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**PHOTOVOLTAIC MODULE AND SHADOW:
STUDY AND INTEGRATION OF A CURRENT BALANCING SYSTEM**

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ABSTRACT: Current crystalline photovoltaic modules (PV) are designed with 36 or 72 series – connected PV cells. Usually, in order to protect the PV cells, a bypass diode is connected in anti-parallel every 18 PV cells. Furthermore, the series connection of PV modules is necessary in order to obtain the input voltage for the converter. Yet, each PV cell has its own current-voltage characteristic. The manufacturers guarantee a dispersion of 3% of maximum power between solar cells; so series connection of heterogeneous PV cells generates mismatch losses. Mismatch losses can increase in case of shading which may greatly reduce power output. Moreover, building integrated PV (BIPV) has seen an important development in urban areas bringing to the light shadow related problems. This paper proposes a PV module with an integrated power electronics topology able to replace bypass diodes while extracting maximum power of each 18 PV cell string. The operating principle of the current balancing system (CBS) is studied with multiple input levels and various PV generator characteristics. Five different layouts of the CBS are studied using a 144 PV cell string subdivided in 18 cell groups which are submitted to 21 shade scenarios. Furthermore, the optimal CBS can be implemented easily into current 72 cell modules. Experimental results on a prototype are compared to simulation results in chosen shade conditions. The performance analysis carried out shows interest in using the 4 input level CBS rather than traditional bypass diode modules.

KEYWORD: Power Electronics, Energy performance, Shadow

1 INTRODUCTION

The grid connected application knows a strong development these last years thanks to the very attractive price incentives of the electricity produced by this kind of application [1, 2]. This study is aimed at residential PV installations. It is assumed that the PV technology used is a crystalline one, according to its large spreading on the current market [3]. These devices with their strong buildings integration and their developments in urban zones are subjected to severe shadows. In this condition the PV field is very often working in mismatching conditions which can bring important power losses [4, 5, and 6]. The proposed solution will have to decrease the effects of shadow, keep the reliability and the cost imposed by the market [7, 8, and 9].

This study concerns a power electronic topology integrated to the PV module which is able to extract the maximum power of each PV generator whatever their characteristics. This topology operating principle is presented in the first part. The topology model of losses has been specified and was used to evaluate the power output in various lighting scenarios and different CBS layouts. The theoretical results are presented in the paragraph 4. The final section presents the prototype and experimental results.

2 THE TOPOLOGY

2.1 The topology and the control

Literature reveals numerous advantages of the balancing current topologies because they permit every generator to operate at their optimum power point [10, 11, 12]. The proposed topology, with n levels, is presented on Figure 1. PV generators are connected in series and in addition each level of the CBS is connected to a PV generator in parallel. The CBS is a power electronic device designed to replace bypass diodes used in traditional PV modules. The operating principle of the

CBS is to extract the maximum power from the PV generator by balancing global current flowing through the PV string. The power flowing through the CBS is not entirely that of the PV generator, in fact, only the difference between modules flows through the CBS bringing high efficiency values.

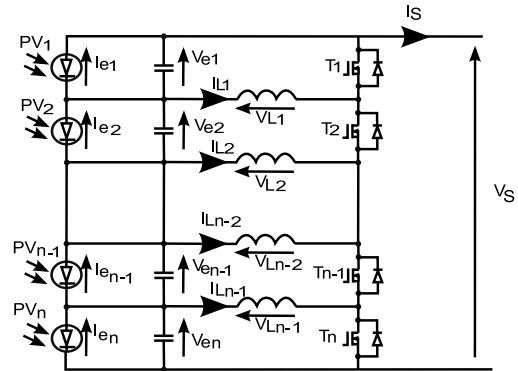


Figure 1: Diagram of n-level current balancing system

The operating principle is expressed with the following equations:

$$\overline{\alpha}_i = \frac{V_{e_k}}{V_S} \quad \text{and} \quad \sum_{k=1}^n \overline{\alpha}_k = 1 \quad (\text{Eq. 1})$$

Using this proposed control strategy, output voltage, current and power can be expressed using the following equations:

$$V_S = \sum_{k=1}^n V_{e_k} \quad (\text{Eq. 2})$$

$$I_S = \sum_{k=1}^n \overline{\alpha}_k \cdot I_{e_k} \quad (\text{Eq. 3})$$

$$P_s = V_s \cdot I_s = V_s \cdot \sum_{k=1}^n \overline{\alpha_k} \cdot I_{e_k} = \sum_{k=1}^n V_{e_k} \cdot I_{e_k} \quad (\text{Eq. 4})$$

Because all V_e and I_e can be different, this topology is able to extract the maximum available input power of heterogeneous PV generators.

