REDUCING MISMATCH LOSSES IN GRID-CONNECTED RESIDENTIAL BIPV ARRAYS USING ACTIVE POWER CONVERSION COMPONENTS

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ABSTRACT: Building-integrated photovoltaics (BIPV) have seen an impressive development throughout the world this last decade. In France, photovoltaic (PV) installations under 3 kW_p represent 90% of the plants in service as of 2009, and count for 42% of the national installed photovoltaic power [1]. Residential BIPV installations are not only characterized by there relatively small peak power but also by their sensitivity to perturbed environmental conditions such as partial shading. Partial shading of BIPV plants can be caused by several factors such as nearby trees, chimneys or buildings, consequently causing PV module mismatch losses. Such losses are mainly due to the dispersion in electrical characteristics of interconnected modules which leads to significant decrease in plant energy production. The introduction of additional power converters in the plant layout intends to reduce the influence of one module on the entire installation, thus reducing module mismatch. In this work, five grid-connected PV installation topologies: centralized inverter, string inverter, module inverter, parallel connected choppers with centralized inverter, series connected choppers with centralized inverter are presented and compared. Furthermore, average modelling of Boost DC-DC converters and grid-connected inverters with their associated control strategies are proposed. Performance analysis of these topologies is carried out through normal operation and two partially shaded scenarios representing chimney and nearby building induced shade. Simulations using the proposed average models have been implemented in Matlab/Simulink© environment for each topology using a 3 kW_p rooftop-type plant. Simulation results show that a considerable amount of additional solar generated energy can be grid-fed using alternative plant layouts.

1 INTRODUCTION

During this last decade grid-connected photovoltaics have experienced a tremendous expansion bringing the total installed capacity to 13.4 GW at the end 2008 [2]. A major growth market perceived by many institutions is residential building integrated photovoltaics (BIPV), which consists in installing PV plants on top of or directly into roofs of buildings [2][3]. In France, such installations account for 90% of the grid-connected installations (under 3 kW_p) and represent 42% of the installed PV power. Moreover, modules composing a photovoltaic plant may induce losses due to their heterogeneous electrical characteristics; these are often referred to as mismatch losses. They are defined as the difference between the available power from the PV modules of the array and the extractable power from the array. Mismatch losses inside a PV array can be caused by mainly two phenomena: manufacturer tolerances and heterogeneous environmental conditions of the array. Indeed, module manufacturers usually guarantee a peak power value with a tolerance, ranging from 3-5%. As modules are commonly series-connected, thus sharing the same current flow, peak power of each module is not necessarily obtained given the dispersion of maximum power current values. Furthermore, plants may be subject to uneven environmental conditions, such as partial shading or heterogeneous temperature distribution on the PV array. In BIPV applications, partial shading of an array may occur due to nearby buildings, trees, antennas or chimneys, which are usually inherent to the solar plant's environment. In order to reduce mismatch losses in a PV array, that is to say reducing the impact of one module on the global production of the array, two main methods have been proposed in literature: modifying module interconnection schemes [4] and introducing power electronic converters [5]. This paper deals with comparing various converter-oriented solutions to reduce mismatch losses in a residential-sized PV installation.

2 REVIEW OF GRID-CONNECTED BIPV TOPOLOGIES

Traditionally, photovoltaic plants are composed of series-connected modules, also known as PV strings, which are then connected in parallel in order to fit the desired plant power rating. Grid connection is achieved by using an inverter using maximum point tracking algorithms with a voltage elevation stage followed by a current inversion stage. Such layouts are referred to centralized inverters and are the most widely used in PV plants, especially for large installations [6]. However, in order to increase photovoltaic grid-fed energy other topologies have been proposed: string inverter, module inverter, parallel chopper, and series chopper. These layouts are presented on figures 1 & 2.

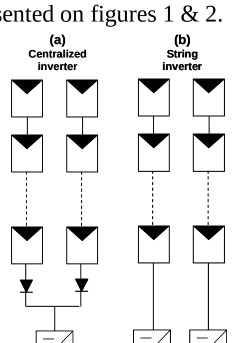


Figure 1 : Diagrams of traditional centralized inverter and string inverter layouts

The prominent idea of multiplying the number of inverters, albeit for PV strings or modules, is to reduce the impact of module mismatch and maintenance perturbations. Indeed, in the case of a faulty centralized inverter, the entire plant cannot feed the grid, whereas in the case of a string inverters one faulty string inverter will only prevent the production of one string. Module inverters, more commonly known as AC modules, have the advantage of increasing module independence in a plant as well as reducing maintenance disturbances on plant production.

