Real time monitoring of solar fields with cost/revenue analysis of fault fixing

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***Abstract*— This paper proposes a monitoring approach based on single string real-time measurements. An electronic board was developed able to sense string voltage and string current along with open circuit voltage and short circuit current of a selected solar panel belonging to the string. Acquired information allowed real time monitoring of the power actually produced by each string. At the same time, information gained from the monitored solar panel allowed the definition of a production target which is dynamically compared with the actual value. Each string is both compared with stored data regarding the string itself, in order to identify performance degradation during time, and with all the other strings, in order to immediately identify an underperforming string. Experiments performed on a medium size solar field allowed the evaluation of energy losses attributable to underperforming strings. The conversion of energy losses into money losses can be adopted to quantify the revenues of fault fixing.**

Keywords—monitoring, solar fields, partial shading, PV modeling.

I. Introduction

Effective monitoring and diagnostic of photovoltaic (PV) fields by means of both thermographic [1-4] and electrical [5-10] methods is a very important challenge for the PV community. In fact, in spite of the progresses made in both silicon solar cells technology and characterization techniques [11-17], along with the efficiency of electronic converters [18-22], it is common experience that many solar fields experience lower energy yields than expected, often because of low quality materials or because of poor assembling. Customers that experience yield problems usually ask for system revamping and sometimes decide to take legal actions against installers. In both cases the precise evaluation of the energy actually producible is needed. Moreover, in order to evaluate the revenues achievable by the replacement of a certain component, energy losses attributable to that component should be quantified. Same considerations can be repeated for usual maintenance procedures; for instance it would be desirable to schedule a cleaning intervention only if the value of the recoverable energy is expected to be greater than the intervention cost. Unfortunately, although solar fields are quite simple electrical systems, some inherent features make them very difficult to monitor. Two are the major issues: (i) energy production depends on wheatear conditions; thus, the simple monitoring of the energy supplied by the system doesn't give significant information. (ii) An enormous number of elemental power generators contributes to the overall performance of the system, the fault of even a single generator has a strong impact on the energy production, nevertheless the localization of the faulted generator is hidden by the interaction with the others.

As said before, monitoring techniques can be roughly classified into two main categories: thermographic imaging and electrical methods. The first one is increasing its diffusion thanks to the cheap availability of UAV vehicles which makes acquisition of thermal images fast and accurate; moreover it can be performed on existing solar fields without the need of any kind of infrastructure. Thermal images allows the reliable identification of faulted solar panels but cannot give information about energy losses attributable to that fault. On the other hand electrical monitoring can give very accurate information, especially if the monitoring is brought at the single panel level [3]. The drawback of this solution is the need for a pervasive sensor network that should be embedded in the solar field during mounting.

In this paper we propose an electrical monitoring system trying to achieve a compromise between accuracy and pervasiveness.

The system is based on a single string monitoring architecture able to perform real time measurements of both operating string current and operating string voltage. The hardware of the system (see section II) consists of an electronic board mounted on the rear side of a selected solar panel belonging to the string. Additionally to the aforementioned quantities, the board also provides real time measurement of the open circuit voltage V_{oc}, the short circuit current I_{sc}, the operating voltage, and the operating current of the solar panel where it is mounted. All the boards communicate with a central unit by means of a wireless protocol, so that very little extra-wiring is required. This latter features makes the system also suitable for equipping existing PV fields with an acceptable effort.

Measured data are managed by means of an information system pursuing the twofold aim of localizing faults at the string level and quantifying energy losses attributable to each detected fault; thus, the cost needed for fixing a specific fault can be compared with the revenues coming from the expected energy recovery.

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II. System Architecture and Control Logic.

The architecture of the monitoring system is shown in Fig.1. As can be seen, the solar string is equipped with an electronic board, labeled as "string sensor", connected to the first (lower voltage) solar panel of the string.

The board is crossed by the string current and, in order to measure the string voltage, is also connected to the last solar panel, (red wire in Fig.1; this is the only required "extra wire").

