Analyzing and Modeling the Power Optimizer for Boosting Efficiency of PV Panel

Miodrag Forcan, Jovana Tuševljak, Slobodan Lubura, Milomir Šoja
Faculty of Electrical Engineering East Sarajevo
East Sarajevo, Bosnia and Herzegovina

Abstract— **This paper presents a design procedure of the power optimizer, with the aim to enhance more energy from solar string. It is suggested suitable topology, as well as a controller with ability of Maximum Power Point Tracking (MPPT) and idealized mathematical calculations for selecting converter's components. By simulation analysis were shown advantages of using the power optimizer to operate in cascade with the solar panel.**

Keywords- Power optimizer;MPP tracker, Assisted panel; Panel mode.

I. Introduction

In recent years, in the world is present expansion of the use of renewable energy sources, primarily solar sources. In order to achieve higher levels of power, individual PV panels are connected into a string. One of the basic problems that occur by using a string is unequal conditions of insolation and temperature. The most represented solution is the use of DC-DC converters. In this way, the module should be less sensitive to changes in the string and capable to work in the maximum power point. This is usually achieved by using buck-boost converter, with panel operation mode, where input and output of converter are bypassed.

The key to obtaining high efficiency of this application is the minimization of power losses. By designing a control with the possibility of tracking the maximum power point, and selecting the appropriate components, is achieved a significant reduction of power losses. This concept of processing power, obtained from solar sources, is relatively new in the world of solar technology and offers high efficiency.

II. Partial Shading of a String of PV Panels

The solar radiation spectrum in the urban and suburban settings is widely non-uniform. Uniformity of the PV cell operating conditions, including uniformity in irradiance and temperature, is essential to maximize the power output of a string of PV panels.

All the PV cells in the string share the same current, and when a cell or group of cells is shaded, one of two scenarios may occur [1]:

- The group of shaded cells will try to drive the unshaded ones into operating at a lower current level. In this case the system output power is limited by the current produced by the panel generating the lowest output current.

-The unshaded cells will try to drive the shaded ones into operating at a higher current level.

In order to address and try to mitigate the series string problem, a concept called the Module Integrated Converter (MIC) was developed. The overall tolerance of the system against irradiance mismatches is improved because now each panel is not affected by the operating conditions of its neighbors.

Solar strings with usage of DC-DC converters are usually called assisted strings. It is common that string contains one or more reference panels (panels without DC-DC converters) and that the rest of solar modules are coupled with DC-DC converters. The value of the output current is fixed and dependent of insolation and temperature of reference panels [2]. If the reference panel is more insolated than the rest of a string, DC-DC converters of assisted panels need to buck its output voltage in order to adjust its output current to the common string current. When the assisted panels are more irradiated than the reference panel, DC-DC converters need to boost up their output voltages in order to adjust the output current to the lower string current of the reference panel. Described operating modes of DC-DC converter are shown in figure 1.

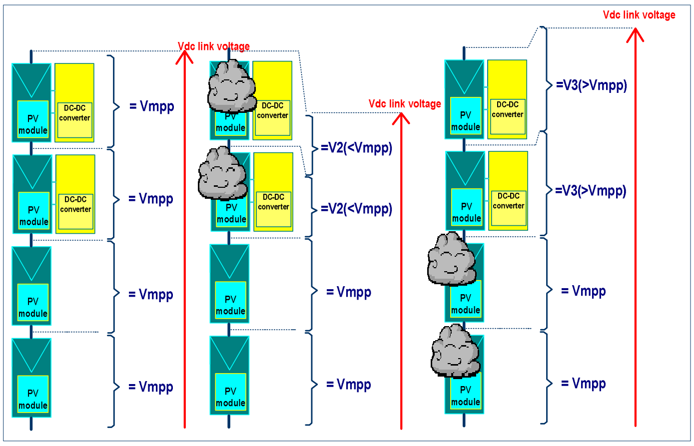

Figure 1. Buck and boost operating modes of DC-DC converters

In terms of current-voltage (I-V) curve characteristics, when the panels with different characteristics are connected in the same string , with DC-DC optimizer assisted panel, the MPP of DC-DC converter can move along the curve of "*Pout* = constant" in order to adjust the output current to the string current, which is shown in figure 2.

DC-DC converter with capability of MPPT is called power optimizer.

