Photovoltaic Output Power Improvement Applying DC-DC Converters on Submodule Level

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***Abstract*—This paper investigates the output energy of power optimizers for partial shading conditions and introduces a novel concept for boosting output energy in such situations. A MATLAB/Simulink model on cell level is developed for comparing the output energy of the different circuits to the theoretical maximum. It is shown that for power optimizers even small amounts of shading reduce the output energy significantly. Based on these results, the so called submodule concept is introduced, which overcomes these drawbacks. By integrating ASICs into the PV modules, the number of series connected solar cells is decreased, while additional costs are kept low and high reliability is maintained. The submodule concept provides the largest output energy improvement for low amounts of shading. From an economic point of view this is the most important operating area, since the theoretical harvestable energy decreases with increasing shading. Therefore, the submodule concept is a good and economic solution for increasing the overall energy yield of PV installations.**

I. Introduction

Photovoltaic (PV) energy generation is growing rapidly due to decreasing prices for photovoltaic modules and has the potential to become the dominant electricity generation technology for the 21st century [1]. Still, further price reduction is required to meet grid parity in an increasing number of countries [2]. To achieve this, it is important to look at the complete PV installations and their energy yields instead of considering only module or inverter efficiency.

Different non-idealities, such as inverter reliability, module degradation, or shading, influence the energy yield of PV installations. Analyzing the operational performance of grid-connected PV systems in Germany shows that shading can decrease the output energy up to 20 % [3]. Even a small shade only covering one cell, causes all cells in the same substring to be shortend by the bypass diode. This results in a 20 times higher impact of the shadow for a state-of-the-art 60 cells PV module with three bypass diodes [4]. Typical obstacles for roof top installations, such as trees, antennas, or gables, cover several cells. Nevertheless, these shades cause larger power losses than their theoretical limit due to the series connection of the PV cells and the low number of bypass diodes. Additionally, shading creates multiple local maximum power points (MPP) in the $I - V$ characteristic of the PV string, which makes MPP tracking (MPPT) more difficult and increases the probability that the system is not operated in the global MPP [5]. Deviations of the individual MPP currents of the modules connected in series can increase the losses for shaded conditions even further [5].

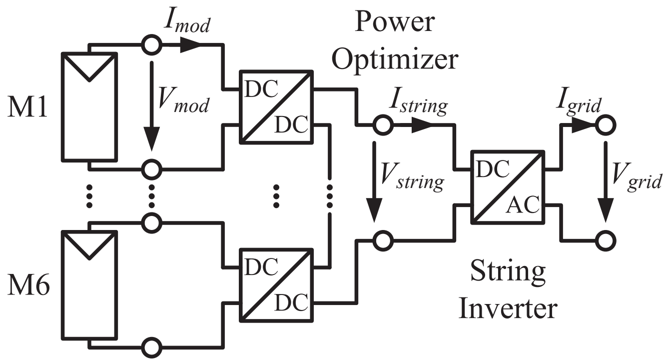

Fig. 1. Power optimizer topology.

To deal with this issue, power optimizers have been developed. They are connected to every module enabling an individual MPPT on module level, as depicted in Fig. 1. This reduces the MPPT losses to module level and enables simpler MPPT lowering the probability of operation in a local instead of a global MPP.

This paper focuses on the influence of shading on the energy yield of PV systems on module level. Therefore, the performance of power optimizers under different levels of (partial) shading is investigated and compared to the theoretical available energy. A MATLAB/Simulink model on cell level taking cell parameter mismatch and different levels of irradiance into account is developed to enable this comparison. For boosting the performance under low partial shading conditions, DC-DC converters on submodule level are applied. After presenting simulation results for this novel concept conclusions are drawn and an outlook is given.

II. MATLAB/Simulink Model

To compare the output energy of power optimizers to its theoretical limit under partial shading conditions, a model of PV modules on cell level is required. In oder to keep the simulation times reasonable, the developed model is limited to one 60 cells c-Si module and its bypass diodes, based on [4], [6]. Not only inhomogeneous irradiance patterns but also variations in the cell parameters can cause mismatches in the output powers of the PV cells connected in series.

These different output powers can cause additional losses, since the string current is equal for all cells due to their series connection. To take this effect into account, Gaussian distributions of the cell parameters have been included in the model based on [7]–[9].