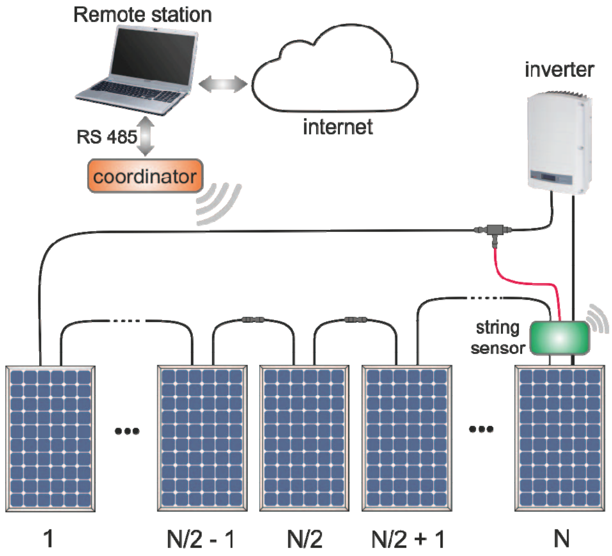

Fig. 1. Monitoring system architecture.

As said before the same board also monitors the solar panel were it is mounted.

Monitoring features relies on (i) the availability of the instantaneous power produced by each solar string, recorded over the whole daylight; (ii) the availability, over the whole daylight as well, of both open circuit voltage and short circuit current of each monitored solar panel.

Information acquired on individual solar panels allows to define an expected target for the power producible by the corresponding string according to the formula

$$P_{\text{target}} = N(k_V \cdot V_{oc})(k_I \cdot I_{sc}) \tag{1}$$

where N is the number of series connected solar panels forming the string, k_V and k_I, taken from data sheets, are the ratio between the voltage at the maximum power point V_{MPP} and V_{oc} and the ratio between the current at the maximum power point I_{MPP} and I_{sc} respectively (the knowledge of the actual V_{oc} allows straightforward evaluation of the operating temperature as well; thus all evaluated quantities are correspondingly adjusted). Equation (1) relies on the assumption that all the N solar panels perform at their best with the actual weather conditions (revealed by I_{sc}).

It is worth noting that the simpler measurement of the operating current and voltage of the solar panel (in place of I_{sc} and V_{oc}) do not allows the estimation of the power producible by the string because, as it is widely known, the series connection of the solar panels implies the constraint that the current is unique, so that an underperforming element limits the performance of the whole series.

Differently from other systems, where the production target is evaluated on the basis of historical irradiance data, in our system the target power is a dynamically changing quantity because depending on the instantaneous irradiance impinging on solar panels , thus representing the real power that the string should produce in a given instant.

III. Experiments.

The monitoring system described in the previous section was embedded in a 100 kW solar field composed by 24 solar strings, each of them made by 17 series connected solar modules. An aerial photograph of the site is reported in Fig 2.

Fig.2. Aerial view of the monitored 100 kW roof top solar field.

The site was connected to the grid in October 2014, hence the whole 2015 was available for data analysis.

Voltages and currents were relieved from the field every 10 minutes. Measurements were taken by means of a parallel polling procedure, so that data from different strings can be assumed as synchronous.

For each string the target-power profile was evaluated according to the definition (1), along with the actually produced power. As an example, Fig. 3 shows the target power (green line) and the power actually produced (red line) by an underperforming string during a winter day. Since the target is built by assuming that all solar panels behave like the only one which is monitored, the gap between the curves suggests that at least one solar panel of the string is faulted. It is interesting to note that, if the monitored panel was faulted, the target would be lower than the actual power, thus indicating, even in this case, the presence of some malfunctioning. The general adopted rule was that a large gap (> 5%) between actually produced power and target power is classified by the information system as a possible fault event and monitored over the time.

The above rule does not recognize cases where the whole string is underperforming. In order to tackle this issue the information system also evaluates the maximum instant power produced by the most performing string in the field.

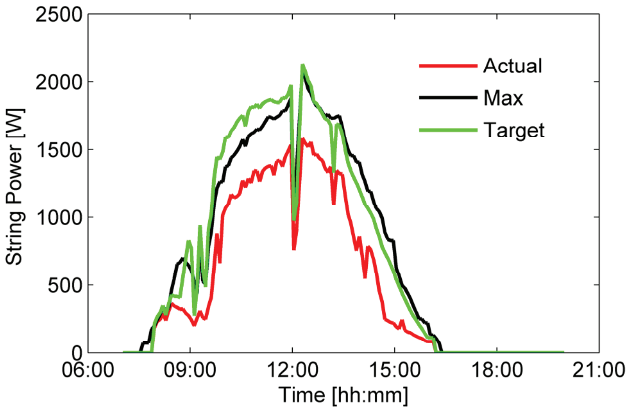

Fig. 3. Actual and daily targets power profiles for a selected string in the field .