2.2 The Maximum Power Point Tracker (MPPT)

The maximum power point tracking modifies all Mosfets duty-cycle to maximize the output power. Thus the MPPT requires only the knowledge of V_s and I_s . The existence and uniqueness of the MPP for this kind of structure is presented in [13].

3 DIFFERENT LAYOUTS OF THE CBS STUDIED

3.1 Models of Losses

To compare different CBS layouts we have defined the waveforms and values of voltages and currents experienced by semiconductors and inductors for structures with n stages.

Losses in this converter are due to four components: the inductance, the Mosfet, the diode, and the capacitor.

The inductance losses have been assessed in two different parts. The first part, the copper losses are estimated with the Equation 5 and, the second part, the core losses are estimated with the Equation 6 [14, 15]:

$$Losses_{ohm} = \sum_{h=0}^{\infty} R(h) \cdot I_{eff-h}^2 \quad (\text{Eq. 5})$$

$$Losses_{Core_vol} = k \cdot B_{ac}^a \cdot f^b \quad (\text{Eq. 6})$$

Concerning the semiconductors, conduction losses, switching losses but also Miller effect losses were modeled with a classical model. The model of these losses is based on the following equations.

$$Losses_{MOS} = R_{ds(on)} \times I_{off}^2 + \frac{1}{2} \times V_m \times (I_{Ton} + I_{RM}) \times (t_{on} + t_{RM}) \times F + \frac{1}{2} \times I_{Toff} \times t_{off} \times V_m \times F + \frac{1}{2} \times (C_{oss} + C_d) \times V_m^2 \times F \quad (\text{Eq. 7})$$

$$Losses_D = V_F(I) \times I_{d(moy)} + V_d \times Q_{RR} \times F \quad (\text{Eq. 8})$$

It is assumed that the capacitor losses are neglected considering its weak influence in regard of other components.

3.2 Different layouts of the CBS studied

The goal of this study is to design a PV module with an integrated CBS system. In order to limit the size of the studied module, the maximum number of cells is set to 144, which represents the size of two current modules. A comparison of four different layouts of PV module with an integrated CBS system is done keeping the input PV cells number and the input available power equals. All layouts have 8 groups of 18 PV cells connected in series (Figure 2). These 4 CBS layouts are also compared to a traditional PV module: 144 PV cells connected in series with a by-pass diode all 18 PV cells.

To have the same output voltage the different layouts are connected to a 400 V DC bus throughout a DC/DC converter (Figure 2) and the efficiency of these different DC/DC converters is considered dependent to the input-output voltage ratio. The efficiencies of the DC/DC converters in function of their input voltage have been measured. They are presented in the Table 1.

Table 1: Efficiencies of the different DC/DC converters

	Maximal efficiency	European efficiency
18 V – 400 V (Layout 1 & 4)	95.19 %	94.42 %
36 V – 400 V (Layout 2)	96.29 %	95.45 %
72 V – 400 V	96.57 %	95.80 %

The global efficiency of the system takes into account this efficiency.

