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Online Remote Monitoring and Diagnosis of Photovoltaic Plant

R.Hariprasad[1] and R.Chitra[2]

[1,2] Embedded System Technologies
Chennai, Tamil Nadu, India

***Abstract*—This paper deals with the metrological management of an acquisition system that has been developed for monitoring an experimental photovoltaic (PV) plant. The acquisition system has been conceived for comparing the performance of different PV technologies and for verifying the nominal specification of the PV modules. It also allows remote access through Ethernet in order to measure the I-V characteristics at different levels of lightning and the dynamic behaviour of solar cells using light or current pulses. The system tries to identify anomalies as soon as possible with respect to the normal behaviour expected in the operation of photovoltaic plant. Once an anomaly is detected, an automatic and intelligent diagnosis process is started in order to investigate the possible causes.**

***Keywords*— Photovoltaic Plant, I-V characteristics,Anomaly, Diagnosis.**

I. Introduction

Multi-channel measuring systems are wisely employed in different fields, such as in the monitoring of industrial processes, environmental pollution and energy-generation plants. A series of common characteristics can be high-lighted for these systems, which are the following:

1) heterogeneous nature, since different quantities have to be acquired;
2)employmentof software acquisition and processing algorithms, which have a large impact on the final measurements these system provide.

While the mentioned characteristics make these systems very flexible and suitable for different scenarios, they maypresent problems with traceability and quality assurance. Common calibration procedures that require measuring devices to be moved to a calibration lab oratory cannot be easily adopted, since these devices are usually deeply integrated into the monitored system. Furthermore, the calibration results might not always be representative of the behavior of the measuring chains in operating conditions and the effects of the software components are not taken into account.
This approach is based on a remotely-exercised monitoringprocedure: a traveling standard is sent to the site where the system under calibration operates and the calibration proceed- re is remotely managed by interacting with the standard and the system under calibration through the network. For this purpose, a network-capable traveling standard must be available to acts as a reference for the quantities measured by the monitoring system.

Usually small and mid-sized photovoltaic plants are located in rural areas and typically they operate unattended. Some technicians are in charge of the supervision of these plants including their usual maintenance and, if an alarm is automatically issued, they try to investigate the problem and correct it. These technicians tend to live close to the geo-geographical area of the plant but they need some time to attend an alarm. In this context it is necessary to have the appropriate tools available that can continuously and remotely monitor the normal behavior of the plant and diagnose the causes of possible anomalies resulting in losses of production or damaging some components of the plant.However, in some cases the behavior of the plant can be slowly degrading over important periods of time without over passing any threshold and without issuing any warning of this situation.In many cases in order to detect anomalies either some specific expert knowledge is required to analyze the behavior of the solar plant, or some knowledge is desired to be automatically extracted from its operation, or bothdesigned to work in real-time whose main contribution in this field is an architecture that integrates in a unique framework the capability of data acquisition, anomaly detection and diagnosis of an unattended solar power plant.

II.REMOTE MONITORING

The performance indexes that can be employed to characterize a photovoltaic plant can be sub divided into two main categories: instantaneous and cumulative indexes.Among the instantaneous indexes, the ones of main concern are the PV module efficiency ηPV and the dc-ac efficiency of the power conditioning unit (PCU) ηPCU, ie.,

$$\eta \mathrm{PV} = \frac{\mathrm{P_{DC}}}{\mathrm{G.C}} \; ; \; \eta PCU = \frac{P_{AC}}{P_{DC}}$$

Where P_{DC} and P_{AC} are the dc (upstream of the PCU) and ac (downstream of the PCU) powers, G (in watts per square meter) in the solar irradiance, and S (in square meters) is the actual plant area. These definitions assume that the behavior of the maximum power point tracker algorithm of the PCU is ideal. The estimation of these indexes requires the measurement of voltage and current signals upstream (DC) and downstream (AC) of the PCU, of the solar irradiance G, and of the module temperatures, thus allowing the estimated indexes to b e referred to the Standard Test Conditions (STC): irradiance of 1000 W =m/2 and cell junction temperature of 25°C.The wind speed is also measured because it affects the module temperature and, in turn, the efficiency, which depends on the cooling of the PV modules.Other measured quantities are temperature and humidity of the external environment and of the environment inside the site where the monitoring system is installed. Table I summarizes the quantities that are measured by the monitoring system, which has been developed in order to meet the requirements indicated in the same table in terms of range, sampling rate and maximum allowable uncertainty.

