Implementation of a switching matrix operating PV field-storage interconnection

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Abstract— **The need to find an alternative to traditional energy sources has led to a strong growth in electricity production from renewable sources; among these, a widespread source of electricity is solar energy. Due to the nature of this energy source, one of the main limits of photovoltaic (PV) systems is the partial shading of the modules, due to weather conditions or cleaning of the module. In these conditions, the value of the PV generator voltage drops below the minimum power range of the solar inverter. To exceed this problem a solution to extend the Maximum Power Point Tracking (MPPT) range of the solar inverter is proposed; it consists of a control logic for the series connection between the PV source and a storage system, e.g. a battery, including a DC/DC converter, automatically by means of a switching matrix. Based on the values of the control quantities - PV generator voltage and State Of Charge (SOC) of the storage system- the system provides the proper commands to the switches. In this way the Battery Energy Storage System (BESS) is enabled to boost the input voltage of the solar inverter achieving the voltage minimum power point limit and avoiding any disconnection of the equipment.**

Index Terms — ***Battery Energy Storge Systems, Photovoltaic Fields, Grid-Connected Inverters, Switching Matrix, DC-DC Power Converters***

I. INTRODUCTION

To make our planet actually sustainable, environmental pollution must be significantly and continuously reduced. The 2015 Paris Agreement aimed precisely at keeping the increase in average temperatures below 2% [1].

From this point of view, the energy transition towards 100% renewable energy sources (RES) proves to be a relevant and attractive solution to reduce Greenhouse Gas (GHG) emissions and limit the impact on climate change. This topic is one of the most significant issues of government policies of the EU countries and has gained increasing attention within the scientific community, as the National Energy and Climate Plans (NECPs) issue directives to the Member States of the European Union on how to contribute to achieving the climate and energy objectives by 2030 [2].

In particular, the new EU directives impose a 55% emission reduction target [2].

At the same time, a climate-neutral energy system must largely rely on renewable sources. It is estimated that to achieve the 55% reduction in emissions, the share of RES must reach 40%. It will therefore be necessary to further increase the share of renewable energy sources, tending towards an ideal 100% both at EU and global level, that is a very recent research topic [2].

The goal of a 100% energy production from RES has been widely investigated, along with the implementation of microgrids and the use of hybrid energy storage systems [5-9].

Focusing only on the electricity sector, the target of a 100% "renewable electrical grid" has already been achieved or almost achieved by several countries, especially due to production from hydroelectric plants. Given that the share of hydroelectric production will hardly continue to increase, given the limits imposed by hydrogeological resources, it will be necessary to focus almost exclusively on wind and solar energy.

Contribution by these renewable energy sources (RES) is therefore essential for those purposes. In recent years, along with the development of alternative RES, incentives have been decided to help the renewable energy sectors [10-12].

Concerning solar energy, due to its features, such as volatility and large scale access, it causes a large impact on the network considering variables such as voltage levels, the loading cables and transformers, short circuit contribution, protection issues [13]. The Battery Energy Storage System (BESS) is a solution to overcome some of these negative elements.

Regarding grid-connected solar inverters, the scientific literature reports different solutions of BESS-PV integration, whose main drawback is represented by low efficiency and high cost arising from a full power processing approach [14]. Therefore, solutions of partial power processing can be convenient to overcome those issues [15-17].

In [18] charging and discharging of BESS obtained from optimization is analyzed: the storage system covers load demand when there is surplus of photovoltaic power generation and, through islanded mode, if the main grid is not available; the BESS is used to grow distributed generation integration and islanded mode in case of fault in the network. In addition to the above, the main contribution to PV system growth trend is the PV self-consumption, that is the possibility to consume the energy produced by PV generation installations located close to the place where that energy is consumed. PV self-consumption is possible with a correct BESS sizing.

However, the possibility of producing energy from a PV system is strictly connected to weather conditions, both in warm regions and in cold ones. Partial shading of the modules and cleaning of them are the main limits of PV systems. Indeed, they could generate energy, but the PV source voltage drops below the minimum power range of the solar inverter, thus disconnecting from the grid.

In this paper, a flexible integration between a grid-connected PV field and a Battery Energy Storage System is described. The proposed system provides for a switching matrix which interconnects PV field, BESS and solar inverter, according to specific electrical connections based on the state of charge (SOC) of battery and on the solar irradiance on the PV modules, aiming at the working continuity of the grid-connected inverter no matter what the irradiance conditions are. Indeed, if the irradiance level decreases so that the PV power is not enough to guarantee the minimum voltage for MPPT, then the PV field is connected in series with the BESS, thus leading again the DC voltage level inside the MPPT range.

