM and commercial data acquisition modules to detect faults that reduce the power production on PV arrays. Garcia et al. [15], proposed an architecture of datalogging modules that measure the important values with the use of wireless sensors scattered throughout the plant. The architecture also employs a high-precision protocol to synchronize all data gathered from the hardware. Finally, the work of Reatti et al. [16], focused on the creation of a power monitoring system for a hybrid (photovoltaic and thermal) power plant that can track, in real time, both electrical and thermal data from the solar and thermal systems, using sensors and digitizing modules.

A. Criteria of evaluation

In order to assess the various power management systems, certain criteria should be set

i. IoT capability: In industry, the Internet of Things provides various benefits for day-to-day operations. The adoption of IoT improves resource consumption efficiency. IoT devices can reduce human effort since they interact and communicate with one another and perform a variety of tasks, they. This results in time and cost savings [17].

ii. Fault detection: Faults can have a significant impact on the energy production [18] of the PVS. Thus, fault detection is a necessary condition for ensuring the greatest possible energy production.

iii. Power monitoring per array/string/cell: Offline analysis of these data can be used to produce energy performance records and statistical results [5]. Offline data analysis can be used to optimize the current system performance and retrofit the complete power plant in order to increase power output.

III. ANALYSIS OF THE DESIGNED SYSTEM

The developed power management system comprises (a) a hardware interface attached to the power lines of each monitored PV array, (b) a fault detection algorithm and (c) a software that allows the power monitoring and the configuration of each of the monitored PV arrays. The block diagram of the system can be seen in Figure 1.

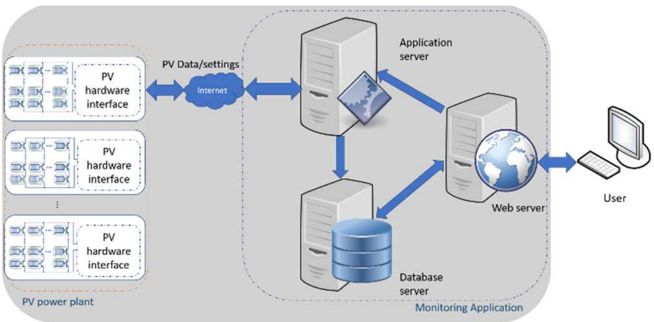

Figure 1: Block diagram of the developed system

A. Hardware

The interface installed in each PV array, consists of:

i. A microcontroller unit (NXP iMXRT1062) to process the data received from the PV cells and transmitted to the monitoring service and vice versa. The hardware interface is presented in Figure 2.

ii. An ethernet network interface to exchange data with the developed software. The hardware interface is connected to the power line of the PV array using special circuitry. All transmissions to and from the PV cells are performed via the main power line.

This research has been co-financed by the European Regional Development Fund of the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship, and Innovation, under the call RESEARCH – CREATE – INNOVATE (project code: T1EDK-01485).

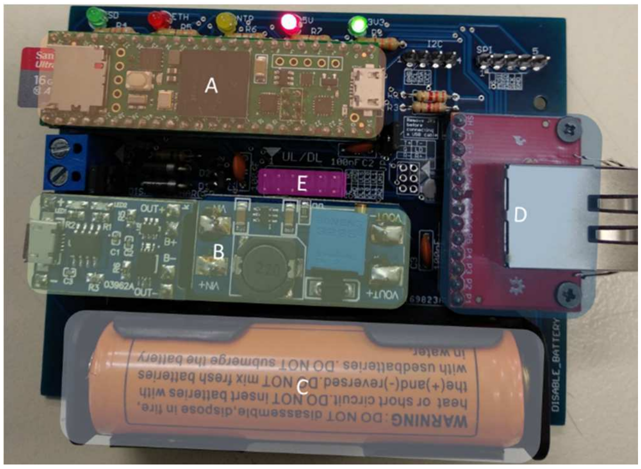

Figure 2: The hardware interface. A. shows the microcontroller unit. B. and C. shows the power supply unit the charger and the battery. D shows the ethernet module while E. shows the connector that connects the hardware interface with the rest of the circuitry of the PVS.

Each PV cell is connected to a custom-made circuit that transmits its unique cell-ID, its operating voltage and current measurements as 10-bit integers. Furthermore, each cell receives its configuration through the hardware interface. It should be noted that the cells belonging to the same string must be configured with the same settings.

Each hardware interface has the same generic firmware, responsible for the initialization of the modules and failure checks. Each PV array has a unique configuration, required to differentiate the interface, avoiding conflicts during initialization; the configuration is provided via a configuration file. Each interface receives the code of the PV park and the corresponding PV array, as well as the necessary settings (IP address, gateway, subnet mask, and DNS address) from the configuration file. Additionally, any event that occurs during the operation of the user interface, is stored in a log file. When the initialization completes, the interface transmits the configuration of the PV Strings (received from the main service) to the array, therefore the cells can start transmitting their measurements. Then, the interface packs the measurements along with the identities of the solar park and the PV array that correspond to the interface, accompanied with a timestamp and transmits the package to the monitoring application for further processing.