In the developed monitoring system, the AC and DC voltages are conditioned through specifically designed circuits. These circuits essentially act as attenuators and ensure the galvanic insulation between the plant and the acquisition system, which employs three data acquisition boards installed inside a PXI chassis. The AC and DC currents are instead sensed by means of thru-hole Hall-effect sensors, which provide an output voltage proportional to the input current and ensure the galvanic insulation. The PXI chassis also embeds a PC-board with networking capabilities, which allows the acquisition system to b e remotely managed through the LAN. Custom software, which has been developed in Lab VIEW, acquires and processes the input signals of the three acquisition boards. The version of Lab VIEW used in this system allows the development of a remote user interface.

Table I

Measured Quantities	Range	Minimum Sampling rate (kSa/s)	Maximum uncertainty
DCV	(100÷450) V	1	1%
DCI	(0.5÷6) A	1	1%
ACV	230 V_{rms}	25	1%
ACI	(0.5÷ 8) A_{rms}	25	1%
Global and module irradiance	(0÷1500) W/m^2	1	5%
Module temperature	(-10÷ +80) °C	1	1°C
External temperature and humidity	(-20÷ +40) °C	1	1°C

To monitor the AC current and thecalibration of the corresponding measuring chain, the thru-hole Hall-effect sensor is installed into the sealed part ofthe plant. The sensor allows a spare wire that crosses its hole to be employed as the current calibration input. Such an input, which does not interact with the plant in a significant way, remains op en during the normal operation ofthe plant (switches SW1 and SW2 closed), while it is usedto stimulate the sensor with a known current during thecalibration of the monitoring system (switches SW1 andSW2 op en). The voltage sensor is immune to this problemand can therefore be installed outside the sealed part of the plant, as shown in the Figure 1.Further details about the monitoring system can be found in [4].

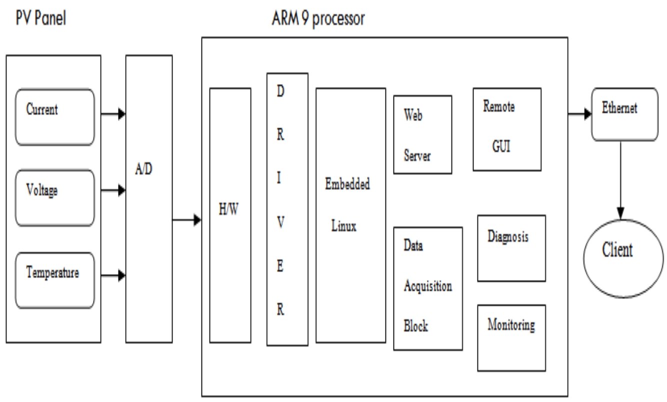

Fig.1. Block diagram of remote monitoring

III. METROLOGICAL MANAGEMENT OF THE MONITORING SYSTEM

A. *Calibrator architecture*

The device that allows the described monitoring system to be remotely calibrated has to act as a reference for the measured quantities and has to exhibit networking capabilities, in order to be controlled by a remote calibration laboratory. Another important requirement this device hasto meet is related to the uncertainties of the quantities it provides, which have to be lower than the uncertainties of the system under calibration (see Table I). During the design phase, the device has been essentially conceived as a program-
Able source of DC and AC voltage and current signals; furthermore, it has ben equipped with standard sensors for temperature and irradiance.

