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Original scientific paper

System Control and Data Acquisition of University Photovoltaic Power Plant

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Abstract: The paper deals with design of System Control and Data Acquisition (SCADA) of Photovoltaic power plant FERIT 1, its configuration and connection with server unit for data archiving and removal approach by either android or PC devices. SCADA is developed according to ideas and need for scientific research of data generated by photovoltaic power plant built on the roof of the Faculty of Electrical Engineering, Computer Science and Information Technology Osijek in Osijek, Croatia. Designed system enables real-time analysis and of course subsequent time analyses based on storing data of high frequency measurement samples of photovoltaic (PV) power plant. The first part of the paper describes hardware components and system configuration and the second part deals with software background. Measurements of PV parameters and meteorological conditions are continuously performed, and these data are stored locally and instantaneously stored also on remote servers. Acquired measurement data is presented by graphics on developed web server platform. Developed SCADA presented in the paper is unique, adaptable open source which enables long-term performance of power plant and its components' function.

Key words: graphical display of performance and operation, PV power plant, real-time measurement, SCADA

1 INTRODUCTION

Renewable energy has become a very important part of electricity generation in the last 20 years with enormous increase of installed power capacities due to ecological aspect but also self-sustainability principles of new smart buildings and in near future of modern smart cities. It motivates technical engineers to adopt new knowledge, cope with renewable energy sources (RES), to perform continuous measurements of all parameters of RES technologies operation and malfunction and research based on measured data with a goal to improve RES technologies present operation and their future design [1]. Furthermore, new challenges on distribution power grid design have become important due to bidirectional power flows in low voltage network caused by integration of particular photovoltaic (PV) power plants distributed along the network. Design requirements for PV inverters directed by distribution network companies make a new smart grid concept based on measurement data communication exchange. Brand new design of distribution gird becomes multidisciplinary engineering in the fields of power system, automation, communications, computer science, optimisation algorithms, SCADA and similar [2]. Study programmes and educational equipment and devices in technical laboratories of universities, engineering colleges and expert secondary schools need to be modernized and revaluated to respond on new challenges of RES design, integration, mounting, control and maintenance.

Smart grid concepts are adopted and applied in design of many of modern university power laboratories in different countries. Development of an example of online RES power laboratory which can share measurement data with other researhers and experts is described in [2]. Hardware of hybrid AC/DC smart grid model is presented and described in [3, 4]. Also, in [3, 4], description of installed software is given with developed control strategies for distributed electricity generation and feeding model of priority loads inside laboratory up to 35 kW(AC) and 36 kW RES and bateries. The model of hybrid power subsystem laboratory which contained PV power plant, wind generator, energy storage and control unit based on remote access (TELELAB) for possible further scientific and expert research is explained [5]. The application of SCADA in modern maintenance decision support process and application of programmable logic controller for RES are presented in [6-9]. Authors in [10-11] explained artificial intelligence application in process control.

This paper describes design of System Control and Data Acquisition (SCADA) of Photovoltaic power plant FERIT 1, explains its configuration and connection with server unit for data archiving and remote approach by either android or PC devices. Laboratory is established as a part of the Faculty of Electrical Engineering, Computer Science and Information Technology (FERIT) in Osijek, Croatia and tends to be initial step to the smart grid laboratory.

Developed SCADA is based on and directed for scientific research of data generated by PV power plant mounted on the roof of the Faculty of Electrical Engineering, Computer Science and Information Technology in Osijek, Croatia. SCADA concept, topology and communication protocols are explained in detail by the analysis of the measurement data from two viewpoints: hardware aspect and software aspect.

RESLAB (**R**enewable **E**nergy **S**ources **Lab**oratory) is established and installed with initial equipment in 2014 as a part of Photovoltaic Systems as Actuators of Regional Development (REGPHOSYS) project funded under IPA cross-border programme Croatia-Hungary. RESLAB consists of outdoor equipment located on the building roof (PV modules) and indoor (inverter, data measurement, processing and storage).

