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Remote and Centralized Monitoring of PV Power Plants

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Abstract - **This paper presents the concept and operating principles of a low-cost and flexible monitoring system for PV plants. Compared to classical solutions which can require dedicated hardware and/or specialized data logging systems, the monitoring system we propose allows parallel monitoring of PV plants with different architectures and locations by taking advantage of the intrinsic monitoring capabilities of the inverters and their internet connectivity. The backbone of the system is a software system capable of collecting production measurements and current-voltage (I-V) characteristic curve measurements from the inverters within each PV plant. The monitoring software stores the PV measurements in a data warehouse optimized for managing and data mining large amounts of data, from where it can be later visualized, analyzed and exported. By combining PV production measurements data with I-V curve measurements the diagnostic and condition monitoring capabilities of the PV system can be greatly enhanced. The practical implementation and operation of the monitoring system is demonstrated with a study case system deployed at Aalborg University.**

I. INTRODUCTION

As the installed capacity of Photovoltaic (PV) power is continuously increasing [1], the need for management and optimal energy harvesting from such plants is of high importance. A crucial part in achieving this is adequate supervision and monitoring of the performance and health of the system. Large PV plants can afford to have sophisticated PV monitoring systems as well as trained personnel available on site for continuous monitoring and maintenance. Compared to large plants, smaller PV systems such as residential or commercial installations are often insufficiently monitored after installation. In this case faults can go unnoticed for long periods of time until they are detected and proper maintenance actions can be performed, causing significant power loss of up to 18% as was reported for some cases [2].

Faults and degradation affecting the PV generator inherently leads to a decrease in the energy production of the plant and thus decreased revenue. There can be many factors that impact performance of a PV plant, such as front surface soiling [3], partial shading [2], increased series losses in the electrical components or the PV generator [3], potential induced degradation [4], etc. Most of the degradation modes can be detected by performing current-voltage (I-V) curve measurements [5-7] or even simply by monitoring the production of the PV arrays and the ambient conditions [2, 8].

Nowadays most commercial inverter manufacturers integrate monitoring functions in their products capable of measuring a wide range of system operation parameters. New generation string inverters such as the Danfoss TLX Pro are able to measure the I-V characteristic of each connected PV string separately[9].

The monitoring capabilities of the inverter can be a cheap and efficient monitoring solution; nevertheless there are some limitations that can come into play when considering more advanced monitoring requirements.

One limitation is related to the interoperability of the monitoring system, most commercial inverters can cooperate only with inverters from the same manufacturer, having proprietary communication protocols. This leads to additional integration efforts when monitoring heterogeneous PV plants, where different types of inverters are present from different manufacturers. The same problem can arise when monitoring several plants, distributed geographically, and where a centralized monitoring system is required.

This limitation can be solved by implementing a dedicated monitoring system. There are numerous PV monitoring systems examples presented in the literature. Some of them include dedicated tools such as NI LabView [5] or the installation of special data transmission networks using wired [10] or wireless [11] technology. However most of these solutions require the installation of a dedicated hardware which means additional cost.

A second limitation which is more relevant when advanced PV condition monitoring functions are required, is related to the difficulty in extending the inverter built-in monitoring functions with additional diagnostic and condition monitoring functionality. This is not possible since the software of the monitoring system is proprietary. An example of such an additional function is recording and analyzing changes in the I-V characteristic of the PV generator, which can provide a wealth of diagnostic information about the state of health of the PV system.

In order to overcome these limitations whilst keeping the cost down by not requiring additional monitoring hardware, a centralized PV monitoring system was developed that collects and aggregates monitoring data from PV inverters over the internet, and stores them in a data warehouse optimized for managing and data mining large amounts of data, from where it can be later visualized, analyzed and exported.

Initially the centralized PV monitoring system was designed to collect I-V characteristic measurements and time series production data from PV plants distributed over a wide area in Denmark, and which were based on the Danfoss TLX Pro inverter. As the system was developed the goal was kept of having flexibility in the monitoring of various types of PV systems without requiring extra monitoring hardware on the PV system side. Consequently the principles presented next as well as the monitoring system itself can be extended to other PV inverter types.

This paper presents the operation principles of the centralized PV monitoring system along with the most important implementation details, along with a study case where the system has been deployed and is in operation.

II. MONITORING SYSTEM DESCRIPTION

The centralized PV monitoring system, illustrated in Fig. 1, was designed to run on a central PC with internet connectivity. The software itself was developed in the C#/.Net 4 and the Microsoft SQL Server platform.

The monitoring system takes advantage of the intrinsic monitoring and internet connectivity capabilities of the inverter and can collect and aggregate different types of PV measurement data from each PV inverter monitored over the internet. The measurement data is then consolidated in a data warehouse in a unified format, where it can be later visualized and exported for analysis.

The different types of measurement data collected as well as the sampling and averaging periods depend on the inverter type and configuration. The most common PV system parameters measured are listed in Table I.