The proposed switching matrix has been designed to operate in connection with a 2 kW PV string, a BESS consisting of a 48 V battery and a solar inverter including a Power Conditioning System which implements a MPPT strategy.

II. PARTIAL SHADING CONDITIONS LIMITS

A focus on the implementation of a MPPT algorithm is beyond the scope of this paper, since MPPT is entirely delegated to the Solar Inverter stage, which is by *Gefran* manufacturer, with the following specifications:

- DC input voltage: 150-450 V;
- AC output voltage: 230VAC, one phase;
- AC output power: 3.6 kW.

MPPT and grid connection are allowed if a minimum PV voltage is seen at the DC input side of the inverter.

In order to prevent unwanted current and to facilitate the battery disconnection in case of fault, galvanic isolation is recommended between the PV module and the battery. Therefore, an isolated DC-DC converter is required as intermediate stage between the battery and the PV circuit, so that the BESS is mainly consisting of the battery and the isolated DC-DC converter itself.

In the proposed scheme, the output voltage of this DC-DC converter is put in series connection with the PV module in case of request from the control system of storage support. When no integration of the storage system is requested, the DC-DC converter output is disconnected and the PV module is connected only with the solar inverter.

Many factors influence the operating condition of the system, such as partial shading phenomena caused by cloud transit, the presence of dust and residues on module external surface and thermal disposal problems, causing a substantial alteration of the characteristics curves I-V and P-V [19-20].

Analyzing these curves, it is clear that the minimum power point limit is out of the MPPT range of the solar inverter; because of Power Conditioning System (PCS) limits the system will be disconnected causing significant losses of production. In standard conditions the PV field is enabled to achieve the minimum voltage value fixed by the MPPT range, therefore it is necessary to choose field configuration and PCS properly, according to the limits of MPPT range.

Traditionally, storage – along with a proper DC-DC stage - is in parallel with the PV generator to collect excess energy from the PV field and use it when the solar source is not able to satisfy the user's needs.

Nevertheless, even if a boost converter is used as a DC-DC stage, the obtained DC voltage could not be enough to supply the inverter, so that an alternative option consists of connecting in series the BESS to the PV generator.

In this way the BESS voltage is added to PV generator ones, thus the input voltage converter is:

$$V_{DC} = V_{PV} + V_{BESS} \quad (1)$$

where V_{DC} is the inverter supply voltage, V_{PV} is the PV voltage and V_{BESS} is the BESS voltage. Therefore, solar inverter is activated.

To realize the above, there could be the possibility to switch from parallel connection into the series one between storage and the PV generator [21]. This paper gets back from the studies presented in [22] proposing a technique to change PV array and storage battery connections, so the input solar inverter voltage is compliant with the range of MPPT in partial shading conditions too.

The case study of extending the power range of a solar inverter proposed in [22] consists of an auxiliary circuit of a Battery Energy Storage System (BESS) - which comprises a battery storage element and an auxiliary boost converter- that is enabled overcoming the minimum MPPT limit. The BESS, connected in series with PCS and PV generator instead of parallel connection, is enabled to overcome the minimum MPP limit in PSCs, avoiding the equipment disconnection and waste of solar energy. Simulation results under partial shading conditions in [22] showed that the input PCS voltage is the sum of the PV field - that dropped below the minimum MPP limit- and BESS system voltages, so avoiding any disconnection.

In this paper an isolated DC-DC converter is considered as part of the BESS, and a switching matrix made of 4 switches is proposed to reach different electrical configurations, aiming at the optimization of the power transfer according to all the possible conditions.

III. STORAGE CONTROL LOGIC

The storage control logic is enabled to carry out the interconnection, from parallel to series and vice versa, automatically providing the command to the switches based on the control variables values. Two analogical inputs linked with two sensors are used to measure output PV source voltage and BESS voltage respectively; these inputs are converted into digital ones determining value 0 or value 1. Specifically, there are two operation states for each sensor:

- state 1 if the output voltage of PV generator is higher than 150 V or state 0 if the output voltage of PV generator is lower than 150 V;
- state 1 if the percentual voltage of the battery storage system is higher than 90% or state 0 if the percentual voltage of the battery storage system is lower than 90%.