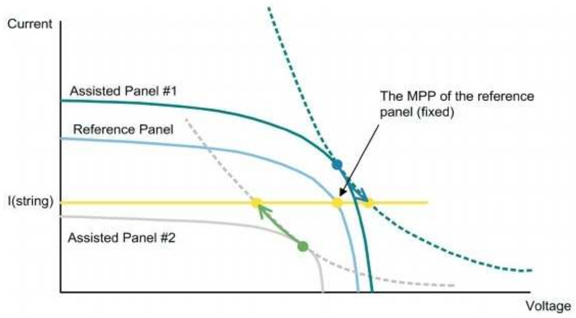

Figure 2. I-V curve of a single string with partial DC-DC units (1 reference panel and two assisted panels)

III. Topology of the Power Optimizer

In real conditions current-voltage characteristic of PV panel is very sensitive to changes in temperature and insolation. For this reason, the converter must be designed with great flexibility in these variations and should be able, if is necessary, to boost or buck the input voltage. So, as a logical solution is imposed the use of topology converter buck-boost. There are two basic variants of this topology, which are used: with four transistor switches and with two transistor switches. In figure 2 is shown the selected topology of the synchronous rectifier.

Topology is consisted of power inductor L_1, buck switch leg including Q_1 and Q_2, boost switch leg including Q_3 and Q_4, input and output filter capacitors C_{in} and C_{out}, output bypass diode D_1 and panel mode switch, implemented with common-gate and common source MOSFETs Q5A and Q5B [3].

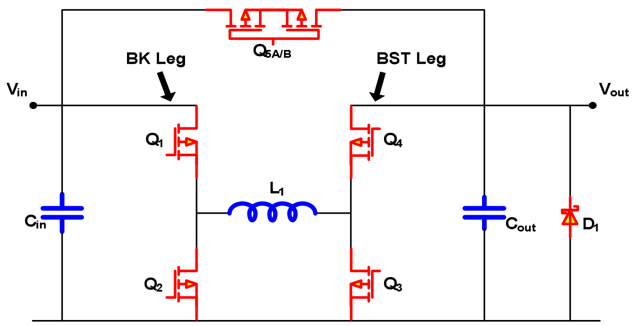

Figure 3. Selected toplogy of synchronuous rectifier

Theoretically Q_2 and Q_4, the two synchronous rectifiers, can be replaced with rectifier diodes without affecting the operating function. The circuit seems simpler, but efficiency-wise the diode will cause more conduction losses than the synchronous rectifier, making the use of a diode prohibitive in the converter legs.

IV. Operating Modes of DC-DC Converter

Based on real time assessment of the operating conditions, the MPPT/ PM ("Maximum Power Point Tracker/ Panel Mode") controller will dynamically determine an optimal mode among the three, so as to operate the converter to track the maximum power point of the PV panel. There are three possible modes, as shown in figure 3:

A. Panel mode

When the optimal operating conditions falls into a narrow window that I_{in} and I_{string} are within about ±2% of each other, the panel mode is engaged to take the advantage of the almost lossless energy harvest feature. In this mode $Q_{5A/B}$ remains ON while the DC-DC converter shuts down, establishing a direct link between the PV panel output and the string. When the panel mode is not the optimal operating condition, the MPPT/PM controller will turn-off PM switches and engage the DC-DC converter for maximum power tracking.

B. Buck (BK) mode

When the PV panel's input current is lower than about 98% of string current, the controller will run the converter in the buck mode. In this mode, Q_1 and Q_2 are switching, while Q_3 remains OFF and Q_4 stays ON.

C. Boost (BST) mode

When the PV panel's input current is greater than about 102% of the string current, the controller will run the converter in the boost mode. Only Q_3 and Q_4 are switching, while Q_2 remains OFF and Q_1 stays ON.

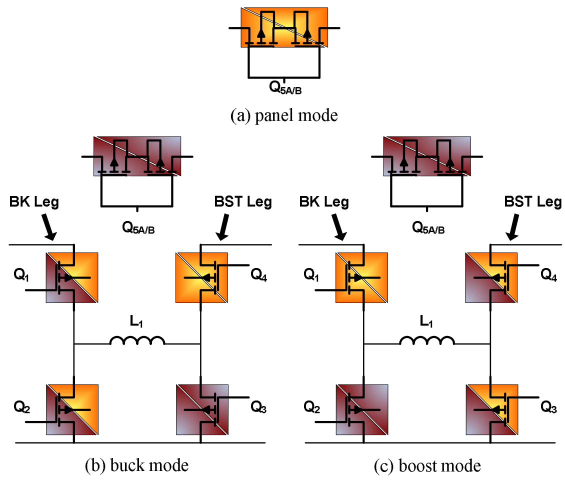

Figure 4. Operating modes of buck–boost converter

In the case when there is a total collapse of the converter or when the panel is very little sunlighted ("heavy shading"), current string is blocked. Due to the appearance of a small negative voltage at the output of converter, it is enabled the use of diode which allows an alternative path for the current string.

