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Dynamic Reconfiguration of Electrical Connections for partially shaded PV Modules: Technical and Economical Performances of an Arduino-based Prototype

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Abstract- The partial shading phenomenon is a well known problem of photovoltaic plants. Partial shading leads to undesirable effects such as the electrical mismatch, the generation of hot spots and generally the decrease of production of electric energy. To mitigate the last effect, a dynamic reconfiguration of the electrical connections between modules was taken into account. In this paper, starting from an already developed system for a small-scale PV plant reconfiguration, the study of the economical benefits of the employment of a reconfiguration system are traced. Five different incentive policies of diverse Countries have been considered to evaluate the increase of Net Present Value of PV modules with and without a reconfiguration system.

Keywords- photovoltaic reconfiguration; solar modules; renewable energies; photovoltaic array.

1. Introduction

Nowadays, a massive use of renewable energy sources is a favorable option towards a sustainable development of the human community. It can be stated that the solar energy is one of the most commonly adopted sources of energy because of its benefits such as inexhaustibility and cleanness [1].

In this context, the energy efficiency enhancement is a very critical issue faced by the scientific community for the production of maximum power [2-4]. For this purpose, new generation of PV arrays and multitudes of modules integrated on different surfaces are investigated worldwide. However, photovoltaic arrays composed by a high number of modules can be more easily affected by partial shading, which is a very crucial challenge determined by different causes, such as the non uniformity of either the clouds distribution or the solar radiation on the array, leading to a significant loss in terms of PV energy production.

The effects of the partial shading can be understood through the obtainment of a proper model [5-14], in order also to evaluate the economical aspects.

The mismatch among cells of the same module leads to a performance deterioration of the whole photovoltaic module: in case of series connection, the lowest-current cell limits the whole array; in case of parallel connection, the lower-no-load-voltage cell limits the parallel array. The electrical mismatch leads to a reduction of the produced power, meaning that the total available power is less than the maximum power which is available from the single cells. The mismatch losses (ML) concerning a single PV module represent therefore the difference between the sum of the maxima power levels obtainable from the single separated cells and the maximum power obtainable from the whole module in case of electrical mismatch.

It is commonly known that partial shading conditions could lead to a significant reduction of the electrical energy generated by the PV modules. This drawback has been extensively studied in the scientific literature and several methods have been proposed and mainly divided into two categories: the active methods and the passive methods. Among the latest category, the adoption of bypass diodes is one of the most used techniques [15]. Nevertheless, bypass diodes connected in anti-parallel with PV cells or modules determine the variation of their electric characteristics in case of non-uniform irradiation [5]. In case of uniform irradiation, the voltage-power (V-P) characteristics of a PV module shows one peak; instead, in case of partial shading on the module, multiple peaks on the V-P characteristics occur. In the general case of series-connected cells, with bypass diodes and under different irradiation levels, on the V-P characteristics of the whole series array different peaks are visible, as shown in Fig. 1. In the case of parallel connection of different series PV arrays, with bypass diodes and under different irradiation levels, the characteristics of the whole PV module show an analogous shape. As shown by Fig. 1, two different regions are identifiable: region A, showing the lowest voltage values, and region B, showing the highest voltage values. In Fig. 2 a detailed explanation of the electrical operation is reported, concerning the simple case of two series-connected PV cells.

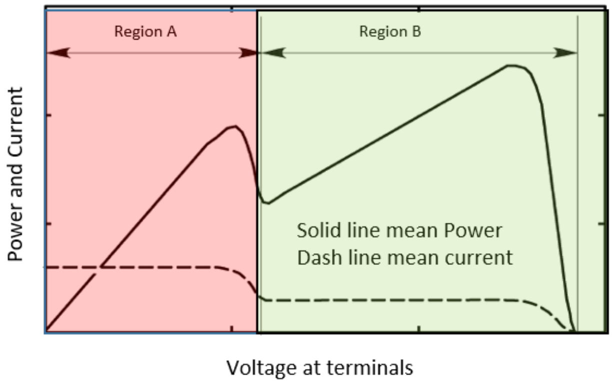

Fig. 1. V-I and V-P characteristics of two series-connected cells, provided with bypass diodes, in partial shading [8].

If the current in the cell A (I_a) is equal to the current in the cell B (I_b), meaning that both the cells present the same irradiation level, the total series voltage is the sum of the single nominal voltage cells. If I_b is higher than I_a, meaning that two different irradiation levels concern the cells, part of the current in the cell B may flow across the diode connected to the cell A: in this case, the voltage across the cell A is ideally zero, so that the total series voltage is about the single nominal voltage of the cell B, meaning that the working area is the region A, according to Fig. 1.