Most commercial inverters only measure averaged values of the PV generator current and voltage related to the current operation point of the maximum power point tracker (MPPT), but new generation inverters [12] can also measure the I-V characteristic of each PV string connected to the inverter. This can be a very cheap solution to monitor the I-V characteristic of all PV generators and implement advanced diagnostic and condition monitoring functions [6, 7].

Table I Types of PV system parameters monitored

System Component	Parameter(s)	Obs.
PV String/Array	d. c. current and voltage	Averaging period depending on inverter type and configuration
	I-V characteristic	If I-V sweep functionality is available.
Inverter	a. c. current, voltage, power, frequency, power factor	r. m. s. average values, averaging period depending on inverter type and configuration
	status	depending on inverter type
Local Ambient Conditions	Plane-of-array irradiance and module temperature	If sensors are connected to the inverter system. A veraging period depending on inverter type

A. Data Collection Process

The monitoring system was designed to operate remotely and collect the measurement data over the internet, either directly from the PV inverters or from an intermediate FTP server/data warehouse where the measurement data was previously uploaded by the inverters. The data collection process, depicted in Fig. 2, can also import the measurements from local measurement files, retrieved manually from the inverter, in case there is no internet connectivity.

These three different data collection modes, detailed in the next section, provide a measure of flexibility to the monitoring system in case some hardware or functionality is not available on the PV systems side.

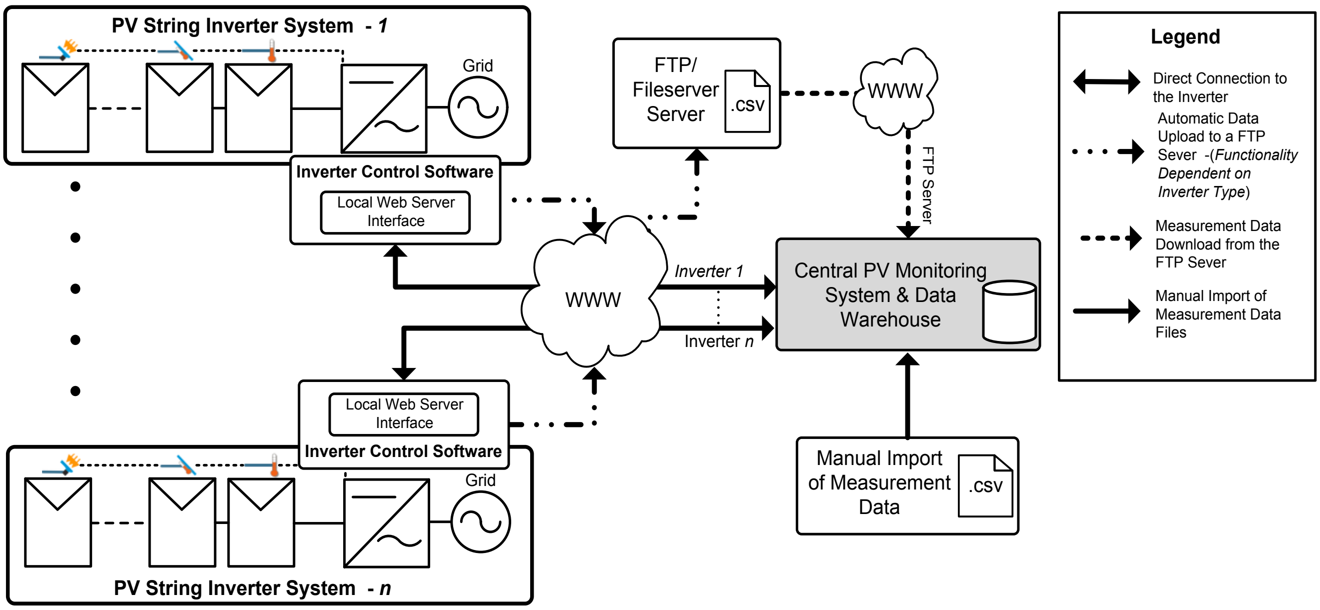

Fig. 1 Operation concept and data flow of the PV monitoring system

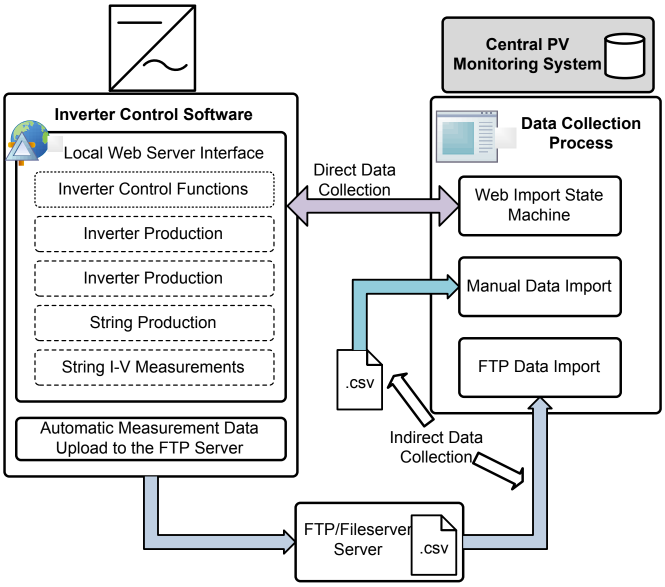

Fig. 2 Data collection modes. 1) Direct data collection - the monitoring system connects directly to the PV inverter web server interface. 2) Indirect data collection - by downloading the monitoring data from an FTP file server, where it has been previously uploaded by the inverter. 3) Manual data import - for PV systems that do not have have internet conectivity.