SCADA was put into function in 2017. Designed system enables real-time analysis but also subsequent time analysis based on storing data of high frequency measurement samples of photovoltaic (PV) power plant. Measurements of PV parameters and meteorological conditions are performed continuously and the data is stored locally and instantaneously shared on remote servers. Acquired measurement data is presented by graphics on developed web server platform. Developed SCADA is adaptable and designed as open source which enables long-term performance of power plant and its components function.

SCADA components configuration and their connections for measurement data flow, process and data storing is presented in Fig. 1.

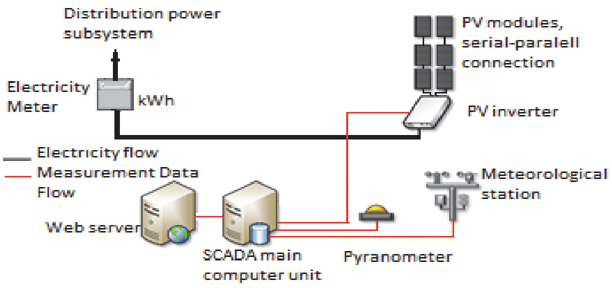

Figure 1 SCADA with its hardware components and connections

2 DESIGN OF DEVELOPED SCADA
2.1 Hardware Components of Designed SCADA

Measurement data inside SCADA is divided into two main parts, one independent on another:

- Data acquisition system of 10 kWp PV system
- Data acquisition of meteorological parameters on the test site

PV system with rated power of 10 kWp contains two PV strings. The first PV string has 20 series-connected monocrystalline silicon Bisol BMO 250PV modules while the second contains 20 series-connected polycrystalline silicon BisolBMU 250PV modules. Two strings are cable connected to the three-phase grid-tie inverter which has maximum power point tracker. The KacoPowador 12.0 TL3 inverter is connected to the electrical installation of FERIT building and further to distribution grid. Measurements of electrical parameters such as DC output currents and voltages and AC output phase currents and phase voltages are performed in a 15 s sample by the PV inverter itself. Measured data are sent to the data logger and then on the station computer and server where they are archived.

Weather conditions parameters are measured by meteorologic station and pyranometer measurement device mounted on the top of FERIT Osijek building. Outdoor temperature, air humidity, wind speed, wind direction and air pressure are measured in measurement sample of 1 min. Pyranometer measurement device (Kipp&Zonnen SMP3) measures solar irradiance in measurement sample of 1 s. All measured data of weather conditions is also sent to the data logger and further to station computer and server to be archived.

2.2 Software for Designed SCADA

Developed software for SCADA is written in C++ on the ATmega 328p microcontroller (Arduino), Hypertext Preprocessor (PHP) and Structured Query Language (SQL) on the data logger (SCADA main computer unit).

Measurement data of PV inverter is processed on the data logger. After data processing, the data is sent into cloud storage and continually visualised on the laboratory website of the faculty [12]. The data flow and history are presented in form of graphical diagrams and numerical data sheets on the SCADA website.

Data processing algorithms control the quality of measurement data given by sensors and recognition of false measurement data caused either by sensor or by data communication process and neglect false or deviated data. Code algorithm performs calculation of current and average PV module efficiency values (η) and current and summary produced electrical power (P). Furthermore, calculation of the efficiency of the 10 kW PV system inverter is made. Data processing inside the ATmega 328p microcontroller deals with data in 30 intervals per second and gives output average data during sample of 1 s. Measurement data is organised in groups as time stamp periods during system function and can be analysed in different time intervals for example on exact period in hours, date (day), weeks, month, season or year.

Programmed algorithms on microcontroller and data logger continuously record and check measured values during time stamp for possible deviation or interruption, recognising false data or a signal loss of SCADA and react by sending alarm through e-mail notification to alarm the problems either in measurement process or in data communication process. The alarm procedure improves high respond time to react and minimise lack of measured data and to get the highest possible continuity of archived long-term measured values and better automatic data storage.