If, even for different irradiation levels, the bypass diode is not in conduction, the same current flows across both the cells, equal to the less irradiated cell current. Therefore, a double power peak occurs, one in region A and one in region B.

From the previously mentioned statements, it appears clear that this passive method is relatively expensive, due to the fact that it requires a high number of diodes. Furthermore, the power losses are not completely avoided and the conduction of the diodes can affect the MPPT algorithms of Maximum Power Point Tracking (MPPT) [16].

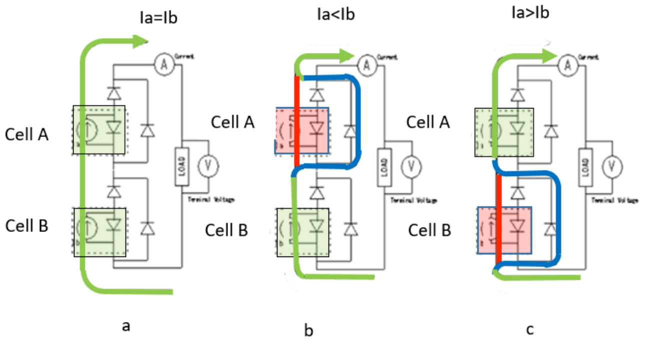

Fig. 2. Possible paths of current in the following cases: a) Ia = Ib; b) Ia < Ib; c) Ia > Ib. With reference to the regions A and B when one of the two cell is shaded: the red line is the current path corresponding to the region A; the green line represents the current path corresponding to the region B [8].

An active method is represented by the distributed MPPT, where each PV module is connected to its MPPT DC-DC converter. In this way, the mismatch conditions caused by the partial shading is corrected through the research of the maximum power, enhancing the efficiency [17-18]. However, the high-cost of this technique limits its diffusion.

Another active method consists in the dynamic reconfiguration of the PV array electrical connections, which is an effective solution consisting in grouping cells (or modules) with similar characteristics.

By considering a specified shading condition, the electrical connections of the PV modules are properly changed by following an adequate reconfiguration algorithm, as reported in [17-30].

In this context, this paper recalls an already developed system, property of the SDES (Sustainable Development and Energy Savings) Laboratory [7] and evaluates the economical benefits of the use of an advanced reconfiguration system on different incentive policies of diverse Countries. The following section proposes the design and the experimental validation of a reconfiguration algorithm of the electrical connections of a PV array composed by six modules. The measurements are carried out on a resistive load and the improvement provided by the proposed algorithm are described and discussed.

Once obtained the performances of the reconfiguration system in the increase of power, the economic aspects are evaluated to establish the return of the investment by the Net Present Value technique.

2. Reconfiguration system

The PV reconfiguration system proposed in [7] has been designed for a small-scale array, which is composed by 6 modules connected in order to obtain an array of two parallel-connected strings of three series-connected modules (E215P, type, Conergy Inc.), whose main characteristics are summarized in Table 1, whereas the maximum power point voltage and current of the whole array are reported in Table 2. The overall power reachable with the PV system is equal to 1.3 kWp at full irradiation.

Table 1. Electrical characteristics of each module [7]

Maximum power	P_m	215 [W]
Maximum power point voltage	V_{MPP}	28.27 [V]
Maximum power point current	I_{MPP}	7.59 [A]
Open circuit voltage	V_{OC}	36.37 [V]
Short-circuit current	I_{SC}	8.21 [A]

Table 2. Electrical characteristics of the PV array [7]

$V_{MPP,array}$	84.81 [V]
$I_{MPP,array}$	15.18 [A]

It is clear that in case of partial shading, the maximum obtainable power is strictly dependent on the electrical connections between each of the PV modules. With an equal level of shading, the maximum reachable power is higher when the shaded modules belong to the same string. Therefore, an algorithm capable of a real-time reconfiguration of the electrical connections of the modules in order to obtain the maximum possible power could be a great aid to the PV array for its efficiency enhancement.

For each module, two possible irradiance states have been supposed for the algorithm: shaded or not shaded. The proposed PV array in its "base configuration" (which is the configuration corresponding to the condition of uniform irradiance where all modules are either shaded or not shaded) is shown in Fig. 3: the photovoltaic array is in the base configuration, where the String I is composed by the modules nr. 1, 2 and 3, while the String II is composed by the modules nr. 4, 5 and 6.

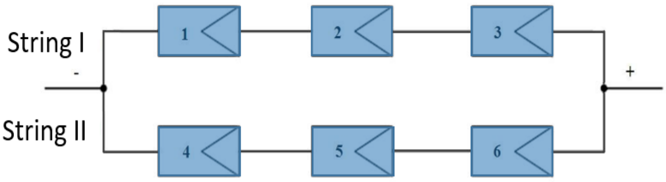

Fig. 3. Base configuration of the connections between the modules.

