13th IMEKO TC4 Symposium
Remote monitoring and control of photovoltaic plants by means of GSM system

M. Gagliarducci, D.A. Lampasi, L. Podestà

Department of Electrical Engineering – University of Rome "La Sapienza"
Via Eudossiana, 18 – 00184 Rome, Italy
Phone: +39 06 44585543, Fax: +39 06 4883235, e-mail: alessandro.lampasi@uniroma1.it

Abstract - This paper describes a system to remotely monitor and control complex stand-alone photovoltaic plants. In normal conditions the developed system registers and reports the overall performances; in case of incorrect behaviors it seasonably informs the operators. Moreover through appropriate instructions sent by users it allows to change the configurations of the plant and the settings of the measurement system as well. Several means of communications are available due to the need to adapt the system to the different operative conditions. However for a more general and flexible implementation, the remote control is carried out through the GSM network and in special way exploiting the SMS (Short Message Service) feature.

I. Introduction

A photovoltaic (PV) plant is a complex system formed by several elements with the aim to transform in electrical power the electromagnetic radiation coming from the Sun. The correct behavior of the plant is related to the correct functioning of each single element.

Many configurations are possible for a generic PV plant. Especially the structure is different for stand-alone and grid-connected systems. To include a significant amount of conditions, a basic configuration was established. It consists in:

- a PV generator, namely the element that converts the solar radiation in electrical power;
- accumulators, which supply the power in case the PV power is too low;
- a charge regulator, with the aim to supervise the accumulator charge/discharge;
- the inverter, which converts the generated dc electrical power to ac electrical power;
- an ac load and a dc load.

Usually the charge regulator incorporates a MPPT (Maximum Power Point Tracker) that optimizes the power generation by changing the equivalent load.

A plant whit this basic configuration is representative of most of the stand-alone and not guarded plants. Usually these systems are constructed to supply electrical power to private isolated houses, radio station, street signs, water pumps, and so on.

The management of the plants is often uneasy because they are not connected to the electrical power distribution network and usually neither telephone lines nor other communication systems are available. Therefore it is necessary to individuate a communication system that allows the user to know the plant status. Moreover the same users should be able to operate remotely on the plant.

The proposed monitoring and control system for PV plants is able to manage several kinds of communication media:

- SMS on GSM system;
- Local Area Network (LAN);
- Internet;
- Point-to-point phone connection (PPP).

In our opinion the GSM system is the right choice for the general case. Indeed it allows to reach almost all the locations on the national territory with an affordable cost. The SMS service was favored, because it is remarkably simple and cheap.

The resulting structure of the system plants can be functionally divided in three sub-systems:

- the PV sensor cell (PVSC), which provides an estimation of the incident radiation on the PV generator and of the relative theoretical available electrical power;
- the data acquisition system, which measures the PV plant interesting input quantities, checks out possible malfunctions and monitors the overall performances; it is essentially based on the

FieldPoint^{TM} architecture;
- the transmission system, which manages communication from and to the measurement system.

As far as the operative principle of the measurement is concerned, the plant can be monitored by measuring the following relevant quantities: voltage, current and power supplied by the PV generator; the actual current received by dc and ac loads; power adsorbed by loads; accumulator voltage; voltage on the ac load.

The power produced by the generators compared with the theoretical value obtained measuring the short-circuit current of the PVSC: if the comparison is negative, a notice is sent. The same is for the power adsorbed by loads and for accumulator voltage that are compared with adjustable limits.

From the same measurements the maximum levels of some plant quantities and efficiency indices can be obtained; they provide information about the regular functioning of the PV plant.

Moreover users may operate on the PV plant, by sending remote commands.

II. The Photovoltaic Sensor Cell

The PVSC was introduced to estimate the incident solar radiation. The usage of PVSC is less expensive than other dedicated instruments such as the pyranometer. It is a standard PV cell with well-known properties.

The PV cells are devices which convert solar electromagnetic radiation absorbed by a semiconductor material, usually Silicon (Si), into electrical energy.

The covalent bond between adjacent atoms can be broken supplying a fixed amount of energy (1,1 eV [1]). The energy $E=hv$ of a solar emission photon is enough to break the covalent bond existing between two atoms when the wavelength λ of the electromagnetic radiation absorbed by the PV cell is less than 1,13 µm. It generates free electrons and holes that are able, moving to opposite directions, to participate to the current transport.