V. The Selection of Components of Power Optimizer

In the process of selecting of converter's components is necessary to take into account many factors which define the electrical characteristics, required by consumers.

A. PV panel characteristics

To select the components for the power stage of the converter shown in figure 3, we first need to have specifications of PV panel:

-P_{max}: PV panel maximum power level

- V_{OCmin}, V_{OCmax}: Minimum and Maximum PV panel open circuit voltages

- V_{MPPmin}, V_{MPPmax}: Minimum and Maximum MPP voltage. Because of PV panel I-V curve linearization process, these parameters may sometimes be approximated by:

$$V_{MPPmin} \cong 0.78 \cdot V_{OCmin}, \tag{1}$$

$$V_{MPPmax} \cong 0.78 \cdot V_{OCmax}. \tag{2}$$

- I_{SCmax}: PV panel maximum short circuit current

- I_{MPPmin}, I_{MPPmax}: Minimum and Maximum PV panel MPP current. Obviously,

$$I_{MPPmin} = \frac{P_{max}}{V_{MPPmin}}, \tag{3}$$

$$I_{MPPmax} = \frac{P_{max}}{V_{MPPmax}}. \tag{4}$$

B. Specifications of converter's output

- V_{OUTmax}: Maximum output voltage

- V_{OUTmin}: Minimum buck down voltage at full power, which may be determined by the following:

$$V_{OUTmin} = \frac{V_{DClink\_min}}{n}, \tag{5}$$

where V_{DClink_min} is the minimum inverter dc link voltage for maximum power operation, n is the number of panels in the string.

- $\Delta V_{OUTp\text{-}p}$: Maximum peak-to-peak output ripple voltage

C. Other converter specifications

- $\Delta V_{INp\text{-}p}$: Maximum peak-to-peak input ripple voltages

- f_{SW}: Nominal switching frequency of converter, with ±10% tolerance.

D. Values for Duty Cycles

Selection of limit values of duty cycles depends on the allowed minumum and maximum voltage conditions of converter's input and output:

$$D_{BKmin} = \frac{V_{OUTmin}}{V_{MPPmax}}, \tag{6}$$

$$D_{BSTmax} = \frac{V_{OUTmax} - V_{MPPmin}}{V_{OUTmax}}. \tag{7}$$

E. Selection of passive elements

In BK mode the inductor L_1 with C_{out} fulfill an output LC filter, and in BST mode with C_{in} an input LC filter. Because both the inductor and capacitors affect on the filter performance, their selections are correlated. The filters are primarily used in the converter to limit the voltage and current ripples by removing high frequency components.

The maximum ripple of the inductor current ("peak to peak"), in the buck mode, is given by:

$$I_{(p-p)bk\_max} = \frac{V_{OUTmin}(1 - D_{BKmin})}{L_1 \cdot f_{SWmin}}. \tag{8}$$

For the boost mode, the maximum ripple of the inductor current ("peak to peak") is:

$$I_{(p-p)bst\_max} = \frac{V_{MPPmin} \cdot D_{BSTmax}}{L_1 \cdot f_{SWmin}}. \tag{9}$$

(2)

A good design practice is to limit the inductor ripple current to below 30% of the maximum DC current, or the peak-to-peak ripple be 60% of the maximum DC current. However, high-quality converters are projected with inductor ripple current of less than 20% ("peak to peak"):

$$I_{(p-p)bk\_max} = 0.2 I_{DCmaxbk} = 0.2 \frac{P_{max}}{V_{OUTmin}}, \tag{10}$$

$$I_{(p-p)bst\_max} = 0.2 I_{DCmaxbst} = 0.2 \frac{P_{max}}{V_{MPPmin}}. \tag{11}$$

Taking into consideration the requirement of the inductor ripple value, the selection of appropriate inductance is made according to the following relations:

$$L_{BKmin} = \frac{{V_{OUTmin}}^2 \cdot (1 - D_{BKmin})}{0.2 \cdot P_{max} \cdot f_{SWmin}}, \tag{12}$$

$$L_{BSTmin} = \frac{{V_{MPPmin}}^2 \cdot D_{BSTmax}}{0.2 \cdot P_{max} \cdot f_{SWmin}}. \tag{13}$$

As a final choice for the inductance value is taken more critical (higher) obtained value.