The control board, which is based on a micro controller, embeds a double-channelvoltage generator. Each channel of this generator includesa DDS chip (Analog Devices AD9833), which provides asinusoidal signal with variable frequency and phase; thissignal is amplified and then employed as the reference voltage of a multiplying Digital-to-Analog Converter (DAC:Texas Instruments DAC8811). The

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communicates with the other devices through SPI interfaces, sets frequency (from DC to 2 : 5 kHz) and phase of the generatedsignals by sending a control word to the DDS generatorsand sets the amplitude of the output signals (from 0 Vto 10 V pp) by sending the input code to the multiplying DACs. The calibrator is networked to a personal computer via an RS-232 serial interface. A first prototype of calibrator was equipped with an embedded PC, thus obtaining a full autonomous devicedevelopment instead employs the PC board embedded inthe PXI-chassis of the monitoring system under calibration. One should note that this solution, which allows argued system to be arranged, can be adopted in almost all the situations where a data acquisition system has to be calibrated, since these systems are usually hosted by a PC.

The output board (see Figure 3) is essentially a phantom-power generator, which provides the high voltage and current signals applied to the inputs of the system under calibration. The AC high-voltage generator includes an audio power-amplifier (ST Micro electronics TDA 2052), which is fed by one of the output signals of the control board. The output of this amplifier drives a step-up transformer with a nominal turns ratio of 40, which providesthe AC output voltage in the frequency range of 50 Hz to 2: 5 kHz. The DC output voltage is obtained by rectifying the transformer output, thus obtaining a continuous voltage up to 500V.The current generator is based on a high output-current operational amplifier (Burr-BrownOPA501) that is configured as a Trans conductance amplifier. The voltage drop across the shunt resistor RS(0 : 5 -; 50 W) is used as a reference for the feedback signal of the amplifier.

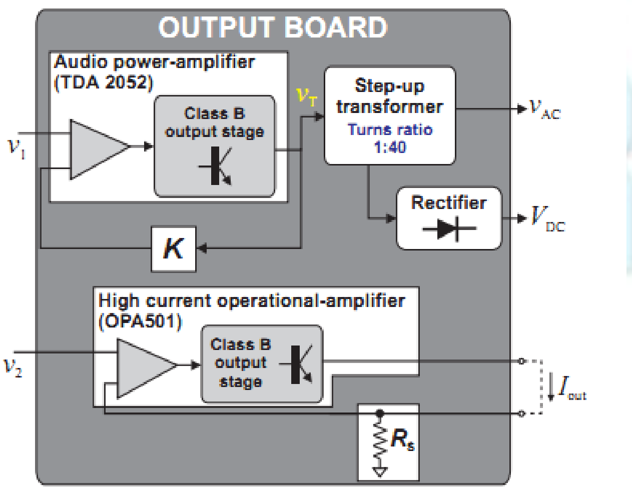

Fig.2. Block scheme of the output board.

The AC output voltage in the frequency range of 50 Hz to 2: 5 kHz. The DC output voltage is obtained by rectifying the transformer output, thus obtaining a continuous voltage up to 500 V. The current generator is based on a high output-current operational amplifier (Burr-BrownOPA501) that is configured as a Tran'sconductance amplifier. The voltage drop across the shunt resistor RS (0: 5 -; 50 W) is used as a reference for the feedback signal of the amplifier. This circuitry allows currents to be generated from DC to 2: 5 kHz with amplitude up to 18 A.

IV. ARCHITECTURE OF ISDIPV

The main characteristics of an intelligent system, named ISDIPV, of which the objective is the automatic detection and diagnosis of anomalies and faults that can occur in a photovoltaic (PV) solar power plant. The system tries to identify anomalies as soon as possible with respect to the normal behavior expected in the operation of a photovoltaic plant. Once an anomaly is detected, its possible causes are investigated automatically and diagnosed. The events detected and their diagnoses are issued to the personnel in charge of the plant.ISDIPV is able to collect information in real-time from different types of sensors installed in a PV solar plant and to pass it through its different modules in order to analyze if this information includes some symptoms of anomalies that must be diagnosed.