To obtain an electric current flow from the electron-hole couple movement, they have to move in an ordered way. By doping the silicon with phosphorus (P) or boron (B) atoms, p-type and n-type matched semiconductor are obtained. Due to the majority bearers' diffusion into the other type semiconductor, two different areas with opposite sign are created near the junction forming the so called depletion region. If the semiconductor is connected to an external circuit, the electrons and the holes generated by the absorbed radiation in the depletion region produce a dc current.

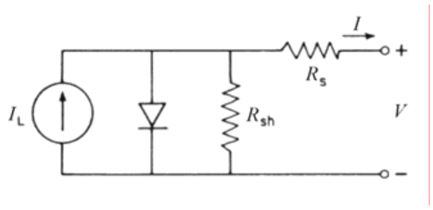


Figure 1. Equivalent circuit of a generic PV cell.

The resulting equivalent circuit [2] [3] is shown in fig. 1. It is a diode whose physical parameters are I_0 and n. In parallel there is a current generator representing the photogenarated current I_L. Accordingly, the characteristic equation of a generic PV cell is:

$$I = I_L - I_0 \left\{ \exp\left[\frac{q \cdot (V + IR_S)}{nkT} \right] - 1 \right\} - \frac{V + IR_S}{R_{Sh}} \tag{1}$$

The relative characteristic curves are shown in fig.2.

If the cell is short-circuited, a current I_{SC} can be measured. By expanding the exponential in (1) in Taylor series up to the first order and considering that $R_S << R_{Sh}$, I_{SC} is:

$$I_{SC} \approx I_L \frac{nkT}{nkT + qI_0(T)R_S} \tag{2}$$

In practical situation, the effect of R_S can be neglected, therefore it is possible to conclude that:

$$I_{SC} \approx I_L \tag{3}$$

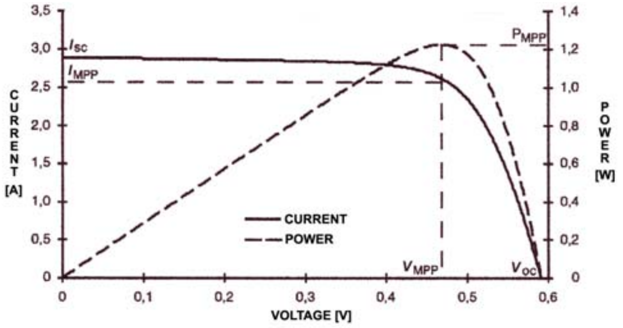


Figure 2. Voltage-current characteristic of a lighted PV cell.

The value of I_L depends on the intensity of the incident solar radiation G [W/m^2], on the cell area S [m^2] and on the responsivity R_{ph} [A·W^{-1}] [2]. Thus:

$$G = \frac{I_L}{R_{ph} S} \approx \frac{I_{SC}}{R_{ph} S} \tag{4}$$

This formula allows to estimate incident radiation on the PV generator from the measurement of the current produced by the PVSC, when it is closed on a negligible resistor.

The PVSC used in the measurement system is a PV cell in polycrystalline silicon produced and tested by ENI Eurosolare. The benchmark tests give a value for R_{ph} almost equal to 0,29 [A·W^{-1}].

The I_{SC} of the PVSC is obtained through the four-terminal measurement of the voltage on a 5 mΩ precision resistor [3].

G is also useful to evaluate the theoretical power W for a PV generator having efficiency η and total area S_{tot}:

$$W = \eta \cdot G \cdot S_{tot} \tag{5}$$

III. Data acquisition system

The most important elements in the data acquisition system are the FieldPoint™ modules provided by National Instruments. In particular the FP-2000 controller module and the FP-AI-100 data acquisition module were used.

The FP-2000 has an internal processor, a 16-MByte RAM and a 16-Mbyte ROM memory. It is able to perform stand-alone and real-time elaboration and control applications also in critical environments. It manages the functioning of the other modules connected with it. The communication with external devices is possible through a RS232 serial port and a RJ-45 connector for Ethernet Local Area Network (LAN).

The applications were developed with NI LabVIEW. The FP-2000 operating system features the LabVIEW RT engine (Real Time), which guarantees that every task has a fixed duration and especially cannot be stopped by other tasks.