The use of DC-DC converters has also been proposed for reducing module mismatch losses by introducing them in PV strings, as in multi-string inverter configurations, or directly at module output terminals. In this paper, series connected choppers and parallel connected choppers will be studied. In the series connected chopper configuration, each module of the plant is connected to a DC-DC converter which is then connected in series making up a DC-DC converter string. These Boost converter strings are then connected in parallel to a 400 V DC bus. A centralized inverter then inverts the extracted PV energy for grid connection. In a parallel chopper configuration, each module uses a DC-DC converter to elevate its voltage to 400 V using a two stage Boost converter while using MPPT algorithms. The voltage and current is then inverted using a centralized inverter.

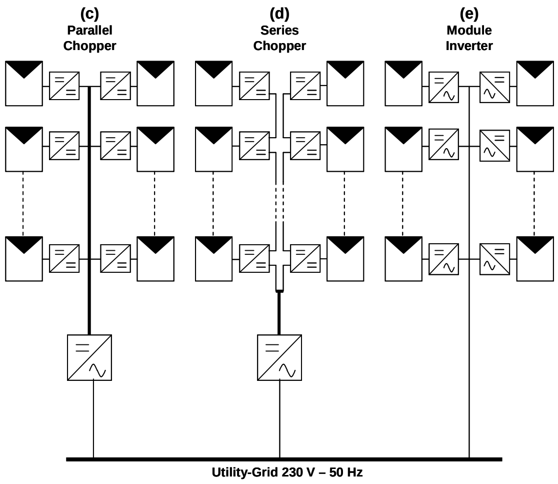


Figure 2 : Diagram of parallel chopper, series chopper and module inverter layouts

3 AVERAGE MODELING OF PV SYSTEMS

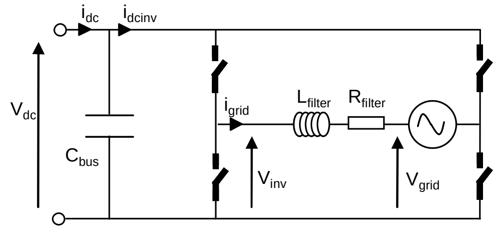
In all the proposed configurations two power converter units are used: Boost DC-DC converters and grid-connected inverters. In order to simulate the steady state efficiencies of the topologies average modeling of these power converters has been developed.

3.1 Average modeling of grid-connected inverter

The studied single-phase inverter average model consists of four power switches used in an H-bridge configuration for current inversion. In this simplified model, the grid is seen as a voltage source of infinite power, which is in assumption widely used in first approach models for grid connection. The grid-tied inverter contains a filter stage both on the AC side, by using an inductance, and on the DC side, by using a capacitor for filtering DC bus harmonics, as shown on Figure 3.

3.2 Control strategy for grid-tied inverter

The grid-tied inverter has essentially two main functions in this proposed model: maintain a DC-bus voltage constant and invert the direct current. From a dynamic point of view, the current inversion constant (equation 1) must be the fastest followed by the DC-bus voltage control (equation 2). For both control loops PI controllers are used, bringing the closed loop transfer functions to the second order.



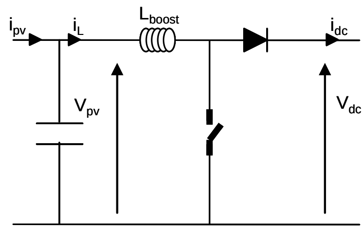
$$\mathbf{C_{bus} \cdot \frac{dV_{dc}}{dt} = i_{dc} - i_{dcinv}} \qquad \mathbf{(1)}$$

$$\mathbf{L_{filter} \cdot \frac{di_{grid}}{dt} + R_{filter} \cdot i_{grid} = \alpha_{inv} \cdot V_{dc} - V_{grid}} \qquad \mathbf{(2)}$$

Figure 3 : Average model equations of single-phase inverter with associated bus capacitor

3.3 Average modeling of Boost DC-DC converter

The Boost DC-DC converter is widely used for voltage elevation and is composed of a semi-conductor switch and inductance. In exact models, the semiconductor switch is controlled by using a controlled duty cycle with pulse width modulation (PWM). Average modeling consists in averaging the value of the duty cycle over a limited time in order to give the average value of the current flowing through both the semiconductor switch as well as the diode. The equations used for average modeling are presented below.



$$\mathbf{L_{boost} \cdot \frac{di_L}{dt} = V_{pv} - V_{dc} \cdot \left(1 - \alpha_{chop}\right)} \qquad \mathbf{(1)}$$

$$\mathbf{C_{pv} \cdot \frac{dV_{pv}}{dt} = i_{pv} - i_L} \qquad \mathbf{(2)}$$

Figure 4 : Electrical scheme and average model equations of PV module capacitor and boost chopper

The losses in the Boost converter consist in the semi-conductor switch and diode losses. These losses are also calculated using traditional semi-conductor switching and conduction losses [7].