It is also necessary that L_1 stay away from saturation. Substituting the worst case values, the peak current that L_1 needs to handle without being saturated is given by:

$$I_{L\_BK\_max} = \frac{P_{max}}{V_{OUTmin}} + \frac{V_{OUTmin}}{2 \cdot L_{min}} \cdot \frac{(1 - D_{BKmin})}{f_{SWmin}}, \tag{14}$$

$$I_{L\_BST\_max} = \frac{P_{max}}{V_{MPPmin}} + \frac{V_{MPPmin}}{2 \cdot L_{min}} \cdot \frac{D_{BSTmax}}{f_{SWmin}}. \tag{15}$$

Substituting the input and output ripple specification limits and applying the worst case parameters obtained previously, we can obtain the minimum filter capacitance required to meet the ripple limits, as follows:

$$C_{INmin} = \frac{(V_{OUTmax} - V_{MPPmin}) \cdot V_{MPPmin}}{8 \cdot {f_{SWmin}}^2 \cdot L_1 \cdot V_{OUTmax} \cdot \Delta V_{INpk-pk}}, \tag{16}$$

$$C_{OUTmin} = \frac{(V_{MPPmax} - V_{OUTmin}) \cdot V_{OUTmin}}{8 \cdot {f_{SWmin}}^2 \cdot L_1 \cdot V_{MPPmax} \cdot \Delta V_{OUTpk-pk}}. \tag{17}$$

Obviously, the capacitor's voltage rating should satisfy the following,

$$V_{rating\_of\_Cin} \geq V_{OCmax}, \tag{18}$$

$$V_{rating\_of\_Cout} \geq V_{OUTmax}. \tag{19}$$

Ceramic capacitors are recommended for C_{in} and C_{out}. In addition, C_{in} and C_{out} can be a combination of multiple smaller valued capacitors connected in parallel instead of a single large valued one. Normally this approach can reduce the overall cost owing to component availability, unit price, and procurement lead time.

F. Determine the Power MOSFET Switches

Power MOSFETs are generally selected according to voltage rating, RMS current requirement and peak current. It is obvious that the voltage rating requirements of the four MOSFETs are determined by:

$$V_{rating\_of\_Q1\_and\_Q2} \geq V_{OCmax}, \tag{20}$$

$$V_{rating\_of\_Q3\_and\_Q4} \geq V_{OUTmax}. \tag{21}$$

The peak current of the MOSFETs have same values as the peak current of inductor.

The values of effective current (RMS) of the switches Q_1 and Q_3 are given by relations (22), (23), (25) and (26), where are used higher values, while for the switches Q_2 and Q_4 are defined by expressions (24) and (27).

$$I_{RMS\_Q1\_BK} = \frac{P_{max}}{\sqrt{V_{OUTmin} \cdot V_{MPPmax}}}, \tag{22}$$

$$I_{RMS\_Q1\_BST} = \frac{P_{max}}{V_{MPPmin}}, \tag{23}$$

$$I_{RMS\_Q2\_BK} = \frac{P_{max}}{V_{OUTmin}} \cdot \sqrt{1 - \frac{V_{OUTmin}}{V_{MPPmax}}}, \tag{24}$$

$$I_{RMS\_Q3\_BK} = \frac{P_{max}}{V_{OUTmin}}, \tag{25}$$

$$I_{RMS\_Q3\_BST} = \frac{P_{max}}{V_{MPPmin}} \cdot \sqrt{\frac{V_{OUTmax} - V_{MPPmin}}{V_{OUTmax}}}, \tag{26}$$

$$I_{RMS\_Q4\_BST} = \frac{P_{max}}{\sqrt{V_{OUTmax} \cdot V_{MPPmin}}}. \tag{27}$$

G. Determine the PM Switch Selection

PM switches current rating should satisfy:

$$I_{Q5A} = I_{Q5B} \geq I_{SCmax}. \tag{28}$$

When the converter is in panel mode, the maximum voltage across the PM switches is given by:

$$V_{rating\_of\_Q5A} = V_{rating\_of\_Q5B} > V_{OCmax}, \tag{29}$$

$$V_{rating\_of\_Q5A} = V_{rating\_of\_Q5B} > V_{OUTmax}, \tag{30}$$

where is chosen more critical value.

VI. The Modeling of Power Optimizer with MPPT Controller for Solar Panel BP MSX 120

The Simulations of the buck-bust converter were done in MATLAB Simulink environment.