Since the insolation for every single cell can be controlled arbitrarily, any kind of shading, such as special shading patterns or partial shading, can be investigated. If only cells antiparallel to one bypass diode are shaded, the output power drop is significantly smaller, compared to the case, where shaded cells would be distributed equally among all cells. Therefore, the performance of the power optimizer depends on the shading pattern, which is typically location specific. To overcome this issue, random shading patterns and a sufficient large amount of simulation runs are applied for the comparison.

For including the dependence of the performance on the irradiance level, the power optimizer is analyzed at three different irradiance levels, which are weighted by representative durations based on the Meteonrom 7 Software for Munich, Germany. Table I indicates the irradiance levels and durations equal to one year of outdoor exposure for the energy calculation. MATLAB/Simulink and the SimElectronics toolbox have been chosen for building the model, since they enable an accurate modeling of all described phenomena with reasonable simulation times.

TABLE I
IRRADIANCE LEVELS AND DURATIONS FOR ENERGY CALCULATION.

Irradiance Level	$200\,\mathrm{W/m^2}$	$600\,\mathrm{W/m^2}$	$1000\,\mathrm{W/m^2}$
Duration	2124 h	983 h	332 h

III. POWER OPTIMIZERS UNDER PARTIAL SHADING CONDITIONS

For investigating the performance of power optimizers under varying shading conditions, the losses inside their DC-DC converters have been modeled using (1) based on the SPV1020 of STM [10]. To avoid disturbance of the results by MPPT issues, an ideal MPPT has been included in the model.

$$P_{loss} = P_0 + R_{DS,on} \cdot I_{mod}^2 + f_S \cdot C \cdot V_{mod}^2. \qquad (1)$$

Fig. 2 shows the energy output of the power optimizer with respect to the shading factor of the module. The shading factor describes the relative amount of shaded cells, which only receive a fraction of the total irradiance being slightly higher than the diffuse irradiance. Typically, high irradiance correlates with high solar elevation angle reducing the area of shades from surrounding obstacles on the PV module. To account for this, the shading factor for $600\,\mathrm{W/m^2}$ and $1000\,\mathrm{W/m^2}$ are always 0.05 and 0.1 lower than the given one on the x-axis for $200\,\mathrm{W/m^2}$, respectively. The comparison of the output power is performed in 0.01 steps of the shading factor with five simulations per point. Due to the medium simulation number a small ripple in the output energies of the different topologies remains, due to the shading pattern dependency of the output energy.

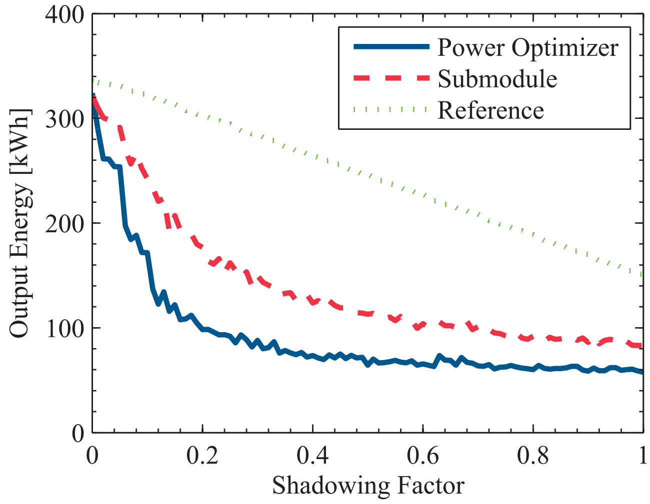

Fig. 2. Comparison power optimizer, submodule concept and reference.

It can be recognized that the output power of the power optimizer drops from 324 kWh to only 254 kWh for 5 % of shaded cells. This is a drop of 70 kWh, which is more than 17 times larger than the 4 kWh reduction of the theoretically available power. For larger shading factors the gap between available power and harvested power increases further to its maximum of about 205 kWh. Another important result of this comparison is, that every time a new irradiance level is minimal shaded the output energy of the power optimizer drops significantly. This can be observed in Fig. 2 at the shading factors 0.01, 0.06, and 0.11.

Increasing the number of bypass diodes per module would improve the output energy of the power optimizer under shading conditions. However, the output power of PV cells in the partial shaded substring would be lost [11]. Additionally, this approach cannot reduce the losses due to mismatch of the MPP currents within one module, which occur even for small amounts of partial shading.

On the other hand the theoretical limit can never be reached, since it implies to connect a separate, lossless DC-DC converter to every PV cell. Hence, some optimal trade-off, which harvests as much energy as possible, but is still economically competitive, has to be found.