This string is dynamically determined, in the sense that, for each instant time, what it is actually stored is the maximum among the powers supplied by all the strings of the field; therefore, a “virtual string" is built that always supplies the maximum allowed power. The curve corresponding to this "string" is reported in Fig. 3 as well (black line). As can be seen the target power is almost coincident with the virtual max power (thus indicating the reliability of the estimated target), while the actual produced power is lower than the target during the whole day. From the above considerations it can be concluded that production losses cannot be ascribable to a generalized problem affecting the whole string (as an example a large shadow); instead, it should be attributed to a localized problem affecting some solar panels, probably causing panel bypassing. Further insight can be achieved by comparing the actual operating string voltage and the target one ($N \cdot k_V \cdot V_{oc}$), as shown in Fig. 4. As can be seen the operating voltage is permanently lower than the expected one, thus corroborating the hypothesis of some bypassed solar panel. As said before this event is tagged and stored by the information system, however the convenience of fixing the problem can be evaluated only after power losses have been converted into economic losses, as will be shown in the next section.

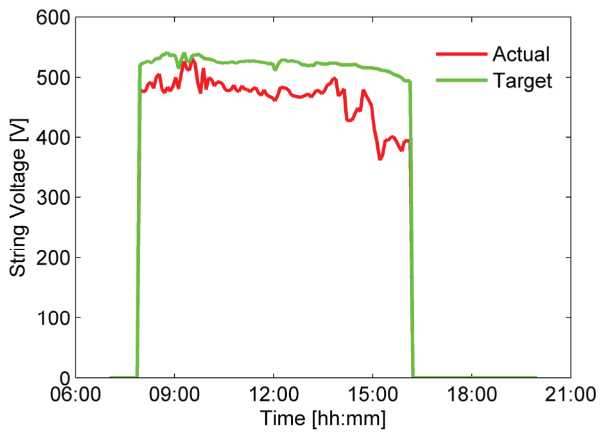

Fig. 4. Actual and target voltage for the selected string.

In addition to the virtual string, the actual best performing string is individuated. This latter string gives the actual reachable target that should be pursued by all the strings. Indeed, if there were no problems, all the strings should behave as the best one. This assumption is based on the idea that the solar field embeds, at least, one optimally performing string. The daily power profile produced by the best string is shown in Fig. 5, it is almost coincident with the virtual max power. The power produced by the best performing is taken as reference to evaluate both the target for the whole solar field and the target for each string in terms of energy production.

As an example Fig. 6 reports the data of Fig. 5 converted in terms of cumulated energy during the given day.

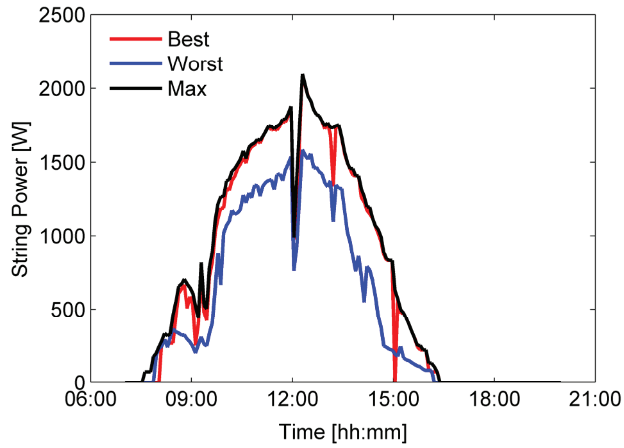

Fig. 5. Comparison between best and worst producing string in the field.

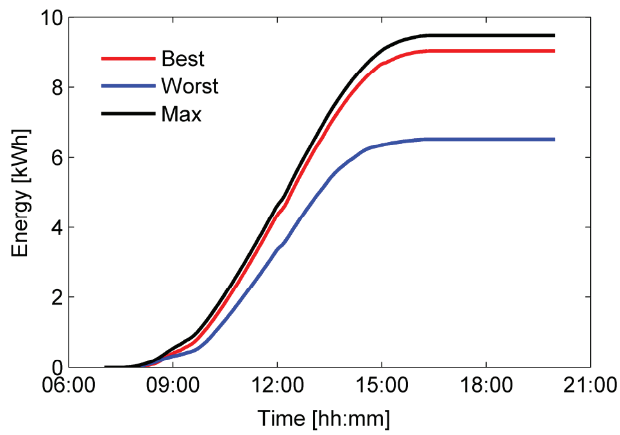

Fig. 6. Cumulated daily produced energy

As can be seen, at the end of the day, the worst performing string produces about 3 kWh less than the best one. If the problem affecting the string is not fixed, energy losses cumulate day after day. Overall results achieved on the solar field for the whole 2015 are summarized in Fig. 7.