The initial designed database is chronologically structured which enables selection of time given periods to be displayed in a form of data sheets and graphically visualised values in average timestamps of 1 min. Described structure of data processing can be used for further analysis to get long-term predictions during different seasons of the year and possible climate changes and to graphically display the technical outputs of PV system.

The basic approach of ATmega 328p Microcontroller (Arduino) component function in developed SCADA is the application of portable and modular microcontrollers based on open-source, cheap and reliable integral elements. Arduino controller is wide available and simple to adapt and integrate as a part of the SCADA system. Depending on measurement signal type, the sensors generate digital or analogue outputs which are acquired by the programmed algorithms inside the microcontroller Arduino. The developed code of data logger is also installed and implemented as C++ scripts. Data logger has direct connections through USB ports to enable data communication. The applied compiler software is ARDUINO.CC. The used method for comunication to acquire readouts is serial monitor by the free software Coolterm, which acquires the accepted measurement values to textual files arhived on the data logger file system. The textual file contains the timestamp of acquired data and the measured numerical data. Fig. 2 presents an example of acquired data inside software Coolterm.

There are several types of textual files - separately archive voltages data, currents data and solar irradiance data depending on Arduino microcontroller limitations of input signals (Fig. 2).

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142.2031555175|xxx3070.56|3503.09|3504.03|3020.68|3053.23|
141.9968872070|xxx3063.07|3522.53|3559.06|3481.78|3075.95|
141.9625244140|xxx3058.15|3483.89|3572.88|3028.18|3042.70|
141.8594055175|xxx3097.49|3474.76|3507.07|3544.54|3044.10|
141.7906494140|xxx3023.49|3543.84|3589.27|2909.21|3068.22|
141.5500183105|xxx3075.48|3496.77|3598.17|2860.04|3066.58|
141.5156250000|xxx3073.61|3476.40|3501.92|3546.89|3048.79|
141.2750244140|xxx3019.75|3489.28|3537.99|3138.94|3027.01|
141.3781433105|xxx3078.99|3554.61|3610.11|3455.09|3058.85|
141.1375122070|xxx3066.11|3464.92|3459.07|3058.85|3028.18|
```

Figure 2 Example of measurement values inside software Coolterm

During measurement procedure the data logger archives the data and communicates with measurement sensors and with web server by means of the textual files generated by the microcontroller. Operating system used here is Microsoft Windows which is the most compatible common tool for variety of used software controls of applied hardware equipment. The web server connected on the data logger uses free and open-source XAMPP distribution and the other applied softwares are the Apache HTTP web server, MariaDB database (SQL), PHP