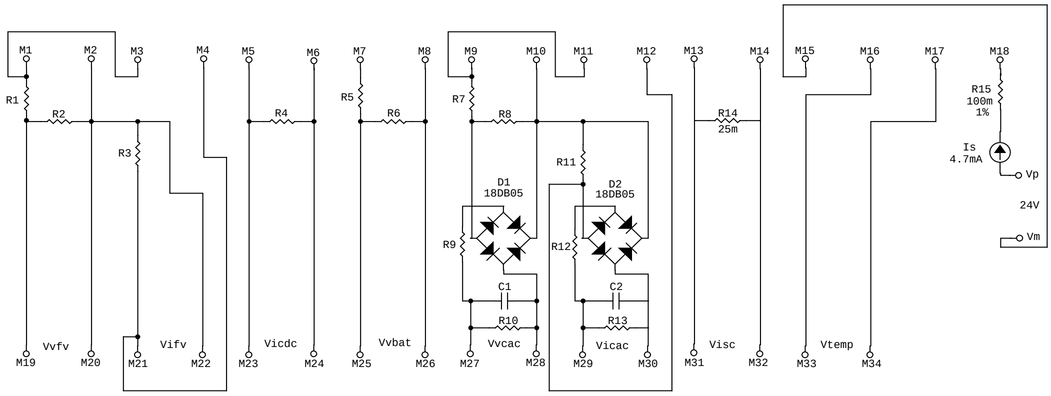


Figure 3. Circuit diagram of the SCC.

The FP-AI-100 acquisition module has eight channel for both current and voltage measurements. The range of measurable values can be set up independently on each channel. The maximum range is ±30 V for voltage and ±20 mA for current. Since these ranges are lower than most of considered quantities, an external signal conditioning is required. This is accomplished by the Sensor-Conditioning Card (SCC) shown in fig. 3. It is based on voltage dividers and current shunts. The influence of the SCC on the measurands and its power dissipation are negligible. The resistors R_1, …., R_8, along with R_{11} and R_{14} have to be dimensioned according to the voltage and current levels of the PV plant.

The values acquired from all the FP-AI-100 eight channels are refreshed and communicated to the controller at least every 2,8 ms (and it is the best performance for the FieldPoint^{TM} family). For this reason each input has a 170 Hz low-pass filter. It is evident that the ac quantities can't be directly measured. To overcome this problem, the SCC includes appropriate diode-bridge rectifier circuits.

Fig. 4 shows the connection terminals (*M1*, …, *M14*) between the PV plant and the SCC.

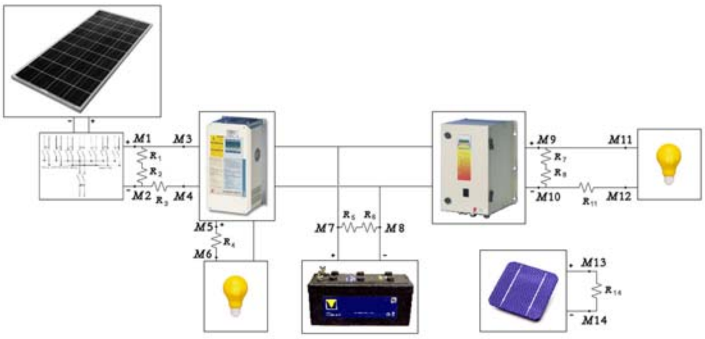


Figure 4. Connections between the PV plant and the SCC.

The PV module characteristics, as stated in specifications, are derived in Standard Test Conditions (STC); it means: $G=1000$ W/m^2 whit perpendicular incidence angle; emission spectrum 1,5 AM (related to the air mass crossed by the radiation); cell temperature 25 °C; wind speed 0 m/s.

In particular the efficiency η of the PV modules decreases 6÷7% every 10 °C increasing of the cell temperature with respect to the nominal value at 25 °C [4]. To take in account of this effect the superficial temperature should be measured. So a platinum thermoresistor PT100 (100 Ω at 0 °C) was included. The resistance measurement is derived from a three-wire configuration, supported by the reference current source I_s in fig. 3. The adopted thermoresistor is in accordance whit the international standards [5].

IV. Transmission system

The transmission is performed through the GSM (Global System for Mobile communication) cellular network. In particular the SMS service available in the GSM network will be described.

The GSM network became the cellular telephone transmission standard in most of the European countries and in many others. The division of the territory into portions called cells allows the maximum coverage. Users are identified by a SIM (Subscriber Identity Module) card.

The SMS service is a GSM function that allows transmitting text messages up to 160 characters to and from a Mobile Station (MS) according to the SMSPP standard (Point to Point) defined by ETSI (European Telecommunication Standards Institute).

The SMS transmission method is different depending on if it is originated from a MS (Mobile Originated, MO) or terminates on it (Mobile Terminated, MT). The former doesn't need a direct connection between transmitter and receiver.