The circuit is powered externally. Each interface is equipped with a battery and a battery charger, so that the interface can operate under power failures and during nights. In case of a network failure, the data coming from the cells are stored in a file. During the night, if such records exist, they are sent to the service. When all telemetry of the PV cells is sent to the service, the file is deleted, in order to prevent the same measurements from being retransmitted at the next disconnection.

B. Software

Extensive research on fault detection and identification algorithms in PVS, reviewed in [19], [20], that methods based on IV curves have many advantages, such as the ability to identify many types of faults, low development cost and their potential use in other PVS installations with slight modifications.

For this reason, the developed algorithm is based on a comparative method [21] the flowchart of the developed algorithm can be seen in Figure 3. Data derived from an I-V curve are compared with data derived from a PV cell. More specifically, the algorithm has been developed on Python 3.9, and runs as a system service on the monitoring server. Through the API calls of the Solcast and OpenWeather services [22], [23], the algorithm receives values of solar radiation intensity and temperature, for the latitude and longitude that the power plant is located. Based on these values, combined with the specifications of the PV cell that is used, the single diode model [24]–[27] simulates the cell, following equation 1. I_{ph} stands for the current created by the presence of light, I_{o1} is the reverse saturation current of diode D_1, q is the electron charge, k is the Boltzmann's constant, a_1 is the diode's ideality factor, T is the temperature in Kelvin degrees, while R_s, and R_{sh} are the series and shunt resistors.

$$I = I_{\text{ph}} - I_{0_1}\left(e^{\frac{q(V+IR_S)}{\alpha_1 kT}} - 1\right) - \frac{V+IR_S}{R_{SH}} \quad (1)$$

The graph generated by the algorithm contains the I-V and P-V curves for the current conditions of the measurement. Additionally, the algorithm calculates from the curve the Maximum Power Point (M_{pp}), the Fill Factor (FF), the Characteristic Resistance (R_{CH}) of the PV cell, as well as the open circuit voltage and the short-circuit current.

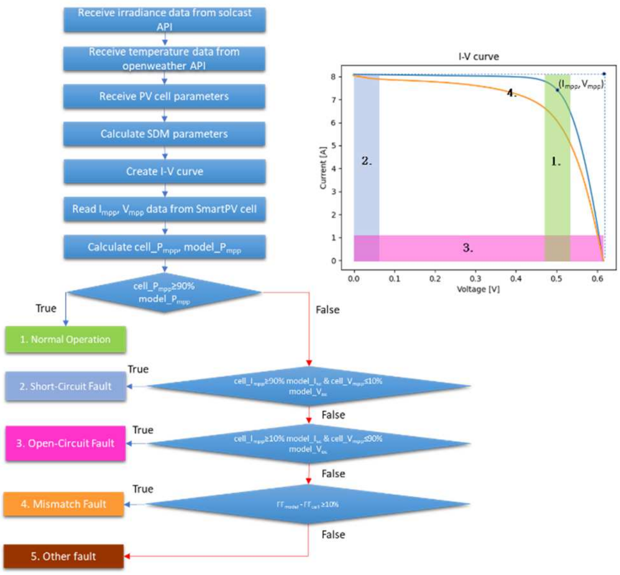

Figure 3: Flowchart of the algorithm [21]

The algorithm is threshold based. It determines the operational status for each cell that is located on a PV array, based on the comparison of the measured current and voltage values of each cell, with the estimated maximum power-point (M_{pp}), the short-circuit current and the open circuit voltage of the PV cell generated from the SDM. From this comparison it classifies the operation of each PV cell into one of five states: normal operation, open-circuit fault, short-circuit fault, degradation faults and other unidentified type of fault.

C. Monitoring software

A web application is developed with open-source software on Ubuntu Linux operating system. Specifically, a Web server, MySQL as a database. As scripting languages for the back-end PHP and Python have been used. HTML, CSS and jQuery were used for the front-end. The MQTT protocol is used to send and receive data from the PV cells.

The application server communicates with the MQTT server (Mosquitto) that receives the data sent from the PV cells of a PV array through the hardware interface and stores them in the database server. After that, it communicates with the system service that is responsible for the fault detection and identification. The algorithm updates the database records that indicate the operational status of that specific PV cell.

The web server is responsible to display information on the selected PV array from the monitored power plant. It communicates with the application server in order to refresh the graphical environment of the application for the operational status of the PV elements of the selected PV array, and refresh the current and voltage plots of each PV cell and each PV string. Each plot by default depicts the daily data, but it can also be configured to display data from a custom time period.

Furthermore, the web server is responsible for the configuration of the strings of the selected PV array. More specifically, it is possible for the user to set the string configuration options (active / not active, standalone / grid-connected, AC / DC output, operating frequency, desired voltage and power output for the embedded MPPT), as well as to set the PV cell failure threshold that deactivates the PV string. Furthermore, these options update the corresponding fields in the database. The communication of the Web server with the hardware interface is performed via the MQTT protocol in the Application server through port 1883.