3.4 Control strategy for Boost DC-DC converter

Maximum power point tracking algorithms are implemented in the Boost converters in order to fix the PV module's operating point and extract the maximum power. Therefore, the aim of this converter control strategy is to regulate the module voltage. This is achieved through the DC-DC converters input current. Therefore, the first step of the control strategy is to determine the duty cycle which corresponds to the desired input current value, i_L* (1). Secondly, voltage control of the PV module is used to determine the input current value necessary to obtain the desired PV module voltage given by the MPPT algorithm, $V_{pv}*$ (2). As in the previous case, dynamic time constants must be respected for proper operation. In this strategy, the Boost converter input current loop control must be faster than the MPPT algorithm control loop.

In the case of double-Boost converters, present in module inverters and parallel chopper configurations, the first stage uses the previous control strategy whereas the second stage regulates the intermediate fixed voltage DC bus (100 V) and elevates voltage to the output DC bus voltage (400V).

4 CASE STUDY: 3 KW$_P$ BIPV PLANT

The aim of the case study is to determine the plant topology which extracts the most energy from a 3 kW$_p$ rooftop plant consisting of fifteen 200W$_p$ PV modules of mono-crystalline technology, with power-voltage characteristics presented in Figure 7(c). The solar array is arranged in three strings of five modules per string. Three scenarios for evaluating the performance of plant layouts are simulated: non-shaded scenario, chimney shade scenario, and nearby building shade scenario, as shown on Figure 5.

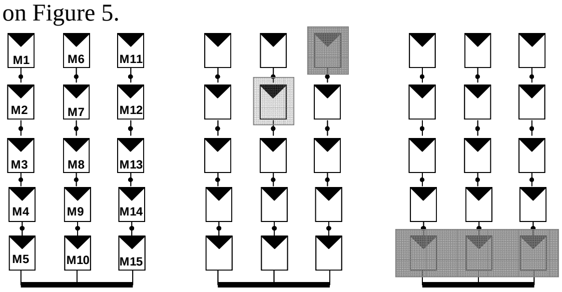


Figure 5 : Shade scenarios for plant topology simulations

4.1 Non-shaded scenario

In normal operating conditions, the rooftop plant is not submitted to any perturbed environmental conditions. Furthermore, it is assumed that all modules are identical therefore eliminating module mismatch due to manufacturer tolerance or faulty modules. This scenario portrays the operating mode in which the PV plant is designed to work during most of its lifespan.

4.2 Chimney shade scenario

Many residential rooftop installations are submitted to dynamic shadows, at sunrise or sunset hours, due to fixed objects such as chimneys, antennas, or nearby electric poles in some cases. The chimney shade scenario shadows two modules of the PV plant following a diagonal line with changing shade factors. The shade factor is a non-dimensional factor which depicts the fraction of solar irradiance that is transmitted to the module the object with reference to the incoming solar irradiance, it can also be viewed as a transparency factor as described in Equation 1. In the chimney scenario module, module M7 receives 50% of the solar irradiance, whereas module M11 has a shade factor of 0.8 that is to say that 80% of the solar irradiance is obstructed by the chimney. The shade factors have been chosen based on field experience and due to the fact that crystalline technologies depend mostly on direct solar irradiation which becomes very small in proportion when an object is between the solar source and the photovoltaic modules.

$$SF = 1 - \frac{E_{\text{recieved by module}}}{E_{\text{solar irradiance}}}$$

Equation 1 : The shade factor (SF) of a PV module represents the ratio between incoming solar irradiance and module percieved irradiance

4.3 Nearby building shade scenario

The nearby building shade scenario illustrates the impact of a nearby building on the rooftop array. This shade scenario is not likely to appear when the sun is the highest, that is to say at midday, but may impact an array much longer than the chimney scenario depending on the height and width of the nearby building. Authors have chosen this case as the worst case scenario, where the building shade affects each string by shading one module of the string with a 0.8 shade factor.

4.4 Simulation results

First of all, it is important to take into account the effect of shaded modules on an array and string. The simulated power-voltage characteristics of partially shaded arrays have been obtained by a program developed in the G2Elab [8], they are presented on Figure 7. It should be noticed that partial shading does not only reduce the maximum power produced by the PV module, but also causes a multi-power peak phenomenon. The multiple power peaks has been a subject for improving MPPT algorithms [9], which typically use power peak detection methods, and therefore may stagnate on local maxima of the power-voltage characteristics. The MPPT algorithm used in our simulations is the commonly known perturb and observe (P&O) algorithm which evolves by calculating the derivatives of power with respect to voltage, and is therefore very sensitive to local maxima. The P&O MPPT algorithm, also known as the hill climbing technique, is initialized at open-circuit voltage (V_{oc}) and slowly climbs the P-V curve hill with 1%V_{oc} steps until it reaches a maximum. This simple algorithm is very efficient in non-shaded conditions, but proves to be very inefficient in partially shaded scenarios.