1. Direct Data Collection from the Inverter

In this data collection mode the monitoring system is directly connected to the PV inverter through an internet connection and is able to periodically retrieve the measurement data from the inverter. This mode is possible only for inverters which have a local web server interface implemented in their control software, which is the case for most new generation commercial inverters.

Such a local web server interface typically allows full or partial control and parameterization of the inverter as well as visualization and export of the various measured system values. The PV monitoring system connects to this web interface and extracts the relevant measurement data by means of a state machine (denoted as *web import state machine* in Fig. 2), which is able to navigate and control the web interface of the inverter.

The operation of the web import state machine is presented in Fig. 3, and has the purpose of connecting to the inverter web interface and transferring the data measured by the inverter to the central monitoring system. This is achieved by emulating the actions of a user, logging into the web interface of the inverter system and downloading the data on a regular basis. This feature is used in case the inverter has no automatic uploading of the data to an FTP server or other data warehouse system.

There are two main advantages to this data collection mode, firstly by connecting directly to the inverter web interface all parameterization and control options are also available to the PV monitoring system, which can take an active role in the operation of the PV system if necessary.

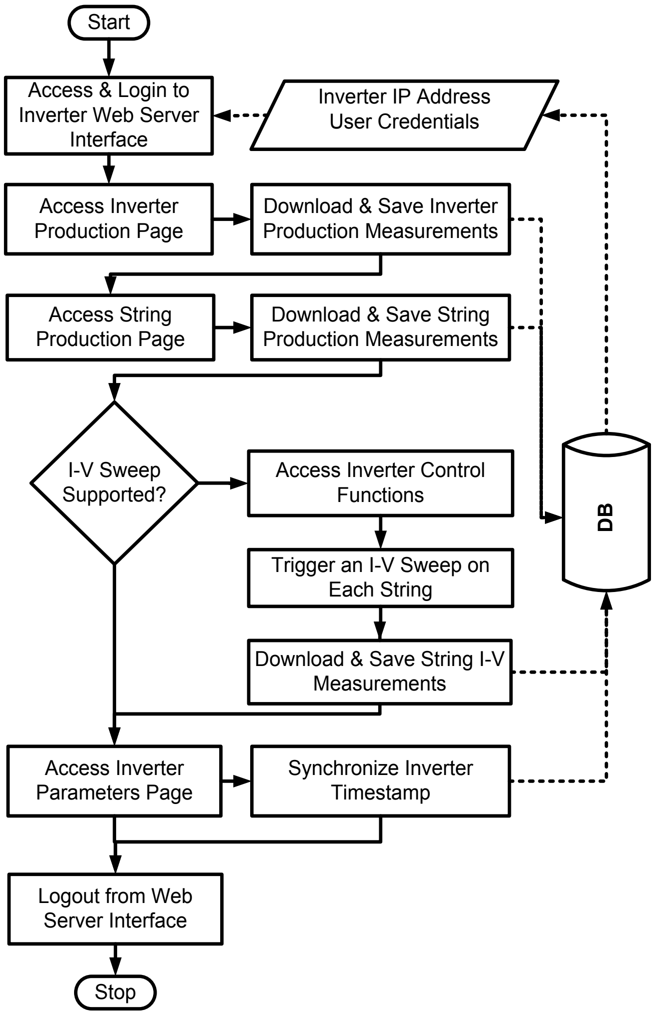

Fig. 3 State machine of the direct control and monitoring process of the PV inverter through its local web server interface.

Examples of active control actions performed by the monitoring system on the inverter are: triggering an I-V measurement (if it is supported by the inverter software), triggering a data upload, or synchronizing the inverter internal clock.

Another advantage of this mode is that inverter status and measurement data can be accessed in near real time, as they are updated on the inverter.

Currently the web import state machine is implemented for controlling the Danfoss TLX Pro web interface, and needs to be developed for every inverter type separately, since the web interface structure is different.

2. Indirect Data Collection

If the PV inverter has no internet connectivity the measurement data files can be downloaded manually from the inverter and then imported by the monitoring software into the data warehouse.

Most new generation solar inverters and commercial monitoring systems have internet connectivity and the option to regularly upload their measurement data to a FTP fileserver or data warehouse.