A. The modeling of a PV panel

TABLE I. ELECTRICAL CHARACTERISTICS OF THE PV PANEL BP MSX

BP MSX 120	
$V_{OCmin} - V_{OCmax}$	35.47 V – 42.1 V
$V_{MPPmin} - V_{MPPmax}$	27.66 V – 33.7 V
$I_{MPPmin} - I_{MPPmax}$	0.73 A – 3.56 A
I_{SCmax}	3.87 A
P_{max}	119.97

The model of a PV panel was realized on the basis of data given by manufacturer [4]. Characteristics of solar panel BP MSX 120 are given in table 1.

B. The modeling of the power optimizer

Table 2 shows additional characteristic of the power optimizer, in the case of designing a string of eight PV panels, with allowed range of voltage changes: 150 V – 450 V.

TABLE II. CHARACTERISTICS OF POWER OPTIMIZER

Power Optimizer	
$V_{OUTmin} - V_{OUTmax}$	20 V – 50 V
$\Delta V_{INp\text{-}p}$	5 %
$\Delta V_{OUTp\text{-}p}$	2 %
f_{sw}	(50 ± 5) kHz

Components of DC-DC converter were chosen in accordance with the equations (1) – (30).

C. Simulation of usage of power optimizer in solar string with one reference panel and one assisted panel

In figure 5 and figure 6 were shown simulation schemes with and without power optimizer, respectively.

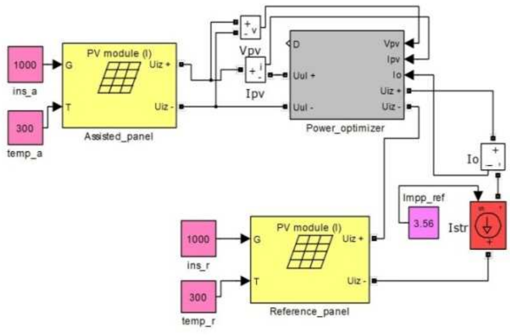

Figure 5. Simulation scheme with power optimizer

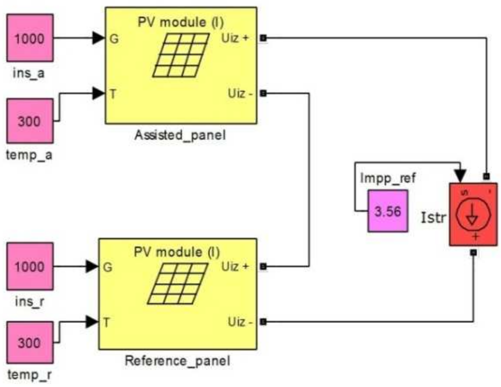

Figure 6. Simulation scheme without power optimizer

Simulations were performed under different circumstances of temperature and irradiance. The value of output current is fixed and for that purpose in simulations was used controlled current source. In the cases when insolation of assisted panel is lower than insolation of reference, DC-DC converter works in BK mode. If assisted panel is more irradiated than reference, DC-DC converter need to boost its output voltage in order to adjust its output current to the common string current.

Simulation results are presented in table 3. With usage of assisted string amount of output power is widely increased.

TABLE III. COMPARATION OF SIMULATION RESULTS FOR NON-ASSISTED AND ASSISTED SOLAR STRING

Insolation (assisted p. / reference p.) [W/m^2]	**String power [W]**			
	Without assisted panel	***With assisted panel***	***Operatio-nal mode***	***Duty cycle***
20/1000	0	120	"BP"	-
500/1000	70	168	"BK"	0.6
800/1000	180	213	"BK"	0.8
1000/1000	240	240	"PM"	-
1000/800	180	211	"BST"	0.2

VII. CONCLUSION

Usage of power optimizers for creating assisted strings improves amount of output power. With precise selection of DC-DC converter components, topology and efficient control with MPPT, power losses can be reduced. The main advantage is independent operation of solar panel from other panels in solar string, which is the perfect solution for main problem called partial shading. Power optimizers represent the basic feature of smart PV systems. This relatively new technology has potential to spread worldwide in the near future.

REFERENCES

[1] Leonor L. Linares, "Design and implementation of module integrated converters for series connected photovoltaic strings", University of Illinois at Urbana-Champaign, 2007, pp 7-9.

[2] Solar Magic by National Semiconductors, "Power optimizers partial deployment for single string systems", application note 2120, Available: http://www.solarmagic.com/en/solaric_solutions.html (accessed: March, 2011).

[3] Solar Magic by National Semiconductors, "Power circuit design For SolarMagic SM3320", application note 2124, Available: http://www.solarmagic.com/en/solaric_solutions.html (accessed: February, 2011).

[4] Marko Lalović, Slobodan Lubura, "PV panel model based on datasheet values", Faculty of Electrical Engineering East Sarajevo, Infoteh, Jahorina, 2010.