The algorithm implies that the base configuration is kept only when three modules in the same string are either shaded or not shaded. In any other case as far as the distribution of radiation is concerned, the algorithm leads to a reconfiguration of the array, so that a new configuration, different from the base one, has to be achieved.

The system is implemented without the use of any pyranometer, which leads to a low-cost solution. In fact, each module can be adequate classified by detecting its voltage.

The choice of the threshold voltage is based on the maximum sensed voltage and a specific voltage difference ΔV_T. The ΔV_i difference between the voltage of the ith module and the maximum sensed voltage is compared to the ΔV_T value, which is properly selected. If $\Delta V_i < \Delta V_T$, the ith is identified as not shaded; if $\Delta V_i > \Delta V_T$, the ith module is identified as shaded. After this classification of the modules of the photovoltaic array, the proper reconfiguration occurs according to the algorithm described in [7]. The whole reconfiguration algorithm is displayed in the flow diagram of Fig. 4.

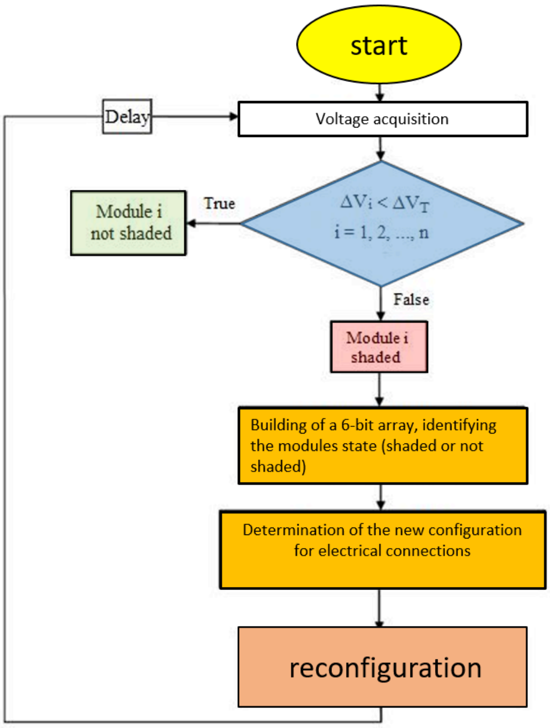

Fig. 4. Flow diagram of the reconfiguration procedure.

The reconfiguration algorithm has been implemented by means of a reconfiguration board, which is mainly composed by the following components [7]:

- a Switching Matrix (*SM*);
- a Sensing Network (*SN*);
- a Control Unit (*CU*).

The switching matrix implements the actual configurations of the electrical connections of the six PV modules.

The *SM* is composed by 25 normally-open-contact relays. The *SN* is composed by two current sensors and six voltage transducers for the real-time detection of both the current and the voltage along the two strings, respectively.

The control unit recognizes the shading conditions of the modules by acquiring the voltages generated by the six modules by means of the sensing network. According to the algorithm, the *CU* outputs the signals needed for the conversion of the PV array in the related new configuration. The CU has been implemented with the *Arduino Mega 2560* system because of its great advantages in terms of low-cost and easy-programmable solution.

3. Experimental tests and results

This Section reports the experimental results concerning the reconfiguration board proposed in [7]. The power/voltage characteristics in three different conditions have been achieved by means of three sets of measurements: the first one with a base configuration of the PV modules and an uniform solar radiation for all six modules, the second one with a shading condition for modules nr. 3 and 6 and the third set of measurement with modules nr. 3 and 6 shaded but with a new configuration of the array, according to the algorithm. A double-layer of a plastic mesh was used to cover the PV modules, artificially emulating specific partial shading conditions and estimating a 60% of reduction in terms of irradiance, as shown in Fig. 5.

Fig. 5. Artificial shading on two modules of different strings [7].

Therefore, the P-V characteristics for these three different conditions are plotted in the same graph of Fig. 6. From this Figure, it can be noticed that for both shading conditions (brown and clue curves), the output generated power is comprehensively lower with respect to a full and uniform irradiation (red curve).

However, the peak of power obtained with the reconfiguration system (curve nr. III) is higher than the power peak for the second set of measurement (curve nr. II). Thus, a 10% of maximum achievable power increase is obtained from the adoption of the reconfiguration algorithm [7].