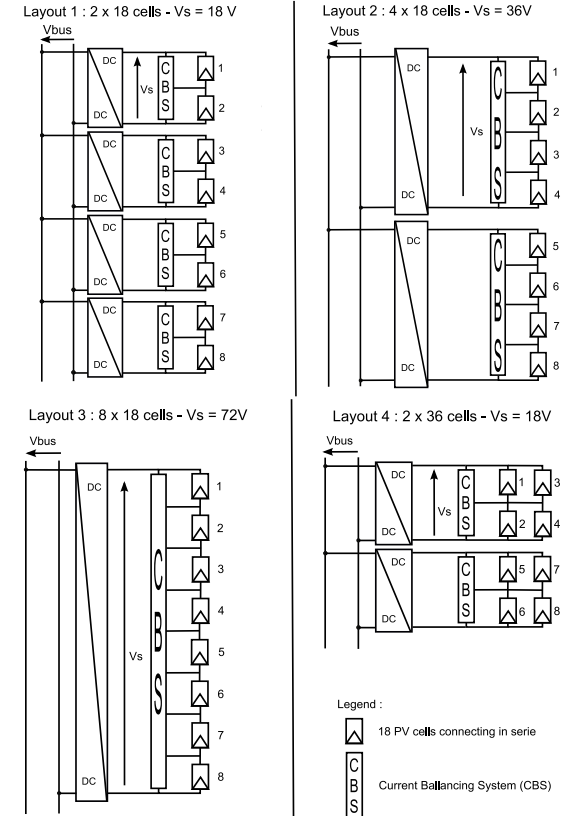


Figure 2: Layouts of the 4 different CBS studied

3.3 Shading scenarios

These 4 layouts are compared in different cases of working with the traditional solution. The PV cells current-voltage characteristics are the real characteristic of 5 inch multi crystalline PV cell. These characteristics are issue of measurements (Table 2).

Table 2: Characteristics of the PV generators at the STC

Characteristics at 1000W.m ⁻² and 25°C		
Ie1 = 7.11	Ve1 = 8.65	P1 = 61.50
Ie2 = 6.91	Ve2 = 8.90	P2 = 61.50
Ie3 = 6.56	Ve3 = 8.95	P3 = 58.71
Ie4 = 6.54	Ve4 = 8.95	P4 = 58.53
Ie5 = 6.52	Ve5 = 8.95	P5 = 58.35
Ie6 = 6.52	Ve6 = 8.85	P6 = 57.70
Ie7 = 6.51	Ve7 = 8.95	P7 = 58.26
Ie8 = 6.37	Ve8 = 9.05	P8 = 57.65
(A)	(V)	(W)
P _{tot} = 472 W		

The first case studied, is the operating in the Standard Test Conditions (i.e. 1000W/m² and 25°C). All PV cells have the same condition of irradiation and temperature.

In order to complete this comparison, the study of the output power is realized using 20 different shade scenarios showed in the Figure 3.

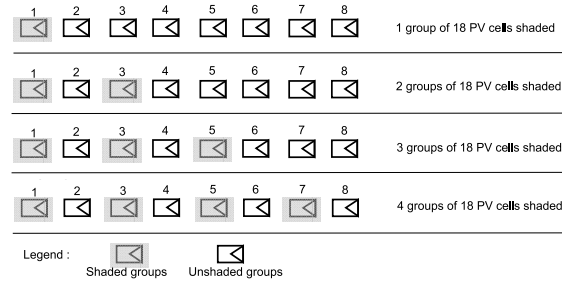


Figure 3: Shading scenarios

The simulated shade can impact 1, 2, 3 or 4 groups of 18 PV cells and this shadow can have an opaqueness of 0% (no shade) to 100% (entirely shaded, no power). Different levels of shadow are simulated: 0%, 20%, 50%, 70%, 85% and 100%.

4 THEORITICAL RESULTS

All models of losses and equations of the CBS are computed using a Mathcad program. This program forecasts the power losses of the topology depending on the number of level and the real characteristics of the components. Then, output power level using CBS is compared to the one obtained with a classical module PV.

4.1 Homogeneous irradiation

The Figure 4 shows the simulation results when the irradiation is homogeneous. In these conditions the layouts 1, 2 and 4 are more efficient than the traditional solution. These topologies produce 4% more power. The CBS with 8 levels (Layout 3) is less efficient than the traditional module due to a lower efficiency of the DC/DC converter when the input-output voltage ratio increases.