If the automatic FTP server upload feature is enabled in the inverter, then the monitoring software will synchronize periodically with the FTP server and download the data to the central database.

This data collection mode has the advantage of simplicity, since it does not require additional implementation of a web import state machine.

One limitation of this mode is that the measurement data is not uploaded immediately to the FTP server; there is a fixed update interval, which can be hours, or minutes, depending on the inverter type and its configuration. This might be of importance if “real-time” update of the production data is required.

A. Data Warehouse

The data collection process is a fundamental element of the PV monitoring system. Equally important is the data warehousing of the measurements in a unified format that allows efficient data mining, analysis and export of the data. In this regard the data warehouse of the monitoring system was developed on the Microsoft SQL Server platform, which is a high performance *relational database management system* capable of managing large amounts of data.

The data warehouse model consists of several data structures designed for organizing and storing the monitoring data. These structures can be divided into two logical groups: one group for organizing the information about the monitored PV plants and related hardware; and a second group designed for storing the actual measurement data, and optimized for fast data access and data mining.

When a new PV plant will be supervised by the monitoring system, the operator has to provide specific information and parameters about the plant configuration and hardware, as summarized in Fig. 4.

For each PV inverter installed in the plant the IP address and user credentials need to be specified in the monitoring software. Similarly the datasheet parameters for each PV module type present in the plant, along with the each array/string configuration, geographical location and mounting types have to be programmed into the monitoring software. These parameters will be later used for modelling the performance of each PV inverter system and for diagnostic purposes.

Unique ids are generated for each inverter and physical PV string or array, and are used to organize the data and to efficiently search and find specific inverter and string/array measurements using the Structured Query Language (SQL).

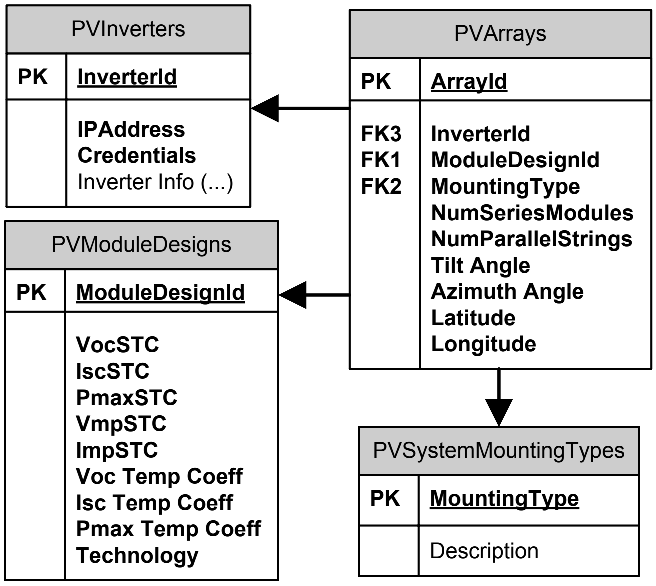

Fig. 4 Data structures containing information the PV plant configuration and hardware parameters that need to specify when a new PV plant will be monitored.

The second group of data structures illustrated in Fig. 5 is designed to store three main types of PV measurements. The first type of data structure manages production measurements of the PV generator (string or array depending on the configuration of the system and connection to the inverter input), such as average MPPT current, voltage and optionally ambient conditions alongside the averaging interval. These types of measurements can be used to check the performance of the PV generator by comparing them with values estimated by a performance model [13], as was done in [14].

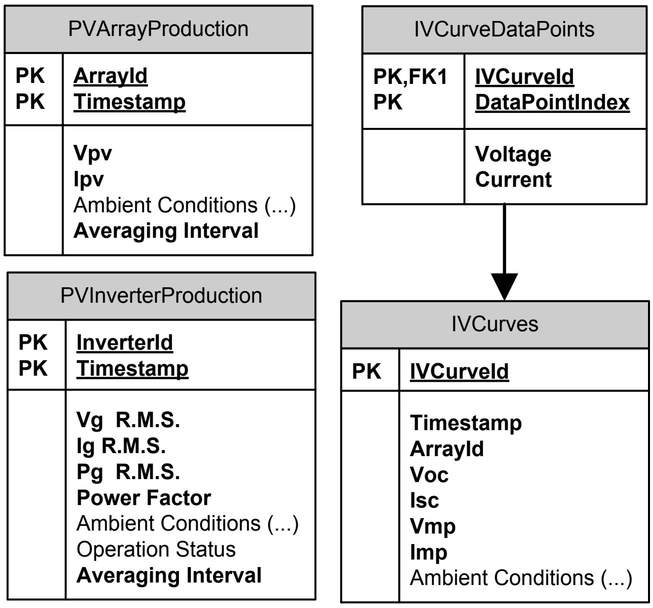

Fig. 5 Data structures for storing production measurements from the PV generator and from the inverter as well as I-V characteristic curve measurements.