IV. SUBMODULE CONCEPT

To overcome the issues of power optimizers the so called submodule concept, shown in Fig. 3, has been developed. The basic idea behind this concept is to integrate several DC-DC converters into PV modules to reduce the number of solar cells connected in series. This decreases the impact of shadows to fewer cells enhancing the output power for shading conditions. Furthermore, this architecture copes better with any kind of output power mismatch conditions of the connected PV cells, which can be caused by cell parameter mismatch or cell degradation.

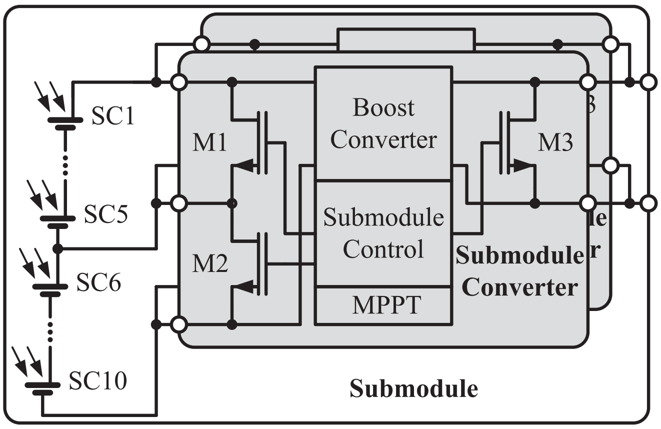

Fig. 3. Submodule topology.

The basic building block of the submodule concept is depicted in Fig. 3. It consists of ten solar cells connected in series and the submodule converter. To enhance the input energy for shading conditions or even single cell failure either the cells SC1 to SC5 or SC6 to SC10 can be bypassed by M1 or M2, respectively. Bypass transistors instead of silicon bypass diodes have been selected, since they have a lower voltage drop in their conducting state and hence lower losses in bypass operation. Furthermore, they can easily be monolithically conintegrated with the other components of the submodule converter, which reduces the component count and costs. An improved MPPT algorithm including a routine for controlling the bypass transistors has been developed for the special requirements of this system [12]. It could be shown that the submodule concept in combination with the improved MPPT algorithm enables very fast MPPT even for rapidly changing irradiance conditions.

The submodule converter itself includes a boost converter, its digital control, the MPPT, and three bypass switches. Inside of the boost converter the input voltage and the input current are sensed. Based on this data the MPPT determines the target input current to keep the PV cells in their MPP. The duty cycle for the boost converter is adjusted by the submodule control to maintain this MPP input current independent of the output voltage. Therefore, the solar cells are operated in their MPP without any disturbance of the string current or voltage applied at the output of the submodule. The MOSFET M3 is used to shorten the outputs of the submodule. This is required, if the input power is too low to properly operate the submodule converter or if the output voltage is too high.

For decreasing the resistive losses inside the boost converter, a second submodule converter is connected in parallel to the first one. If the MPP current of the solar cells exceeds 2 A, the second converter is activated, otherwise it is shut down. The converts have been modeled using (1) and the parameter values given in Table II.

To reduce the costs of the submodule converter it will be fully monolithically integrated in a CMOS technology. Only two external SMD devices, the inductor and the output capacitor, are required for every submodule converter. This enables an integration of the submodule converter inside the modules due to its very flat footprint. Since the module already provides protection for the PV cells, the ASICs might not need any additional packaging and could be placed as bare dies inside the module saving costs for their packages. In general, the integration of the submodule converter into the PV modules reduces costs and keeps the additional wiring inside the module at an absolute minimum.

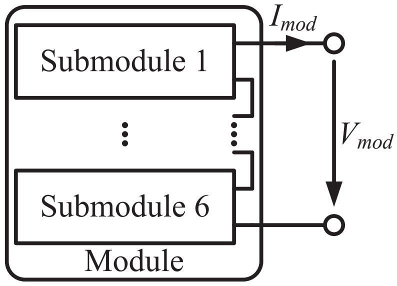

Fig. 4. Submodule configuration for a typical 60 cell PV module.

The safety features of the submodule converter enable a connection of submodules in series, as shown in Fig. 4, without sacrificing error robustness of the whole system. For a typical 60 cells PV module, six submodules have to be connected in series enabling the maximal output voltage boost for the module. To minimize the losses within the boost converters, the ratio of their output voltage to input voltage should be as small as possible. Nevertheless, this configuration can boost the output voltage of the module higher than a single power optimizer for the same input/output voltage ratios due to the increased number of converters connected in series. This reduces the voltage boost required in the inverter and the losses in the DC cabling to the inverter due to the lower DC currents.