For the sake of clearness only the monthly best performing and worst performing are reported; the numbers over each bar refer to the line position of, respectively, the best one and the worst one. As can be seen the best performing is almost always string #20, while, in the first four months, there are strongly underperforming strings (#1, #19).

After this observation many defective solar panels were individuated. By considering revenues, as described in the next section, it was decided to ask for replacement of those modules; this intervention caused many interruptions of power production during the following months (because disassembling and reassembling of many strings was needed), as evidenced by the low production during the summer months.

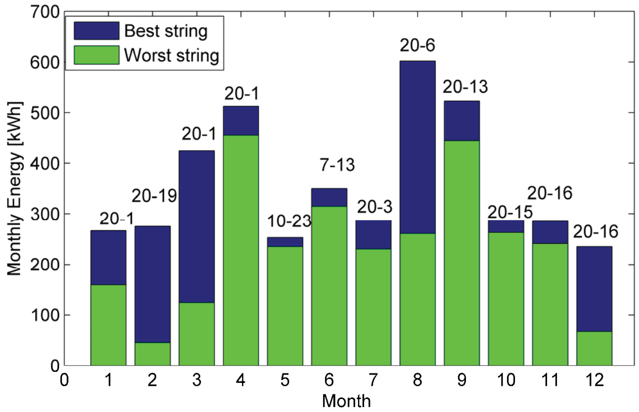

Fig. 7. Monthly energy produced by the best and worst string in the field.

IV. Graphical interface.

In order to facilitate maintenance a graphical interface, converting the topology of the solar field, given by the AUTOCAD drawing shown in Fig. 8, into a color map, evidencing power production associated with each string, was made.

Fig. 8. AUTOCAD schematic of the moitored solar field

As first step the procedure converts vectorial data provided by AUTOCAD into a bitmap image where each string corresponds to an assigned level in the grey scale, as shown in Fig. 9. Then a MATLAB code converts energy data provided, for each string, by the monitoring system into the RGB code. Finally each pixel of the bitmap image characterized by the grey level of the given string is colored with the corresponding RGB code.

An example of the results that can be achieved is illustrated in Fig. 10. This figure reports the differences among the target energy and the energies actually produced by the strings at the end of a given day (the time interval of the colored report can be arbitrary chosen). Therefore a color approaching the red level indicates a string exhibiting a large difference between the produced energy and the expected one. The reliability of the automated procedure was tested by intentionally obscuring for some hours the central string of the field.

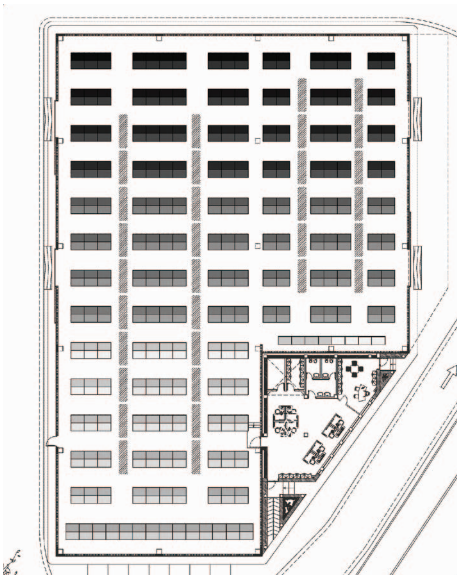

Fig. 9. Grayscale bitmap representation of the monitored solar field.

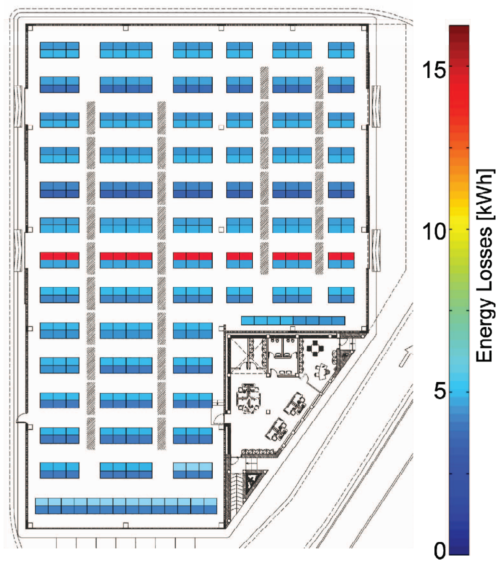

Fig. 10. String level energy losses with respect to the target. Red color corrsppnds to high losses.