When the message is sent by a MS, it is addressed through the GSM network to the operator's local SMS Center (SMSC), identified by a specific telephone number. The position of the destination MS and the relative SMSC are stored in a specific database called Visitor Location Register (VLR). The destination SMSC uses a MT transmission to reach the receiving MS. If the addressee MS is turned off or is not covered by the GSM network, the SMSC stores the SMS and tries for three days to send it again as soon as the MS is available.

Generally the message delivery takes 0,5÷2 s depending on the momentary traffic on the network. Experimental tests showed that the information collected from the PV plant can be viewed by a remote user with a maximum delay of 2 seconds. For this reason the remote monitoring and control are fast but not in real-time. However it is important to stress that the local control is absolutely real-time.

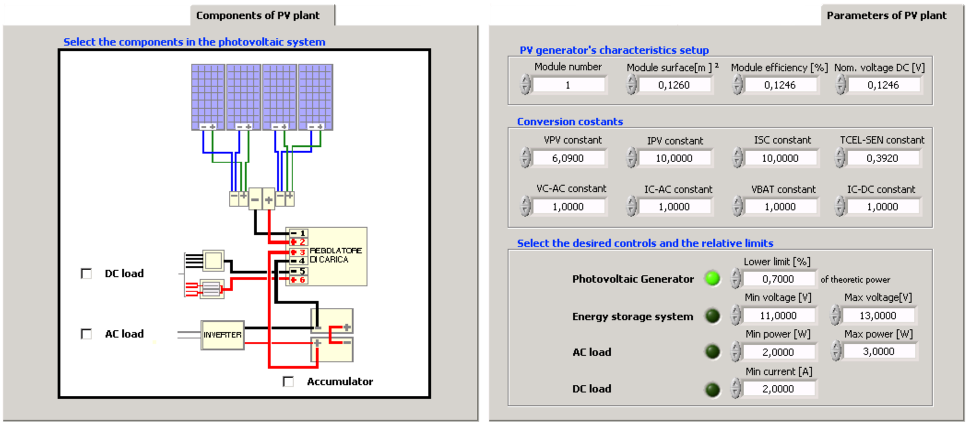
The GSM connection is managed by the controller module through a GSM modem (Pocket GMS by Digicom). The modem is dual-band, so it can work both where the service is operated at 900 MHz and at 1800 MHz.

A RS232 serial port implements the external interface. The modem is completely controllable by means of the AT standard commands and through a specific set of commands can control some of the specific characteristics of the GSM network (especially the 07.07 and 07.05 international standards).

V. Management software

The software for the management of the measurement system was developed in LabVIEW^{TM}. It is a graphical programming language by National Instruments; an application written in LabVIEW^{TM} is called Virtual Instrument (VI).

The programs have to be developed on a PC, then the executable code can be uploaded to the memory of the FieldPoint^{TM} controller. The execution of the developed VIs can be observed by a remote PC, with a direct connection or through the LAN; anyway the controller can independently manage the acquisition and the transmission, restarting the VIs at every reboot.



☐ DC load
☐ AC load
☐ Accumulator

Module number: 1
Module surface[m]²: 0,1260
Module efficiency [%]: 0,1246
Nom. voltage DC [V]: 0,1246

VPV constant: 6,0900
IPV constant: 10,0000
ISC constant: 10,0000
TCEL-SEN constant: 0,3920
VC-AC constant: 1,0000
IC-AC constant: 1,0000
VBAT constant: 1,0000
IC-DC constant: 1,0000

Photovoltaic Generator ● Lower limit [%]: 0,7000 of theoretic power
Energy storage system ● Min voltage [V]: 11,0000 Max voltage[V]: 13,0000
AC load ● Min power [W]: 2,0000 Max power [W]: 3,0000
DC load ● Min current [A]: 2,0000

Figure 5. Two sections of the VI front panel for the selection of the components and of the parameters.

In fig. 5 there are two sections of the front panel of the main VI. Through the left section of the front panel shown in fig. 5, the measurement and control parameters can be adjusted for a PV plant slightly different from the base configuration discussed in the first paragraph.

The controls on the right section allow to choose: the characteristics of the PV generator and of the dc loads; the conversion constants to transform the conditioned values of the input quantities in their real values (they depend also on the components placed on the SCC); the sections of the plant that have to be controlled; the thresholds and the parameters.

The VI consists in three processes executed in parallel. The first one checks if the PV plant components are working well, by measuring the current of PVSC and the temperature of the thermoresistor with a sampling time $T_s=0,1$ s. It is a right period to control quantities related to the solar radiation [6]. The samples are converted to physical values and it is verified if one of the following problems occurred:

- the PV generator does not produce the theoretical power;
- the accumulator system voltage is lower or higher than the set-up limits;
- the electrical power drawn by the ac loads is out of range;
- the current drawn by the dc load is under the minimum limit.