The second type of data structure was designed to store PV inverter measurements, such as average ac power, voltage, current and power factor. The inverter production measurements, combined with the PV generator measurements can be used to assess the performance and efficiency of the inverter and detect faults by comparing them with nominal values obtained for example from an empirical inverter performance model [15].

Optional ambient conditions and inverter status parameters can be included as well and can be useful in diagnosing problems in the inverter.

The third type of PV measurements stored, are the I-V characteristic curves of the PV generator. As was mentioned previously, the Danfoss TLX Pro inverters (for which the monitoring system was initially designed) are able to measure the I-V curve of each PV generator connected to one of its dc inputs. The I-V curves provide more information about the condition and performance of the PV generator than average dc current and voltage measurements resulting from the MPPT. These curves can be used to implement advanced condition monitoring functions, such as detecting partial shadows affecting the PV generation [6], detecting degradation of the electrical connections, characterized by an increase in series resistance [7] or other of faults manifested by a decrease in PV generator performance [14].

All three types of PV measurement data structures are assigned ids identifying the PV generator or inverter for which they were measured. Also each measurement is assigned a timestamp at which it was measured by the inverter.

A problem that can appear when collecting monitoring data from several inverter and/or PV plants is to synchronize the timestamp of the measurement data. This can be an encumbrance when analyzing and comparing production data from different inverters/plants.

In this regard we propose a simple timestamp synchronization mechanism based on the web import state machine functionality which will be detailed next

B. Synchronization of Measurement Timestamp

Considering that different systems are measuring and recording the data, it must be noted that every system has its own timestamp. When the data is entered into the database, the timestamp entered is the timestamp recorded by every separate inverter. In this situation it is difficult to precisely synchronize the internal clock of each inverter in a PV plant or across several plants. Some inverter manufactures provide the option to synchronize the internal clock of the inverters in the same plant, but the problem is still present if monitoring several plants (that cannot synchronize between them) or when employing equipment from a different manufacturer.

Another problem that can appear is that if the inverter internal clocks are once synchronized, the time setting may drift in the course of time. In the diagnostics of PV systems it is essential to know the plane-of-array (POA) irradiance. If not all the arrays are equipped with irradiance sensors, the irradiance can be calculated based on values obtained from other sensors nearby. In order to do this, the instance of sampling must be the same for all sensors, or at least it should be known the exact time difference between them. For this purpose we developed a simple timestamp synchronization mechanism, depicted in Fig. 6.

The monitoring software periodically acquires the current time of every inverter and besides that, at the same instance it saves the time of the central computer. Using this method, the synchronization can be made between the inverters in every instance and thus the measured meteorological data can be accurately reconstructed.

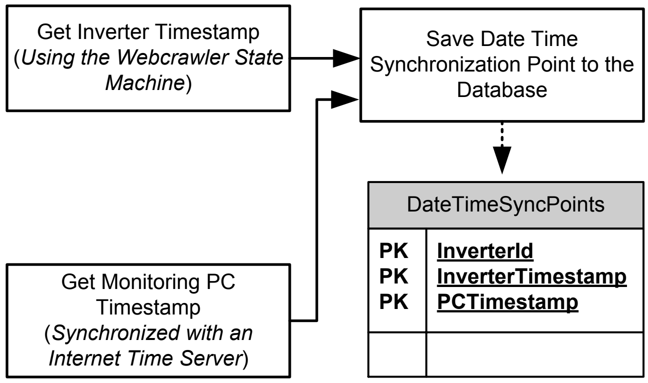

Fig. 6 Timestamp synchronization process between one of the PV inverters and the monitoring system.

Since all the data is stored in one single database, it is easy to archive it or use backup systems to securely save the data in case of malfunction of the system. The database management software has features such as mirroring or saving logs for reconstructing the database in case of hardware failure. This can add extra security to the gathered data.

III. STUDY CASE

The centralized PV monitoring system has been put into practice and tested at Aalborg University, Denmark. The system monitors two PV plants, depicted in Fig. 7, a smaller one (1.9 kWp) located at Aalborg University and second plant (85 kWp) located at a distance of about 20 km from the monitoring computer; the connection between them being realized through the internet.

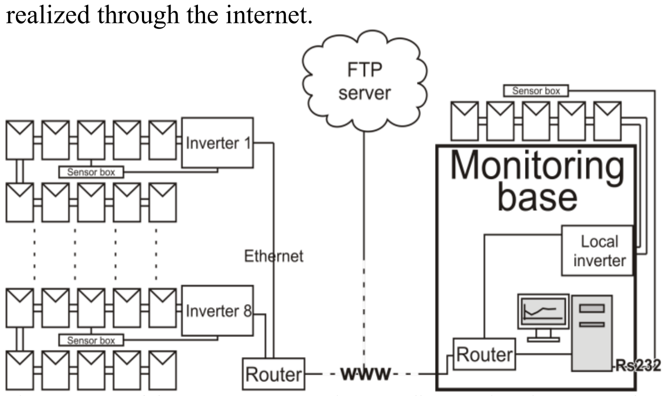

Fig. 7 Layout of the test system operating at Aalborg University, Denmark.