As a result the "faulted" string got colored, thus driving maintenance operators directly to the requesting site. Information like that of Fig. 10 can be conveniently converted from energy losses to money losses, as reported in the following section.

V. Cost and Revenues

As describe in the previous sections the availability of information about the instantaneous power produced by the strings allows to evaluate the cumulated energy produced by each string and to estimate energy losses (compared to the target) imputable to a given fault event. For instance Fig.5 shows the comparison among the cumulated energy produced, in a given day, by, respectively, the best performing string, the less performing string and the “max” (virtual) producible energy.

As can be inferred from the figure, the worst string produced, during the given day, about 3 kWh less than the target, thus giving rise to corresponding money losses (for illustrative purposes, 10 € cents/kWh has been assumed as energy price). In Fig.6a money losses cumulated during the first two months of the year are shown (red circles). As can be seen the losses increase with an almost linear law; thus, a linear extrapolation (red line) was adopted to estimate long term losses without fault fixing. As can be seen the value of the energy loss does not justify a prompt intervention, even though, from Fig. 5, power losses seem significant. In fact, the simple visual inspection of the field has a cost that should never be neglected. Just as an example in Fig. 11a we quantified in about 100 € the cost for an human operator inspection. As can be seen this cost is reached (without problem fixing) after about ten months. Fig. 11a also shows, for comparison, the losses (black line) of the best performing string with respect to the target. By considering that it is reasonable that fault fixing could allow (in the best case) the faulted string to work like the best one, money losses should be more realistically evaluated as the difference between the two curves. However, in spite of the low economic impact of only one underperforming string, the presence of many strings with unsatisfactory energy production (see Fig. 7) made overall losses very significant. The sum of the economic losses imputable to each string is shown in Fig. 11b. Also in this case a linear extrapolation is adopted to foresee long term effects. The figure suggests that a timely intervention is fully justified. In a case like this, where it is expected the presence of many faulted solar panels, an effective diagnostic approach could have been an early thermographic inspection made by drone (UAV), whose cost (without the analysis of the images) has been quantified in Fig. 11b to be about 1000 €. In any case the cost of problem fixing should also been quantified.

VI. Conclusion

In this paper a single string monitoring system has been developed and experimentally verified. The system allows the definition of reliable production targets based on actually achievable performance, strictly depending on instantaneous weather conditions and solar panel technology. The availability of the target allows the quantification of energy losses imputable to each string and, therefore, the recognition of faulted string. The opportunity to convert energy losses into money losses give guidelines to evaluate expected revenues of fault fixing by also taking into account the costs needed for interventions. Experiments conducted on a 100 kW solar field evidenced the reliability of the approach.

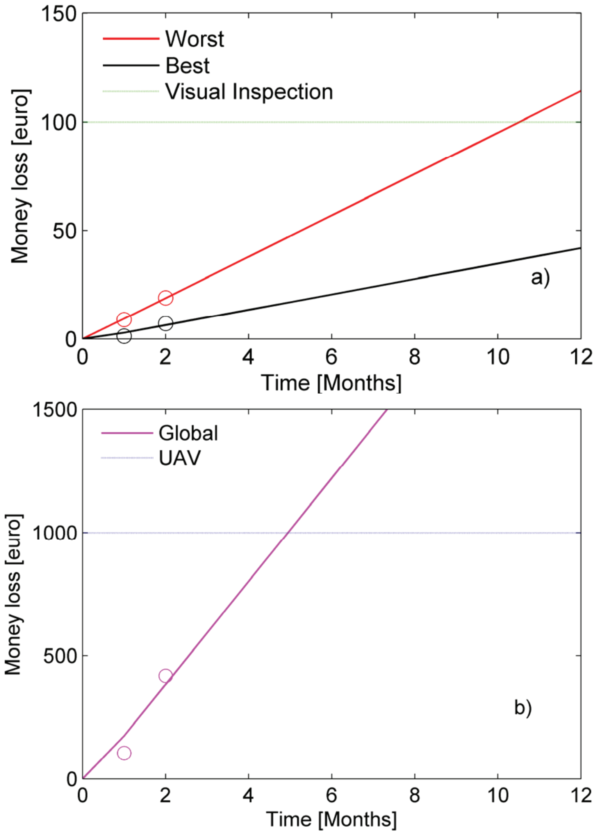

Fig. 11. a) single strings money losses vs. time; b) cumulated money losses vs. time.

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