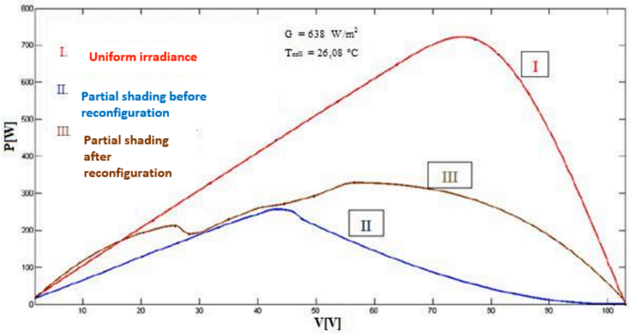

Fig. 6. Comparison between the measured power curves versus the voltage across the photovoltaic array. The parameters T and G represent the average values of irradiance and cell temperature, respectively.

4. Evaluation of the economical convenience

The aim of this section is to establish the economical convenience of the PV reconfiguration system, by considering different factors that influence power productions of the PV plants.

Moreover, the economic analysis has been carried out by considering different countries and their feed-in tariff (FIT) as reference. The reference countries are: Italy, Bulgaria, Romania, Croatia and Turkey.

4.1. Economic tool

The economic convenience is evaluated through the Net Present Value – NPV [31]. This method allows to obtain the result from a sum of cash flows actualized at time zero with a rate equal to the opportunity cost of the financial capital:

$$NPV = -C_0 + \sum_{k=1}^{n} \frac{C_k}{(1+i)^k} \qquad (1)$$

where C_0 is the original investment (cost of the PV plants), C_k is the cash flow at the year k, i is the interest rate and k is the period of net cash flow. Therefore, a positive value of NPV indicates a convenience in terms of investment and *vice versa*. For its computing, the yearly data of the PV incomes and expenses, namely cash flows, are needed and their calculation is based by considering the interest rate MARR (Minimum Attractive Rate of Return). This parameter symbolizes the amount of assumed earnings for the investment. Thus, the NPV allows the estimation of the expected cash flow in a given period. Two investments can be, then, matched by comparing the NPV values obtained from them.

According to [14], the increase of the NPV is evaluated for Italy, Bulgaria, Romania, Croatia and Turkey. In order to take an incentive policy for Italy the Conto Energia V was considered.

For each of the selected countries, the following data have been considered:

- Interest rate *i%* equal to 5%;

Period of investment equal to 20 years.

4.2. Case of Study

The reference case of study consists of a 3 kWp PV plant installed in the capital city. The average estimated price for this type of plant is about 7000 €, including the installation cost. For maintenance and management of the PV plant, an amount equal to a 100 €/year has been considered.

It is well known that the inverter is the most critical component of the PV system, often affected by to several faults during its lifetime. By considering some of these faults, a ten years of lifetime for the inverter is considered and the cost for its substitution has been estimated to € 750,00. During the lifetime of the PV plant, a decrease of the energy production has been taken into account. More in detail, for the first year a reduction equal to 3% and a reduction equal to 0.5% for the later years.

4.3. Data of the reference countries

Among the proposed countries, many differences can be appreciated in terms of incentives, corresponding to prizes paid to private citizens for the same energy fed into the public grid and solar irradiation. For this analysis, the average consumption per capita of a family composed by four elements that live in the capitals of the countries has been taken into account. Table 4 shows the main features of the different countries taken in the study: cost of the PV plant [€], Average annual consumption [kWh/year], energy price [€/kWh], incentive [€/kWh], annual PV production [kWh/year].

4.4. Data of the reconfiguration system

In order to provide the economic analysis, it is supposed that a fixed obstacle near the PV plant determines a reduction of the produced energy during the lifetime of the PV plant. More in particular, the effect of shading comes from the fourth year onwards, and it is assumed a 10% daily loss of energy, which can be compensated by reconfiguration strategies.

For this economical study, an average energy increase of about 10% provided by the use of a reconfiguration system has been assumed. Moreover, the cost of the reconfiguration system of about 250 € with lifetime equal to 6 years has been estimated, after which, as in the case of the inverter, a replacement is required. Thus, the use of the reconfiguration system increases the total costs equal to 750 € during the life time of the PV plant.