The control logic is implemented through a switch matrix consisting of 4 ideal switches (A, B, C, D), as shown in Fig. 1, driven for closing or opening; the commands are provided by two input signals, one arising from PV sensor and one arising from BESS sensor.

In this way switches are driven to make the system work in 3 operating conditions:

1. battery charging phase, described by Fig. 2, where PV and BESS are in parallel connection;
2. battery discharge phase on the system, for which PV and BESS are in series connection (Fig. 3);
3. storage disconnection phase in which the battery is charged and the output voltage from the generator PV is suitable for the PCS system (Fig. 4).

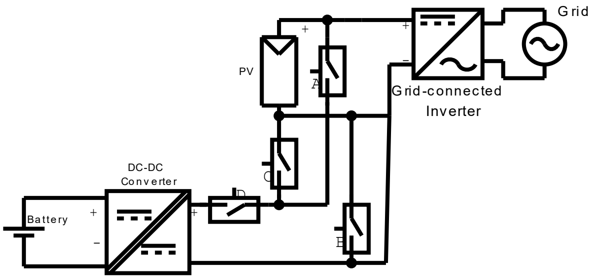


Fig. 1. Schematic of the electrical connections between BESS (Battery + isolated DC-DC), PV field, solar inverter and switching matrix.

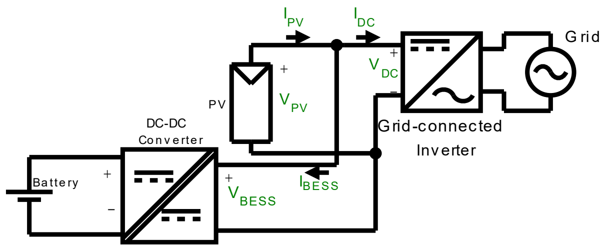


Fig.2. Phase 1 – battery charging: PV and BESS are in parallel connection.

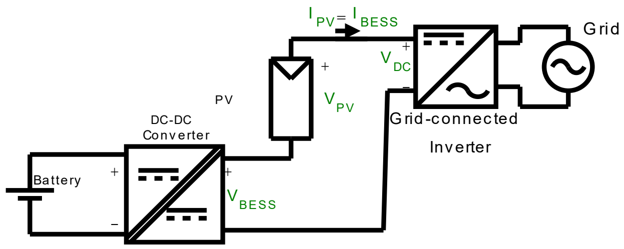


Fig. 3. Phase 2 – battery discharging: PV and BESS are in series connection.

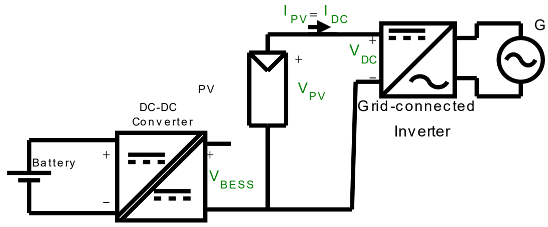


Fig. 4. Phase 3 – BESS disconnection.

The operating states of the three phases are described in the following:

1. battery charging phase: the output voltage of the PV generator is higher than 150 V (state 1) and the percentual voltage of the battery storage system is lower than 90% (state 0);
2. battery discharge phase on the PV system: the output voltage of the PV generator is lower than 150 V (state 0) and the percentual voltage of the battery storage system is higher than 90% (state 1);
3. storage disconnection phase: the output voltage of the PV generator is higher than 150 V (state 1) and the percentual voltage of the battery storage system is higher than 90% (state 1).

The states of the switches according to the operation phase are reported in Table I.