When, considering the average of these samples during a period $T=1$ s, one of these situations occurs, the process sends a SMS. This SMS reports all the data that are necessary to find out what happened. If the anomalous situation goes on, the SMS is sent again and again with an adjustable rate.

The second process records some data regarding the regular functioning of the plant. For this purpose $T=30$ s is enough to monitor quantities related to solar radiation [6]. The recorded data are sent by SMS after a registration time $T_r(n)$ fixed by the user. Normally the maximum and the averaged values of following quantities are sent: solar radiation; electrical power and energy produced; power received by the dc and ac loads, voltage of the accumulator system. Moreover four PV energetic balance indices are evaluated and transmitted: Average Efficiency, Array Yield, Reference Yield and Losses Array Capture [6]. Afterwards the system gets ready to repeat the process for $T_r(n+1)$.

The developed system is also able to accept and execute remote orders. It is accomplished by inserting suitable commands in a user's SMS. These commands can change the setup of the measurement system and of the plant, by acting either on software or on hardware (driving special switch). Therefore a dedicated third process is needed, which checks, every T_c=30 s, if the modem has received a SMS. If it happens, the process checks out if there is an acceptable command.

Obviously this feature requires a security procedure: the SMS must contain a correct (modifiable) password. The access can be limited to a predefined set of telephone numbers. After the execution of the commands the VI deletes the SMS from the SIM card memory.

Since the three processes may request the use of the GSM modem at the same time, the modem is a shared resource that needs an arbitration policy: the access is always granted to the third process and only when the other two processes require it, a reservation queue is established.

VI. Experimental test of the measurement system

The complete system was tested in laboratory with the experimental setup described in fig. 6. The solar irradiation was simulated by means of an array of bulbs enclosed in a box along with a commercial PV module. The power supplying the bulbs is regulated by a variac. It simulates the variation of the sun light. This setup allowed a long-time verification even if in simulated conditions.

A more significant test was carried out on a PV module placed on the roof of our Department.

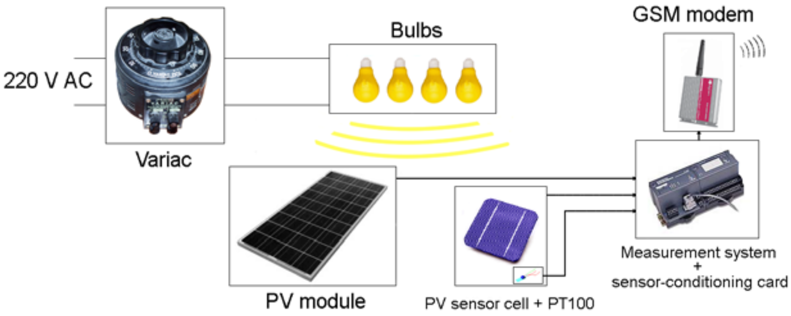


Figure 6. Experimental setup for the simulation of the operative conditions of a PV plant.

VII. Conclusion

A complete system for the remote monitoring and control of PV plants was presented. The performed tests demonstrated that it allows to verify fundamental parameters but also to operate directly on the plants, independently from where they are placed.

The use of the GSM SMS standard extends the effectiveness of the system to the plants far from electrical energy distribution network and from the usual telecommunication systems.

Due to the low cost and diffusion of the GSM device the transmission system is fairly cheap and will be cheaper and cheaper. Moreover, we are working to reduce the cost of the acquisition system by extensively introducing general-purpose microcontrollers.

At the same time we are involved in extending the phenomena that can be remotely monitored and controlled. Especially we are interested in the total management of plants for the generation of energy based on renewable sources.

References

[1] M. A. Green, *Solar cells – Operating Principles, Technology and System Application*, University of New South Wales, 1998.
[2] J. Singh, *Semiconductor optoelectronics*, McGraw-Hill.
[3] F. Lasnier, T. Gan Ang, *Photovoltaic Engineering Handbook*, Adam Hilger, 1990.
[4] F. Groppi, C. Zuccaro, *Solar photovoltaic plants (in Italian)*, Periodici UTET, 2002.
[5] *IEC 60751 – Industrial platinum resistance thermometer sensors*, 1983.
[6] *IEC 61724 – Photovoltaic system performance monitoring - Guidelines for measurement, data exchange and analysis*, 1998.