Table II Description of the experimental monitoring system

	Plant 1	Plant 2
Power rating	1.9 kWp	85 kWp
Sensors (irradiance + temperature)	Connected to the monitoring system through serial port	Connected to every inverter
Connection	Internet+ serial	Internet
Mounting type	Rooftop+ facade	Rooftop

The smaller PV plant (Plant 1) consists of two PV string of polycrystalline modules connected to a Danfoss TLX Pro inverter. The ambient conditions (POA irradiance, module and ambient temperatures and wind speed) for this system are being measured by a separate sensor system with higher sampling frequency connected through serial port directly to the monitoring system PC.

The larger PV system (Plant 2) consists of eight PV inverters connected to rooftop PV arrays (left side of Fig. 7). The inverters are rated from 6 kW up to 15 kW, each equipped with POA irradiance and module temperature sensors.

In this plant the PV modules are of two different technologies: one array of thin film modules (2875 W rated power), and fifteen arrays of polycrystalline silicon module adding up a total of ~85 kWp. Two arrays are mounted on the facade of a building, whilst the rest are roof mounted at different inclination angles.

The parameters of the experimental system are summarized in Table II.

All inverters are configured to log their production measurements (with one minute averaging period – minimum interval) and automatically upload them to a FTP server (each hour – minimum interval). The production data is later collected from the FTP by the monitoring software, operating in indirect data collection mode.

Additionally I-V curve measurements are performed by each inverter every fifteen minutes, which are collected by the monitoring system operating in direct data collection mode, as described in the previous sections.

IV. RESULTS

The centralized PV monitoring system has been running for half a year and some of the measurements and results are presented next.

The production measurements are plotted in two different graphs. After entering the desired date and selecting the inverter(s) from which the production data should be plotted, the yield of the strings is plotted in one graph (top of Fig. 8). The production of the whole inverter and the daily energy produced is plotted in another graph as shown on the lower part of Fig. 8.

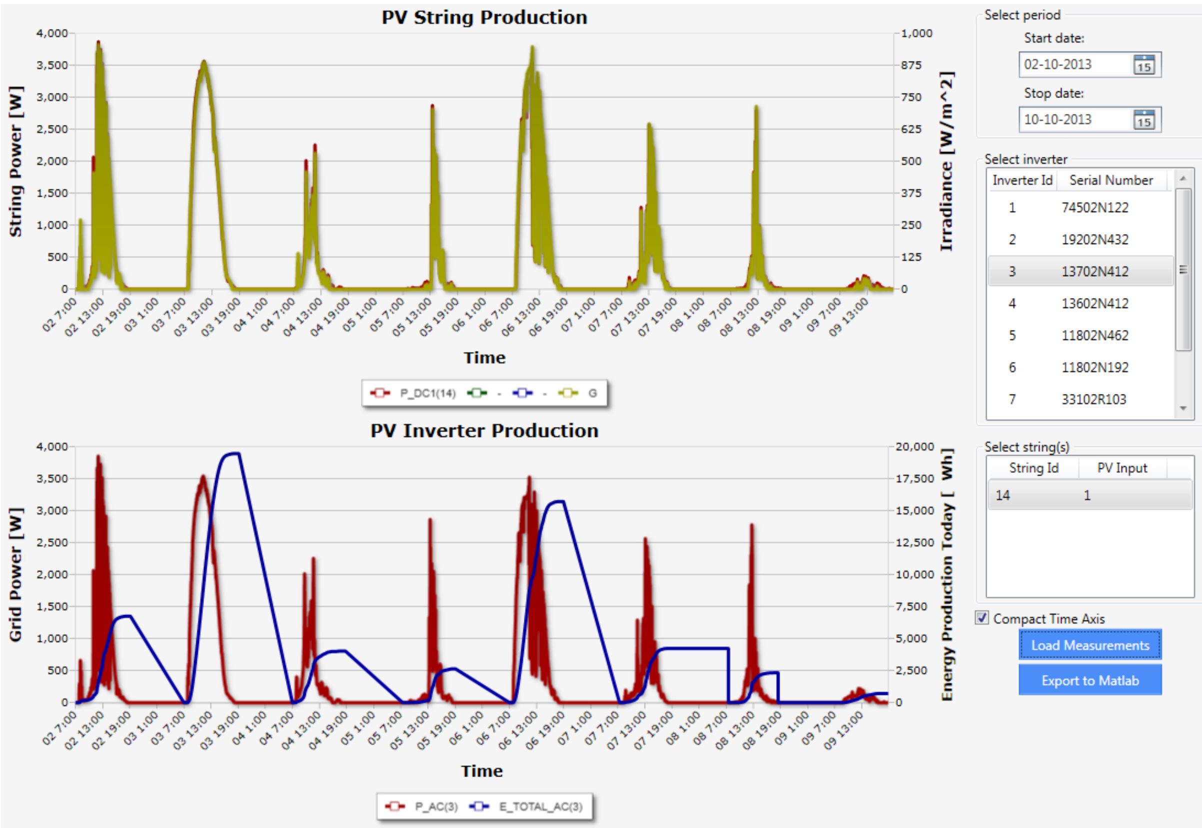

Fig. 8 Production data visualization for a week in October 2013; Upper plot represents string production- yellow: irradiance, red: string dc power; lower plot illustrates inverter production: red: inverter ac power; blue: energy produced on the specific day.