IV. Experimental Setup

The operation of the system was performed in parts:

i. the operation of the algorithm is presented in [21], where the evaluation of the algorithm took place, under normal conditions and under presence of faults. The algorithm handled every scenario of operation and was able to identify the presence of faults on the PV cell.

ii. The communication of the interface with the application was made by connecting the interface to a microcontroller, which simulates the operation of a photovoltaic cell. Tests were performed on sending the configuration to the PV cell and on sending telemetry from the cell to the application. A plot, containing current and voltage measurements from the three days of the testing operation can be seen in Figure 4.

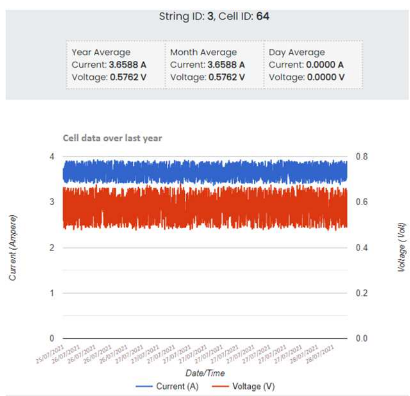

Figure 4: Current and voltage plot

V. DISCUSSION AND FUTURE WORK

This work focuses on power management systems for photovoltaic installations. Table 1 presents a comparative study between the features and limitations of each system studied in the literature, in relation to the system designed. The comparison has been made based on the criteria set at the beginning of the paper.

Table 1:Power management system comparison

Authors	Ref.	IoT capability	Fault detection	Power measurement			Extra Features	Limitations - Drawbacks
				Per PV cell	Per PV string	Per PV array		
Fernandez et al. 2021	[7]	Yes	Partially	-	-	+	Measurements on the Inverters	Difficult configuration
Tina and Grasso 2014	[5]	No	No	-	-	+	Modbus /Ethernet communication	Standalone PVS only. Alarms do not include faults on PV
Jiju et al. 2014	[9]	No	No	-	-	+	Bluetooth connectivity Measurements on the Inverters	Slow communication Insufficient data security
Kabalci et al. 2013	[10]	No	No	-	-	+	Can be also used in wind turbines	Not cross-platform
Rani et al. 2021	[11]	Yes	No	-	-	+	Daily, weekly, and monthly reports	-
Dabou et al. 2021	[12]	No	No	-	-	+	Real-time measurements	IoT → future upgrade
Pereira et al. 2018	[13]	Yes	No	-	-	+	Multiplatform	Requires Wi-Fi for decentralized operation
Harrou et al. 2019	[14]	No	Yes	-	-	+	-	-
Moreno-Garcia et al. 2016	[15]	No	No	-	-	+	Real-time measurements Measurements on the Inverters	-
Reatti et al. 2017	[16]	No	No	-	-	+	Real-time measurements Measurements on the Inverters Fault detection on the hardware of the system. Not on PV cells	-
Voutsinas et al. 2022	Proposed	Yes	Yes	+	+	+	PV array configuration per string.	The software does not calculate the energy produced as money

From Table 1, all methods perform power measurements on the PV array. Some systems are based on commercial equipment [12], [14]–[16]. Only three systems support IoT connectivity [7], [11], [13]. Fault detection is supported only in systems [7], [14] and the developed one presented in this paper. The three criteria that were set at the beginning of this work are fully supported only in the system cited in [7] and in the system proposed in this work.

The developed system provides power measurements for each PV array / string / cell, that is monitored from the system. Power monitoring, in conjunction with string level configuration, and with the developed fault detection and identification algorithm presented in [21], ensure the best possible power generation for all the PV power plant. Furthermore, the configuration of the arrays is simple using the GUI designed for the application. Each string of each array can be configured according to the user. Besides that, the user of the application can select the maximum number of faulty PV cells that exist simultaneously on a PV string in order to deactivate that specific PV string.

The development of this system is based in open-source hardware, so the cost is minimal – the cost of the system mainly concerns the purchase of the components for the manufacturing of the circuits. It should be noted, however, that in the event of a commercial use of this system, the Solcast and OpenWeather services are provided for a fee. In addition, daily plots and exporting data in .csv format helps in the statistical processing of power generation. As a future improvement, the automatic conversion of power into energy is proposed, so that the worth of production per unit time can be calculated automatically. Moreover, redesigning parts of the algorithm such as the model that it is used, or the addition of a neural network as a classifier, would further increase the accuracy of the measurements and the fault detection capability.

CONCLUSION

In this manuscript, a brief discussion on common methods of power management, as well as the developed power management system were presented. Methods proposed in the literature and the designed system were analyzed for their benefits, and drawbacks. Finally, comparisons between the literature proposed systems and the developed system, according to several criteria, such as the precense of an IoT interface, fault detection capability and the ability to take power measurements on sub-parts of the PV array, determined the performance of each one method. The overall performance of the developed system is satisfactory. The proposed system is equipped with IoT interfaces per each PV array, capable of configuring the strings of each array, and transmitting its measurements at the PV cell – level. The developed monitoring application can configure each array, detect the precence of faults on a cellular level, depict and export power data for each monitored PV array.

Acknowledgment

This research has been co-financed by the European Regional Development Fund of the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship, and Innovation, under the call RESEARCH – CREATE – INNOVATE (project code: T1EDK-01485).

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