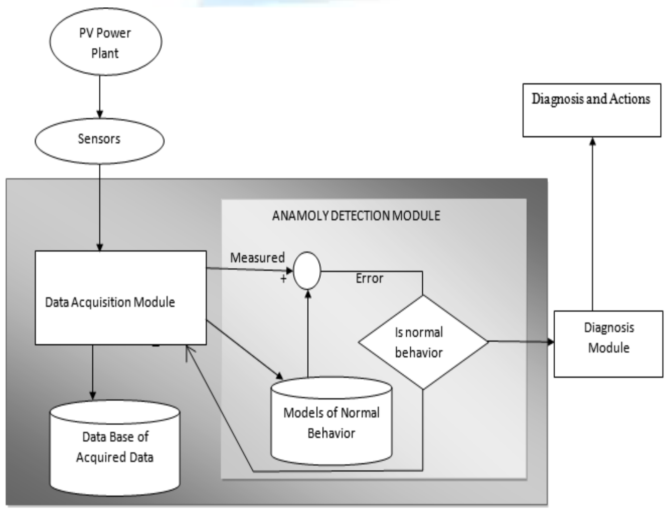

Fig 3. Architecture of ISDIPV

Data acquisition module: This allows for the collection of information coming from the different sensors installed at key points of the PV solar power plant. The information collected

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in real-time includes the following items: solar irradiation, ambient temperature and generated electrical power energy. This data is saved in a historical database.

Anomaly detection module: This module analyses all the data collected in real-time and tries to discover if they include some symptoms of anomalies. In order to do this, a set of models named "models of normal behavior" are used to predict the evolution expected for key variables representative of performance of the PV plant monitored. The models are fitted before they can be used as references of normal behavior. The models allow for the characterization of the typical relationships between a set of input variables and one or several output variables for all the possible working conditions considered as normal performance at the plant being monitored. Once the models are fitted, they can be used in real-time to compare their estimation to the real values of the variables predicted and, if a relevant deviation is observed, the normal performance expected is violated and an anomaly is discovered.

Diagnosis module: In the case that an anomaly is detected by the anomaly detection module, the diagnosis module will try to investigate its root cause and if possible, to suggest corrective actions. This module is based on a small expert system which processes the information about the anomaly detected and its symptoms. The expert knowledge is represented by common production rules with the format: If conditions Then conclusions and Also actions. The uncertainty is based on certainty factors associated to each production rule according to the results of the models and a previous FMEA (Failure Mode and Effects Analysis) The expert system reasons, as is usual in the diagnostic field, in a forward-chaining mode from
symptoms to diagnoses.

ISDIPV includes 2x10 models of normal behaviour inside its anomaly detection module, half of which are based on LTF techniques and another half based on MLP. 'Figure 4' shows a functional scheme of the anomaly detection module and its main components. The next subsections describe the process followed to build the normal behavior models and how they are used by the anomaly detection module.

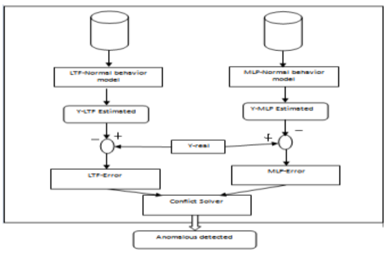

Fig.4. Anomaly Detection

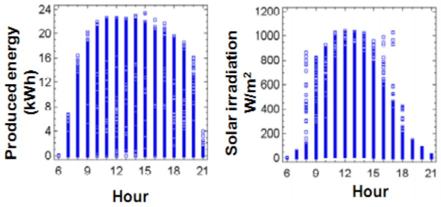

Fig 5. Profiles of generated electrical energy and solar irradiation during the period of time analyzed.