TABLE I – TABLE OF TRUTH O THE SWITHCING MATRIX

PHASE	A	B	C	D
1	1	1	0	1
2	0	0	1	1
3	0	1	0	0

IV. TEST RESULTS

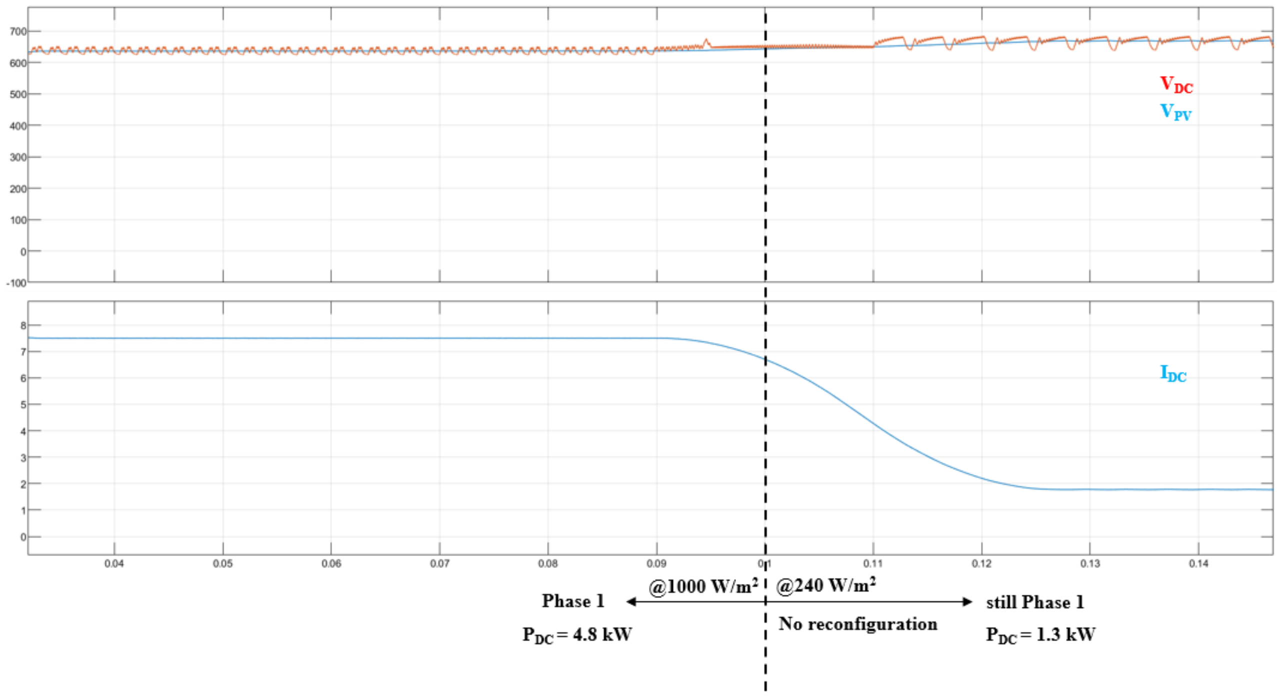
In order to evaluate the proper operation of the proposed algorithm, some preliminary simulation tests have been performed through the software *MATLAB Simulink*.

A. Simulation results

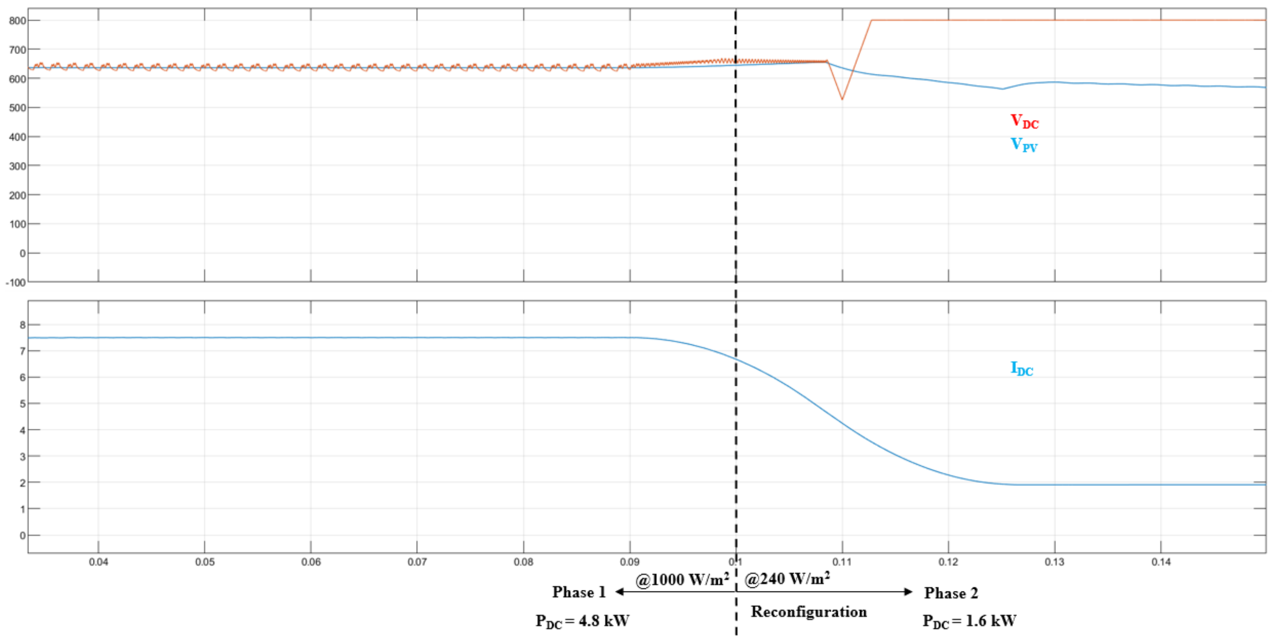
Supposing to simulate a step in the irradiance level from 1000 W/m^2 to 240 W/m^2 after 0.1 s, the case without interconnection from parallel to series has been compared to the case where the mentioned interconnection is implemented.