The harvested energy with respect to different shading factors for the submodule concept is included in Fig. 2. Due to the smaller number of series connected solar cells and their superior bypass concept, the submodules are able to provide up to 98 kWh (80 %) more output energy than the power optimizer, as depicted in Fig. 5. This absolute maximum difference occurs at a shading factor of 0.12, when all three irradiance profiles are affected by shading. As can be seen from Fig. 5, this is the sweet spot of the submodule concept, where its advantage is the largest. Including the bypass structures the submodule module has twelve substrings of only five cells each. Therefore, the submodule concept performs best for low amounts of shades, when as many substrings as possible still operate at their high MPPs of the full irradiation.

Typical PV roof top systems are only affected by small

TABLE II
MODEL PARAMETER SUBMODULE CONVERTER.

Parameter	$R_{DS,on}$	f_S	C	P_0	$P_{out,max}$
Value	61 mΩ	500 kHz	5.7 nF	55.4 mW	20 W

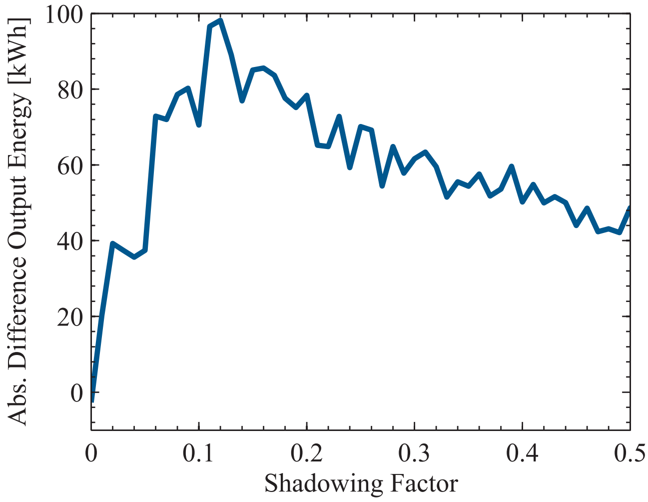

Fig. 5. Absolute output energy difference between submodule concept and power optimizer.

amounts of shade equal to shading factors of a few percent. Hence, this is the most important region for the comparison. As depicted in Fig. 5, the submodule concept provides a higher output energy for all shading factors greater than 0. This means that as soon as some shade falls onto the PV module the submodule shows significant improvements of more than 20 kWh. For the ideal conditions without any shading, the power optimizer performs better, since it has a higher peak efficiency and the output power of the individual PV cells is nearly equal.

Despite its much higher output energy compared to the power optimizer, the submodule is still far away from the theoretical limit. By reducing the number of solar cells connected in series per submodule this gap to the the theoretical limit can be minimized. But this does not come for free. The increased number of required submodule enlarges the cost for the whole system and reduces its peak efficiency. The main part of the losses for the integrated converters are caused by the finite on-resistance of the MOSFETs. Decreasing the number of solar cells per submodule keeps the input current and hence the resistive losses in the switches the same but decreases the voltage and hence the input and output power of the converters. Therefore, their efficiencies drop significantly shifting the break even compared to the power optimizer to larger shading factors. This illustrates, that the PV cell number per submodule has to be optimized for every set of external boundary conditions like PV cell properties, shading factor, or irradiance level. For this comparison ten cells per submodule have been chosen, since this number seems to be a good trade-off between higher output energy yields and additional costs for the external boundary conditions described above.

V. Conclusion & Outlook

This paper investigates the performance of a power optimizer and a novel architecture called submodule concept under different shading conditions. A MATLAB/Simulink model on cell level has been developed to enable a quantitative analysis of the output energy of both architectures. By comparing the output energy for one year with the theoretical limit, it is shown that even small amounts of shade cause huge losses in the output energy of the power optimizer. The novel submodule concept utilizes several DC-DC converters inside each PV module to boost the output power for (partial) shading conditions. To cut down the costs for this approach and to maintain the required high reliability of the PV modules despite two external components, the whole submodule converter should be monolithically integrated in a CMOS technology. In comparison to the power optimizer, significant improvements, especially for low amounts of shade, of more than 80 % can be achieved.

Future steps to prove the benefits of the submodule concept are the development of the required chip, its tape-out, and measurements. Afterwards its performance should be evaluated in longtime outdoor test to gather additional measurement data.

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