'Figure 5' shows the relationships between produced energy, solar irradiation and temperature respectively. This suggests that a possible model can be developed among these variables. In order to enhance these relationships a new analysis was performed dividing the data of the period analyzed into two groups corresponding to environmental conditions close to winter and summer respectively. This made it possible to narrow the areas observed in 'figure 5' and to create a more robust modeling of the existing relationships. Energíavs. Irradiation

V. DIAGNOSIS MODULE AND ISDIPV INTERFACE

The main goal of the diagnosis module of ISDIPV is the investigation of the root causes of the detected anomalies. The diagnosis module has the typical structure of an expert system including a facts database with static information about the main characteristics of the PV solar plant and dynamic information corresponding to on-line detected events and measured variables. These events correspond to the outputs from the anomaly detection module with their associated certainty factors. Also, the diagnosis module has a knowledge base where the knowledge required to investigate the possible causes of the detected anomalies is stored. The knowledge is represented by production rules using the typical schema if conditions then conclusions. These rules were obtained from an FMEA (Failure Mode and Effects Analysis) of the main malfunctions of the PV solar power plant and experience of the plant. As an example, an energy production system failure could be diagnosed as present in PV_1 when:

- an anomaly has been detected by the model that predicts the produced energy of PV_1 as a function of solar irradiation and ambient temperature of PV_1.
- an anomaly has been detected by the model that predicts the produced energy in PV_2 as a function of the produced energy in PV_1.
- no anomaly was detected by the model that predicts the produced energy of PV_2 as a
- function of solar irradiation and ambient temperature of PV_2.

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- no anomalies were detected in the sensors of solar irradiation and ambient temperature.
- Similar reasoning can be asserted for the detection of a failure in the energy production system of PV_2.
- no anomaly was detected by the model that predicts the produced energy of PV_2 as a
- function of solar irradiation and ambient temperature of PV_2.
- no anomalies were detected in the sensors of solar irradiation and ambient temperature.
- Similar reasoning can be asserted for the detection of a failure in the energy production system of PV_2.

VI .RESULTS

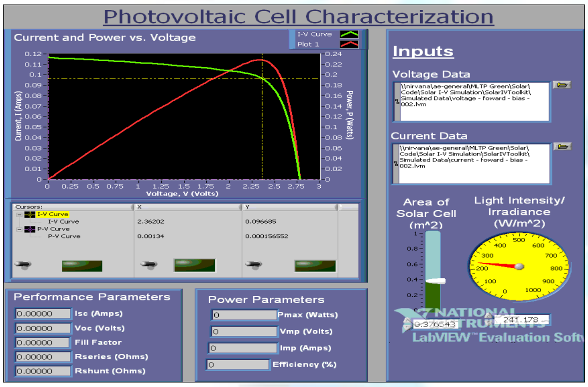

Fig 6 .Pohtovoltaic cell

Fig 6 shows the photovoltaic cell characterization. The IV and PV curve describes the characteristics of the cell. The short circuit current (I_{sc}), open circuit voltage (V_{oc}) and the fill factor are the parameters that describes the performance of the photo voltaic cell. The efficiency of the photovoltaic cell depends on the incident light intensity and the area of the photovoltaic cell.

VII. CONCLUSION AND FUTURE WORK

The LUT obtained in the calibration phase offers a strictly controlled light flow on DUT by monitoring the light flow during testing any other variation of light flow will be compensated; the uniformity of PV cells lighting is monitored avoiding artifacts due to the light flow variation during measurements; by monitoring the cell temperature it is possible to made the correction of PV parameters; having two insulated signals acquisition channels the crosstalk is eliminated; by providing the possibility to customize the measurement gain of the signal amplifier, adapting the characteristics of this test bench at a large variety of PV cells and measuring structures becomes easy; by including an embedded web server, the test bench is ready to be immediately integrated into a network. Finally yet importantly, there is also the advantage of the very low cost of the test bench that makes it suitable for the market. The software applications allow studying the solarcells using the main tool – I-V characteristics. These characteristics are measured at different levels of lighting. Another study is the dynamic behavior of light or current pulses.

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