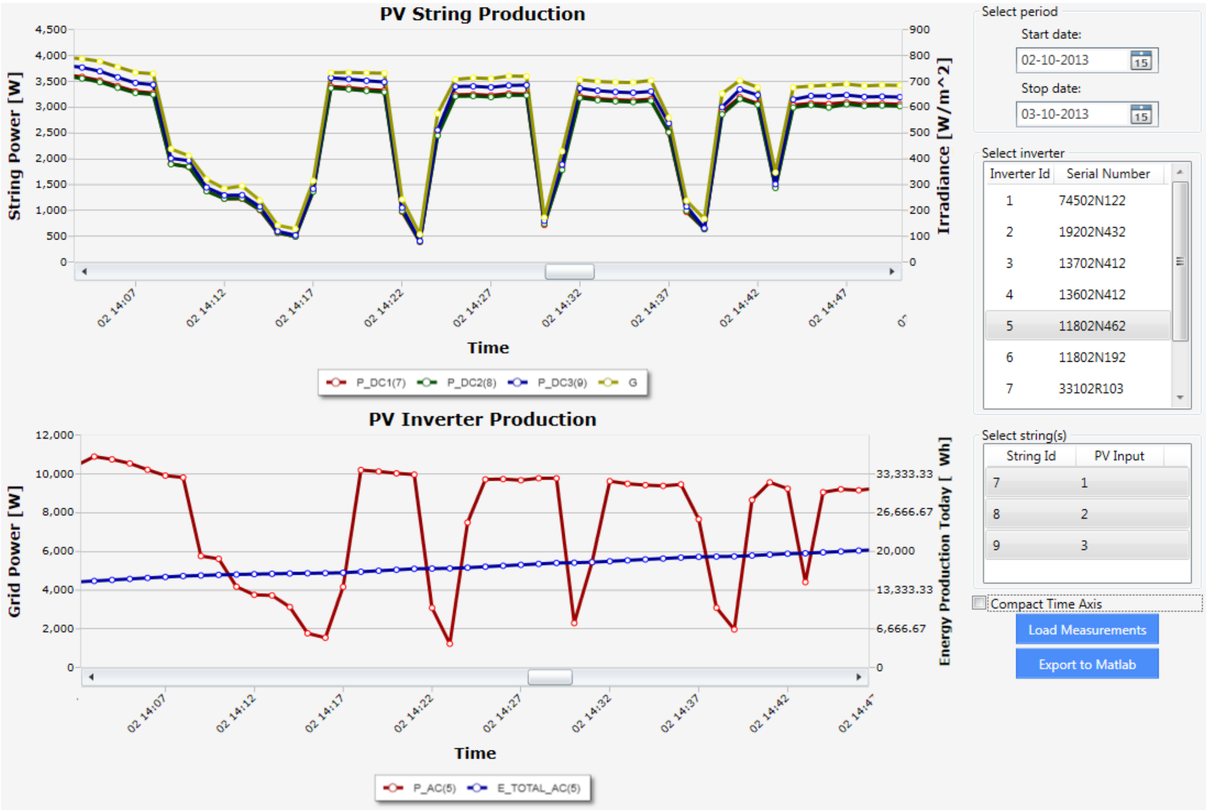

Fig. 9 Detailed view of the production on a minute level. Upper plot: yellow – irradiance; red – string 1 production; green -string 2 production; blue - string 3 production; lower plot: red-inverter ac power; blue - energy production.

There is the possibility to view the production of a longer period, in retrospective, or have a zoomed-in view for a more detailed level (Fig. 9). In Fig. 9 three arrays are connected to the selected inverter, two of them having 16 modules per string and one has 17 PV modules. It can be seen from the figure that the third string (upper plot of Fig. 9, blue line) produces more power than the other two strings (marked with red and green). This is expected behavior, since the third string contains 17 modules, whilst the first and second strings contain only 16 PV panels. The average POA irradiance for this system is shown with yellow on the right axis.

The production data visualization gives a quick overview of the state of the plant. Other performance indicators can also be calculated, but a separate diagnostic module needs to be implemented. This module depends on the demand and the specific application. If quick data processing is needed there is the possibility to export the data to Matlab.