and Perl programming languages for script interpreters. The code written in PHP controls the readout of the data from textual files and populates the MariaDB (SQL) database. After readout process, content of the textual files is flushed to optimize memory resources. The readout procedure is continually performed generating a constant amount of measurement data in communication which is synchronised by timestamp value. That time flag is also a constituted part of outcome textual file as index value of measurement data sets and is archived in a single unique database entry for each measurement point (Fig. 3). The readout process is triggered once per minute by windows schedule operation which calls the PHP interpreter and runs a programming script which opens the textual files, reads the measurement data line-by-line and loops every text line of archived data from measurement process.

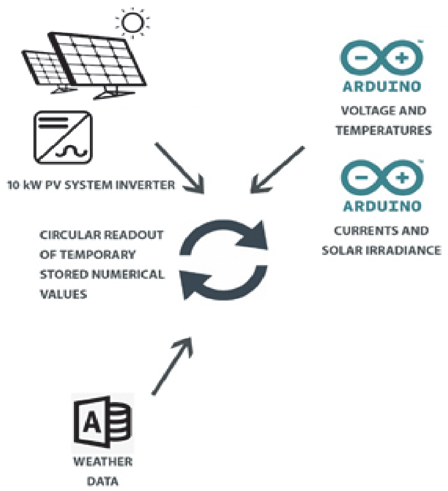

Figure 3 Sheme of measurement data readout process

Simultaneously several computing processes are performed: creation of a new line of the the measurement database, measurement data are archived inside the new line and also verified during the same loop of code. At the end of one pass of the programme loop, a determined backup web server sends a copied line of measurement data initiated by the Client URL (CURL) command. In case of unavailability of internet connection or some other technical communication problems, all undelivered data are stored in a specific textual file which will be sent after efficient internet reconnection.

Weather parameters of the environment of PV power plant are archived in a dissimilar way caused by its embedded measurement protocols of equipment acquisition based on the software package Weathercloud. All measured data are archived into a Microsoft Access database (Fig. 4). Additionaly developed PHP program scripts readout of the weather data; converts them to SQL entries, synchronizes the timestamps of 10 kW PV system data and coordinates them.

The defined web server oversees data flow of communication process inside embedded repetition control loop tailing the time-interval difference of its current clock and time of the archive record line in database. In case time-interval difference is intolerant (greater than defined in code by user), the designated server initialy forms an alarm script and simultaneously sends an e-mail of disruption of measurement data flow. It is enabled through a public IP address accessed by the CURL command initiated by web server. In other words, the designated web server becomes the final location for measured data to be archived because it is available by a public web address. Web server capacity is greater than data flow received by data logger, so it is possible to use web server as host of more data loggers from more different locations. Herein the paper, description of the next step - data analysis of the