Results of topology simulations are presented on Figure 6. In non-shaded conditions, the centralized and string inverters produce the most power due to high power conversion efficiency, whereas the other topologies tend to use more power converters hence lowering the overall sun-to-grid power conversion.

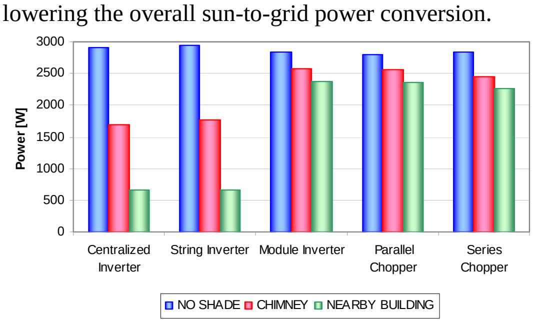


Figure 6 : Grid-fed power of various topologies in the proposed shading scenarios

In the remaining shade scenarios, the module oriented topologies produce more grid-fed power than the string and centralized inverter configurations. The first phenomenon which explains these results is the very low or absence of mismatch losses in the module oriented topologies as shown in Table 1. Furthermore, the basic MPPT algorithm used in simulations has been mislead in the centralized and string inverter configurations by stagnating on the low power peak, located at approximately 320 V. The module oriented layouts have the advantage of eliminating mismatch losses and MPPT maximum peak detection failure due to their proximity with the PV modules.

	Chimney	Nearby Building
Centralized inverter	27,1%	70,9%
String inverter	29,7%	70,9%
Module inverter	0,0%	0,0%
Parallel chopper	0,0%	0,0%
Series chopper	5,1%	7,3%

Table 1: Mismatch losses of topologies in proposed shade scenarios expressed in percent of extractable PV power

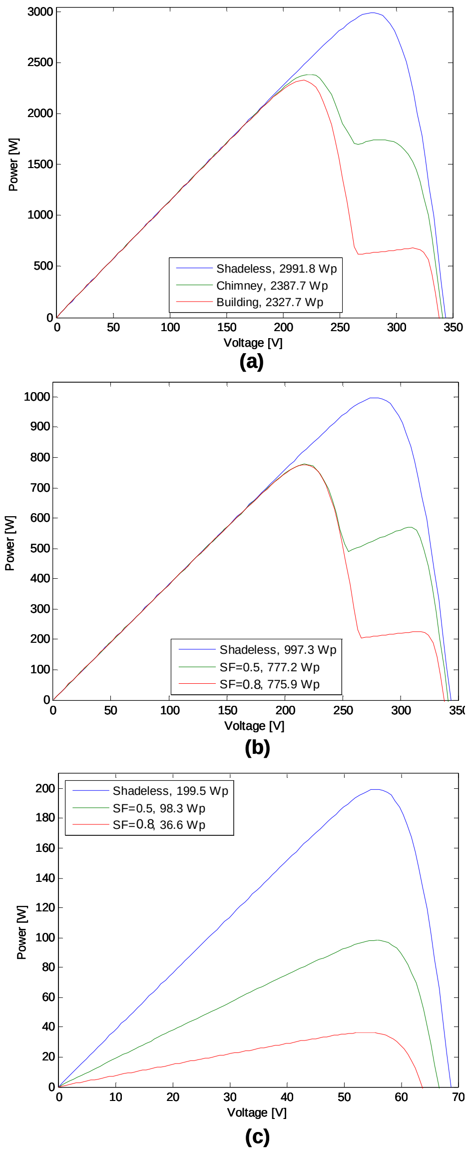


Figure 7 : Power-Voltage characteristics of ¨(a) PV array, (b) PV strings, and (c) PV modules in the three proposed scenarios

5 CONCLUSION

In this work, a review of traditional and module-oriented topologies adapted to BIPV applications. The production performances of these later plant configurations have been compared in both non-shaded and partially shaded scenarios. Results show that traditional layouts produce the most power in normal operating conditions, whereas module-oriented topologies perform better in partially shaded conditions. Depending on the periodicity and intensity of the shade upon a residential installation, the module-oriented arrangements may be interesting to consider. Although, investment costs of the modular technologies may be unfavorable, further investigation taking into account other evaluation criteria than power production should be carried out to decide on the most adapted topology for a given PV installation.

6 ACKNOLEDGEMENT

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