Table 4. Parameters for different countries

	PV plant cost [€]	**Annual consumption [kWh/year]**	**Energy price [€/kWh]**	**Incentive [€/kWh]**	**PV production [kWh/year]**
Italy	7000	3200	0.20	0.208 (20 years)	4950
Bulgaria	7000	4640	0.09	0.24 (20 years)	4500
Romania	7000	2495	0.125	0.16 (15 years)	4200
Greece	7000	5029	0.18	0.14 (20 years)	5550
Turkey	7000	2836	0.131	0.12 (10 years)	5100

5. Results and discussions

The sum of energy self-consumed is evaluated as the minimum between the energy produced and the energy consumed, while the amount of energy injected to the network is calculated as the difference between the energy produced and energy consumed. A positive result of this difference determines the cancellation of the related bill. For each country taken into account, the NPV values have been calculated for three cases: with a 10% decrease of power production, without the decrease of 10% power production and with reconfiguration system. The second case represents the reference values for the other two cases. The results expressed in percentage with respect to the cost of the investment equal to 7000 €, are shown in Figs 7-9, respectively. Firstly, it can be noticed that, after the lifetime of the investment, Italy and Bulgaria present positive NPV values. This phenomenon is due to the high incentivises available in these countries. Another interesting consideration regards the pay-back time. For Italy and Bulgaria the use of the reconfiguration system allows the reduction of the pay-back time for some years.

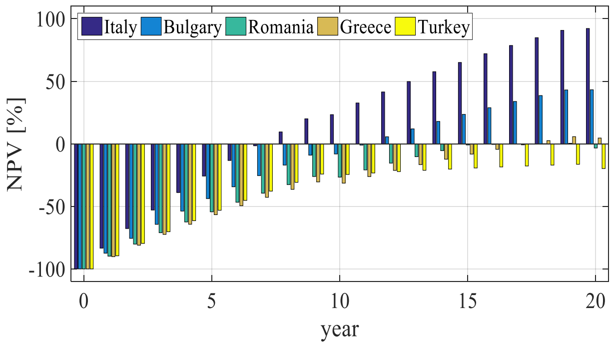

Fig. 7. NPV values for each reference country without decrease of 10% of power production.

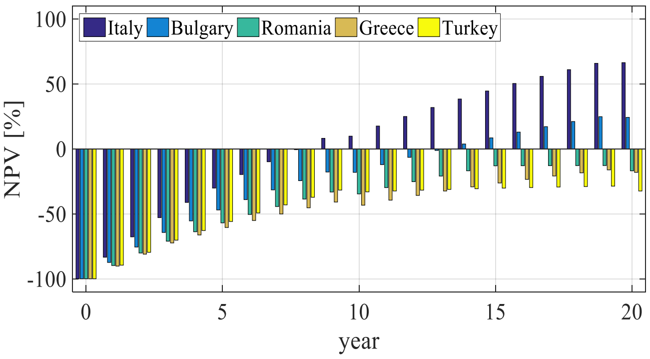

Fig. 8. NPV values for each reference countriy with a decrease of 10% of power production.

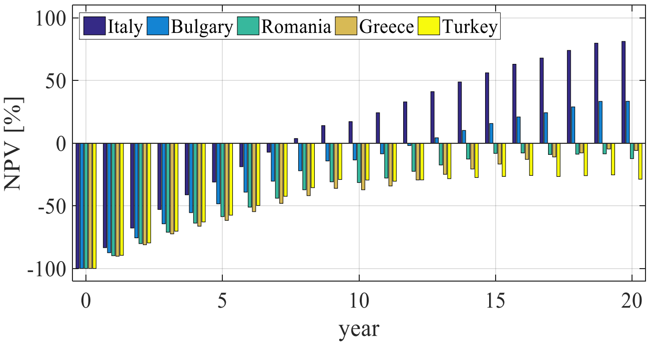

Fig. 9. NPV values for each reference country with the use of a reconfiguration system.

From the comparison of cases 2 and 3, it is possible to notice that the use of a reconfiguration system allows the economic benefits for all countries taken into account, even in countries where the NPV presents negative values.

In particular, Table 5 shows the percentage of the calculated NPV values for the different countries taken into account with respect to the cost of the investment.

Table 5. NPV variation in different countries

	Italy	Bulgaria	Romania	Greece	Turkey
NPV w/o rec	66%	24%	-16%	-18%	-32%
NPV with rec	81%	33%	-12%	-5%	-28%

The positive values represent the gain with respect to the initial investment, while the negative values represent the lost with respect the initial investment.

6. Conclusions

This paper, starting from an already developed prototype in the SDES laboratory, has presented the economical benefit of the use of a reconfiguration system of the electrical connections of a PV array. The printed circuit board of the designed system has been assembled and tested on a small-scale plant, but its results can be exported to more extended systems. In case of partial shading condition, a 10% of increase in terms of maximum produced power is obtained with the implementation of the proposed algorithm.

The economic analysis has been performed and the effects of the reconfiguration system have been evaluated for the increase of the Net Present Value, demonstrating that for all the countries taken into account the proposed reconfiguration system provides economical benefits.

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