measured parameters - is given in detail. It is based on its own programming code as a web application with intention of time-interval filter and displays these data during defined different intervals of measurement process. Detailed data mining of the long-term measured parameters is also possible afterwards by the daily data sets archived inside the available cloud memory. Afterward, it is possible to import analysed data into separate database tables, to be further graphically presented or presented in tables. The schematic diagram of communication process and all measurement system components (Arduino controller, data loggers and designated server) are explained in Fig. 4.

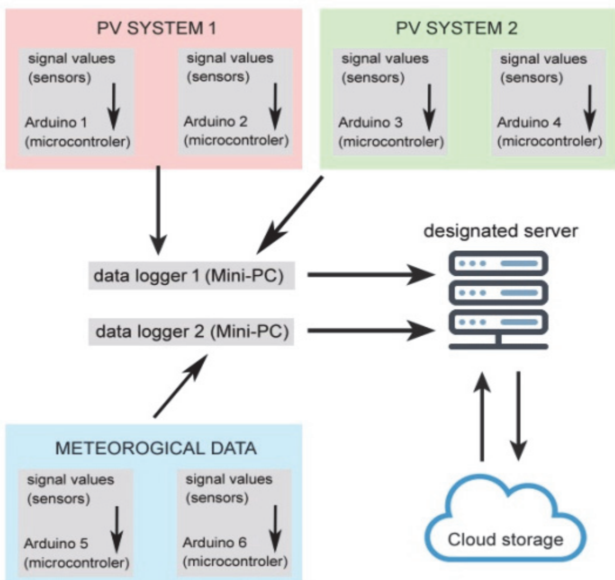

Figure 4 Sheme of SCADA measurement process

3 FERIT 1 PV POWER PLANT SCADA IN PRACTICE

Graphical interpretation of SCADA measurement is continually available on laboratory website. There is option to download measurement data of SCADA saving it into individual files. Furthermore, there are various potentials for outcome representing, only several are presented in the paper. Online real-time measured parameters of 10 kWp PV system and weather parameters on the location for May 19, 2021 are visible in Fig. 5. Here, combination of wide types of SCADA data is presented: output DC voltages (of two parallel PV strings), DC currents, DC powers, module efficiencies and module (cell) temperatures, inverter power on DC and AC side and its efficiency, AC voltages, AC currents (three phases) and AC powers. Current weather parameters such as solar irradiance and ambient temperature are presented and graphically interpreted in 3.5 h time window (interval could be adjustable).Daily solar irradiation and average daily ambient temperatures from 2018 to 2021 are presented in Fig. 6. These data are the expected representative patern for European humid continental climate. Dependence of monocrystalline and polycrystalline silicon PV strings daily yield on daily solar irradiation during from 2018 to 2021 is visible in Fig. 7.

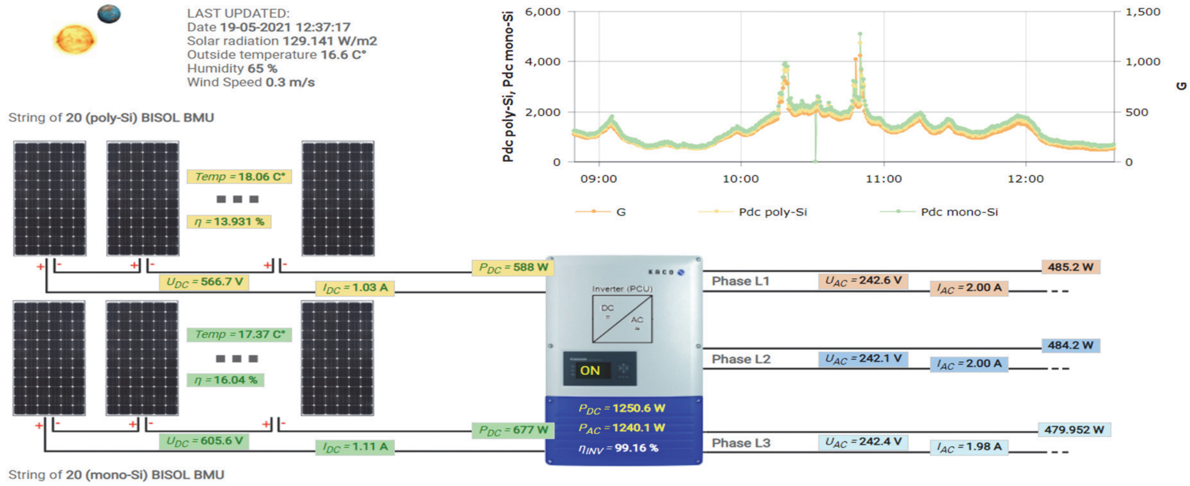

Figure 5 Real-time SCADA parameters of 10 kWp PV system and current weather parameters data [12]

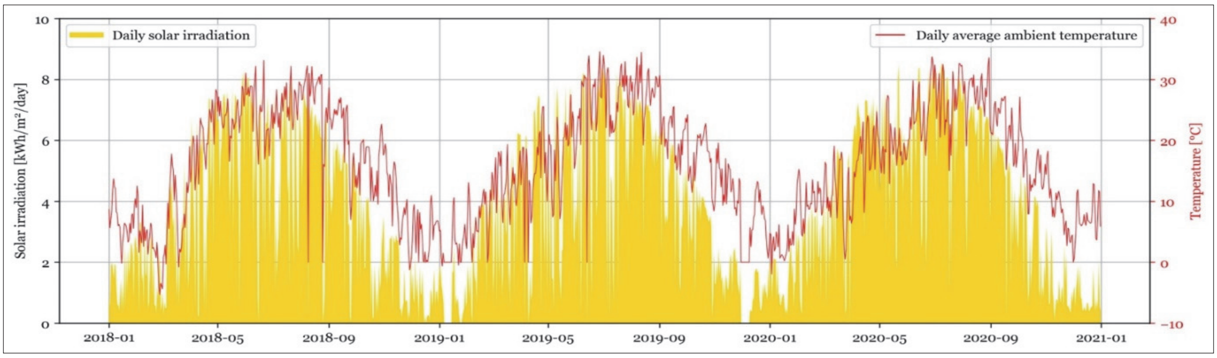

Figure 6 Daily solar irradiation and daily average ambient temperatures from 2018 to 2021 [12]

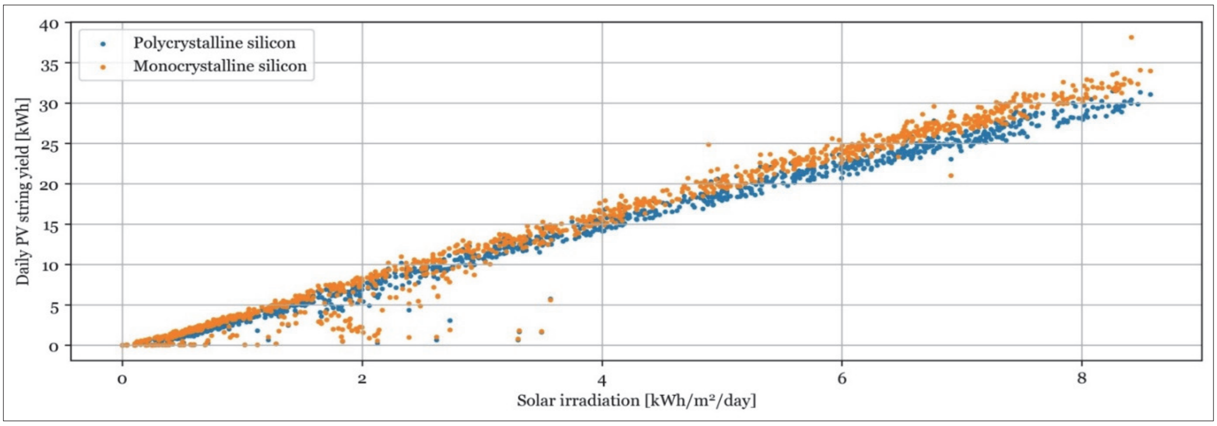

Figure 7 Dependence of monocrystalline and polycrystalline silicon PV strings daily yield on daily solar irradiation from 2018 to 2021 [12]

The efficiency changes its value caused by sun irradiation variation during the day and variation of temperature during the day, which is also function of irradiation, wind velocity etc. It is possible for user to change time frame to get different time-series diagrams for any output parameters such as powers, voltages, currents, and module (cell) temperatures. Described linear trend relation of daily yields of monocrystalline and polycrystalline PV strings in dependence on daily solar irradiation from 2018 to 2021 is presented in Fig. 7.