A more in-depth analysis can be done by looking at the I-V characteristic curve of each PV string. Theses curves hold valuable information about the condition of the PV string additional to their power performance. They can be explored and visualized using the graphical user interface of the monitoring system as in Fig. 10.

More than one I-V curve can be loaded into the graphical user interface at the same time, so a comparison can easily be made between them. Changes in parameters such as series or the presence of partial shadows can be detected.

For the purpose of exemplifying the potential benefit of monitoring the I-V characteristic of the PV generator additional to production measurements, as well as the capabilities of the monitoring system we conducted an experiment on the small PV system (Plant 1) located at Aalborg University.

First the monitoring system collected I-V measurements of string 1 under normal operation (example blue I-V curve in Fig. 10) for several days. Next we covered a small part of the string in order to emulate the presence of a partial shadow the monitoring system acquired I-V measurements over a period of several days. Since the PV modules are equipped with bypass diodes, the presence of the partial shadow is visible in the I-V curve of the PV string as can be observed in Fig. 10 (red I-V curve). Lastly we simulated an increase in the series resistance of the PV system by connecting a resistor in series with the PV string (green I-V curve in Fig. 10). The effect of increased series resistance is visible in the slope of the I-V curve near the open circuit voltage, as can be observed by comparing the red and blue I-V curves in Fig. 10.

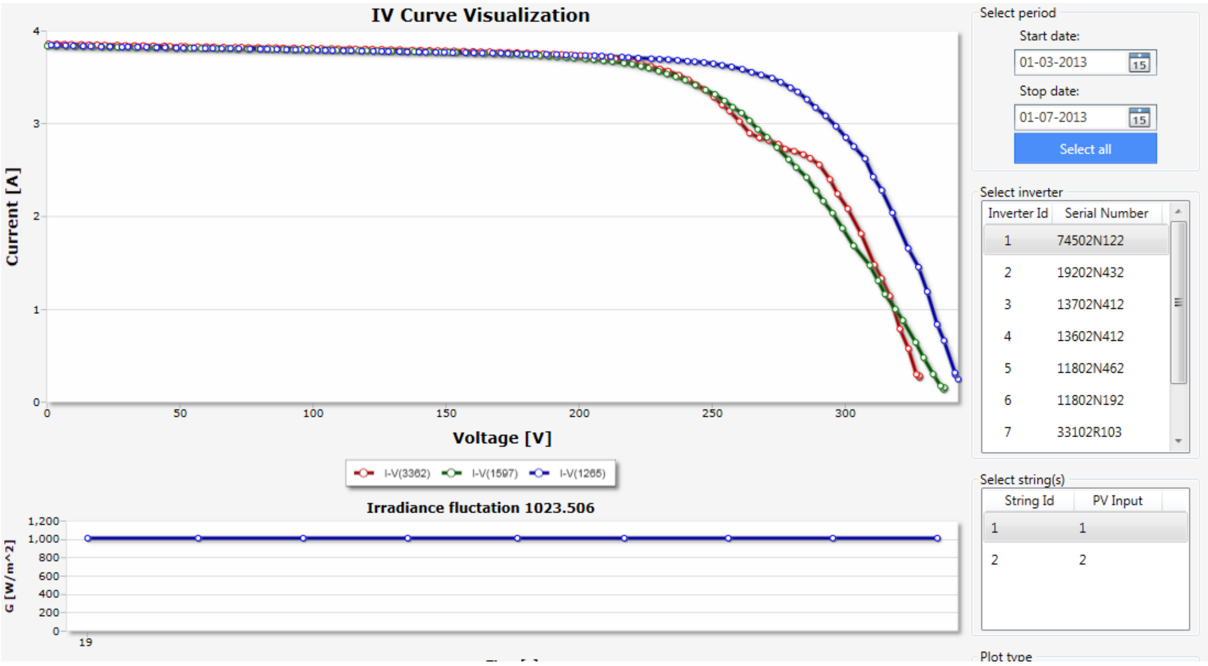

Fig. 10 I-V Curve measurements visualization. blue: I-V curve measurement 1 – no fault; red: I-V curve measurement 2 – indicates the presence of a partial shadow; green: I-V curve measurement 3 – indicating increased series resistance. The I-V curves displayed are measured at ~1000 W/m^2 and ~20 ºC conditions.

If by comparison we would only look at the maximum power produced by string 1 in these three scenarios it would be more difficult to detect that there is a fault affecting the system and which type it is.

V. CONCLUSIONS

In the present paper the main operation principles of a low cost and flexible centralized PV monitoring system have been described, together with a study case of the system implementation for Danfoss TLX Pro inverters.

The monitoring system relies on the measurement capabilities of the inverter and no additional hardware is required. The measurement data is collected over the internet directly from the inverter or from an intermediate data warehouse.

The main advantages of the proposed monitoring system are the low cost, flexibility and potential for implementation on other types of inverter systems, and the capability of monitoring the I-V characteristic of PV string/array in the plant by taking advantage of the PV sweep functionality of the inverter.

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