Fig. 5 shows the corresponding simulation results regarding V_{PV}, V_{DC} and I_{DC}: in Fig. 5a) no interconnection from parallel to series has been supposed; in Fig. 5b) the interconnection from parallel to series has been activated, so that the system goes from Phase 1 to Phase 2 after 0.1 s.

An increase of the input inverter voltage V_{DC} can be noted after the irradiance level decrease, due to the series connection between the PV field and the BESS, thus keeping MPPT in operation and transferring a power level of 1.6 kW, which is 23% higher with respect to the case with parallel connection.



(a)



(b)

Fig. 5. Simulation results: after 0.1 irradiance decreases and inverter voltage increases since PV and BESS are put in series connection.

B. Switching matrix realization

The switching matrix is implemented on *EagleCAD* by using four TO220 MOSFETs driven in pairs respectively by three drivers *ADuM4223* controlled by 4 DC/DC converters *TBA1-1212*.

The two operation states 1 or 0 are sent uniquely by a microcontroller *Arduino* according to both the values of PV generator voltage and SOC.

As measurement and sensing devices there are three LEM to measure the output current of PV source, inverter and storage, and three operational amplifiers to measure the output voltage of them.

In Fig. 6 the layout of the Printed Circuit Board (PCB) implementing the proposed switching matrix is reported, highlighting the different parts of the system.

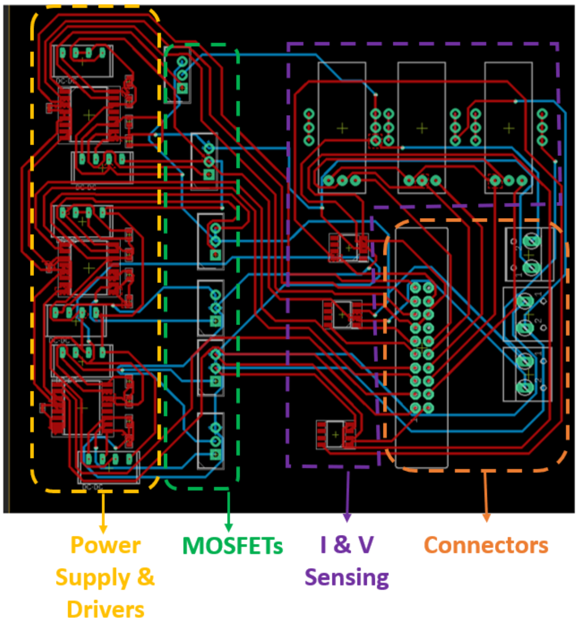


Fig. 6 Switching matrix PCB layout.

V. Conclusions

In this paper a switching matrix developed starting from studies in [22] is proposed. The switching matrix consists of 4 switches operating PV field-storage interconnection; according to the output PV voltage and SOC of the battery it is possible to realize the series or parallel connection of the two systems. In partial shading conditions PV field and BESS are series connected by the switching matrix, in this way the sum of the output PV generator voltage and the BESS one is higher than the minimum MPPT limit of solar inverter; thus it is possible to take advantage of PV generator in PSCs too.

The switching matrix allows connecting PV field and BESS in three different configuration systems: parallel connection in standard conditions, series connection in partial shading conditions, disconnection of PV generator and BESS when the output PV generator voltage is higher than the minimum MPPT limit and the SOC is upper than 90%.

As future development, the authors aim at carrying out experimental tests inserting the implemented switching matrix between PV field - consisting of a PV string of 10 Conergy PowerPlus of 215 W_p PV modules-, a GEFRAN RADIUS APV-3 6K-T-2M inverter and BESS - a storage of 4 YAMADA 12 V and 7Ah in series connection- to obtain the three system configurations.

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