4 OPTIMISATION OF CUSTOM-BUILT SCADA SYSTEM

The system control in the data acquisition process has shown limits in the hardware maintance and software management that has led us to the conclusion that an upgrade of an independent local storage of data was necessary to obtain the functionality to communicate with the cloud storage and maintain the continuous flow of data that can be stored more securely and be later managed by a dedicated processing machine. A Network attached storage (NAS) with expanded network interface to fetch all the data to a cloud storage was chosen for this task. In view of efficient energy consumption, a NAS server has the capability to store all the needed data for further analysis but has limited computing power to deal with the quality and indicators of the stored information. For our purposes it was the maintainer of the information and has prolonged the needed maintenance of the weeker hardware functionality of the data logger. For long time measurements in focus, we hope that everyone can afford to purchase the given hardware equipment that we have chosen, and we have made the conclusion that in the uncertainties of the global warming, it is the essence of this research to obtain as much data as possible to investigate the coming possibilities of the RES power production in dependance on the ongoing climate and weather changes.

4 CONCLUSION

The paper deals with SCADA design for a PV power plant developed at FERIT Osijek RESLAB. Based on the analysed outcomes and variety of the possible graphically visualised options, the developed SCADA presents a strong tool for a further scientific research of the PV power plant performance in dependance on climate and weather conditions. Thanks to open-source design and its scalability, the designed SCADA can be adjusted to analyse performance of large PV power plants acquiring large data sets and performing a wide spectrum of calculations, predictions and analyses.

The developed SCADA can also be of great importance during maintenance and planning of new investments such as RES, microgrids etc. because the accurate measurement data acquired during a past period can be used for simulation of the PV power plant. Real-time measurements also enable real-time control, for example turning on the loads in smart grid power system.

A further research and expansion of SCADA monitoring will cover the electricity consumption on different types of FERIT building loads and follow extension of 10 kW power plant to a FERIT faculty building prosumer microgrid consisting of 90 kW PV with 40 kWh battery storage system, electric vehicles chargers and manageable load to bring technical solution closer to developing smart grid laboratory for the education and research needs.

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