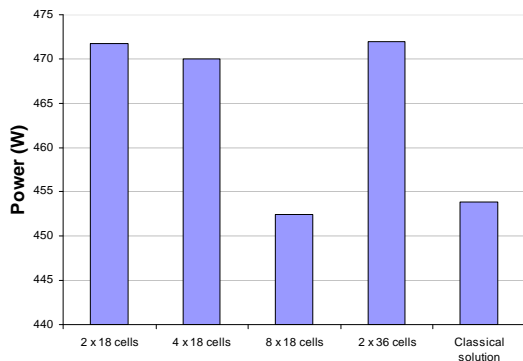


Figure 4: Output power at the MPP (STC)

4.2 Shadow impact

After the study of the performance of the CBS with a homogenous irradiation, this part presents the study of the performance of different layouts of the CBS with different shading scenarios. Figures 5 and 6 show the performance obtained for the different topologies in

comparison with the performance of a classical PV module.

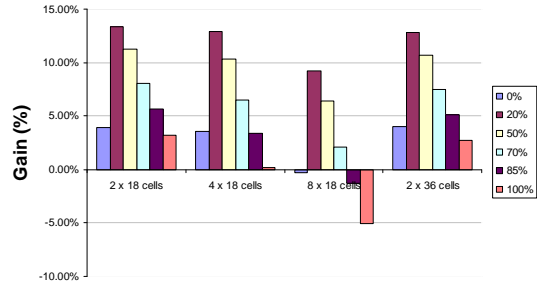


Figure 5: Gain of output power related to the classical solution – One group shaded

As we can notice layouts 1, 2 and 4 are more efficient than the classical PV module and the CBS with 8 levels (Layout 3) is less efficient. This behavior is logical because the Mosfets are designed to withstand a voltage equal to V_s . When the number of levels increases, the voltage V_s increases so the switching losses increase rapidly. In fact, this increase of power losses limits the number of level.

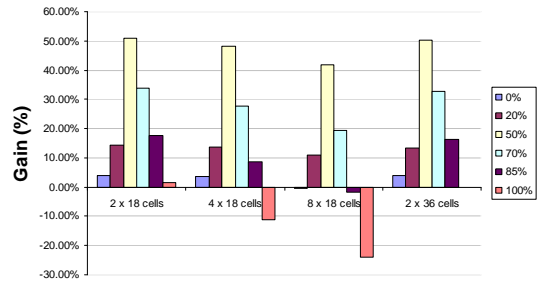


Figure 6: Gain of output power related to classical solution – Four groups shaded

The integration of the shadow impact confirms the interest of the CBS. On one hand, layouts 1, 2 and 4 increase significantly the available output power in comparison with the traditional PV module. These topologies can increase power production up to 50% in some shade scenarios. On the other hand, the integration of the shadow impact in this study confirms the limits of the CBS with 8 levels (Layout 3).

5 EXPERIMENTATION AND RESULTS

The simulations have clearly shown that the layout 2 is the most efficient. A prototype of a 72 multicristallin PV cells module with an integrated CBS has been designed. The CBS have 4 levels with each level connected to 18 PV cells at its input. The efficiency of this prototype is compared to the efficiency of a traditional 72 multicristallin PV cells module. The scenarios studied are the same that the scenarios studied in simulation.

5.1 The prototype

Input voltage of the prototype is 44 V and nominal current is 5 A. During the prototype design, all the components have been chosen carefully to limit the power losses. The modulation frequency of the CBS is 50

kHz and the control is realised with a DsPIC.

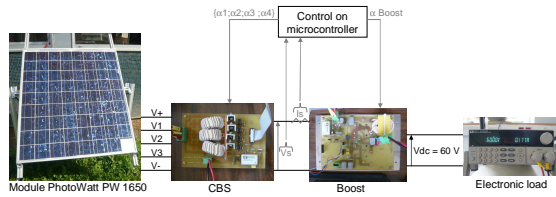


Figure 7: Global view of the prototype

To characterize the performances of the CBS a test bench has been realized. This test bench is presented Figure 7. Outputs of the PV module are connected to the CBS and outputs of the CBS are connected to a Boost and the whole is connected to an electrical load simulating a 60V DC bus.

The input voltage and the input current of the Boost are measured and the CBS can be easily turned off. Therefore the performances of the PV module with and without the CBS can be compared. The results of these comparisons are presented on the Figures 8, 9 and 10.

5.2 Experimental results

The first test is realized with a homogeneous irradiation on the PV module and the characteristic P(U) of the PV module obtained in these conditions with and without the CBS are presented in the Figure 8. It can be seen that the characteristics of the module with and without CBS are similar.

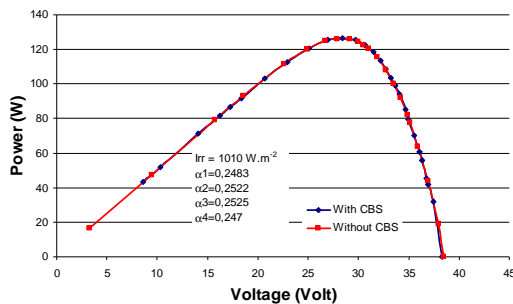


Figure 8: P(U) without shadow

The second experiment is performed with inhomogeneous irradiations using the different shading scenarios presented in part 3.3. In all shading scenarios the CBS increase the available output power related to the classical PV module. The gain can reach up 45% when 2 groups of 18 cells are shaded at 70% (Table 2).

The Figure 9 presents the characteristics P(U) of a module PV with and without CBS when one group of 18 cells is shaded at 50%.

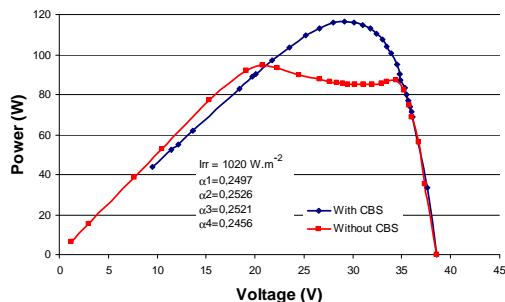


Figure 9: P(U) with one group shaded at 50 %

Two interesting conclusions can be made. First, the module with CBS have a greater output power than a classical module and, second, the characteristic P(U) have only one maximum against two without CBS. This characteristic with only one maximum greatly simplifies the MPP research. The same two conclusions can be made in all shading scenarios.

The Figure 10 shows the characteristic I(U) in this same shading scenario.

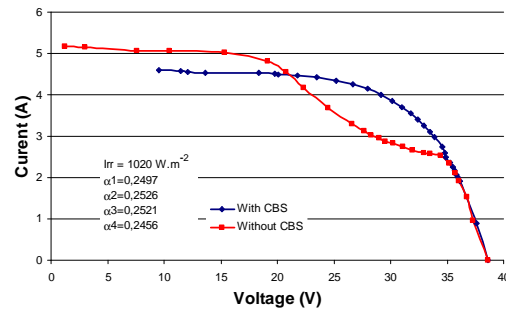


Figure 10: I(U) with one group shaded at 50 %

The Table 3 presents the comparison of the performances of the PV module with and without the CBS.

Table 3: Output power with and without CBS in different shading scenarios

	Maximal Power with CBS (W)	Maximal Power without CBS (W)	Gain (%)
Without Shadow 1	128.6	128.8	-0.17
Without Shadow 2	126.6	126.3	0.20
1 group 20 %	126.52	122.49	3.29
1 group 50 %	116.77	94.76	23.23
1 group 70 %	108.65	94.69	14.74
1 group 85 %	102.37	94.39	3.45
1 group 100 %	96.69	92.75	4.25
2 groups 20 %	117	115.6	1.20
2 groups 50 %	95.6	81.6	17.2
2 groups 70 %	82.8	57.1	45.00
2 groups 85 %	71.9	54.8	31.2
2 groups 100 %	63.7	55.5	14.8

With a homogeneous irradiation the performances with or without the CBS are equal. With a shade on the module the performances with the CBS are greater.

6 CONCLUSION

In this article, a topology of power electronics balancer for a PV system is presented. This topology is able to balance the PV current to permit every PV generator to work at its own Maximum Power Point. To study the interest of this Current Balancing System, a model of the power losses in this topology has been developed. This model has been used to estimate the

efficiency of different layouts of the Current Balancing System. These comparisons have shown that the layout with 4 levels and 18 PV cell on each level is the most efficient. This optimal solution has been realized and experimental results show that this module with the CBS integrated is more efficient than the traditional by-pass PV module in all conditions. This gain can very important in case of shade (+45%).

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