SUBSTRING-MPPT FOR 4-TERMINAL 3-SUBSTRING MODULES

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ABSTRACT: State of the art residential photovoltaic (PV) systems are sensitive to partial shading. Shaded modules subjected to lower solar irradiance result in lower current in a PV-string. To minimize power losses string inverters activate bypass diodes in a shaded module resulting in unused power potential. Common module-based power optimizers (MPO) or module inverters lead to mismatch losses in shaded PV-modules. Individual substring maximum power point tracking minimizes mismatch and shading losses for a partially shaded module, resulting in a higher shaded module power output compared to MPOs and bypass diodes. A first unoptimized Substring-MPPT prototype adapted to one substring shaded by 25 % and another one shaded by 30 % raises the output power from 34 % of the theoretical maximum to 90 % whilst avoiding hotspot generation.

Keywords: maximum power point tracker, partial shading, photovoltaic string, bypass diode, substring power loss,

1 INTRODUCTION

State of the art residential photovoltaic systems connect a number i of photovoltaic (PV) -modules M_Y ($Y = 1\ldots i$) consisting of j substrings S_x ($x = 1\ldots j$) in series to form a PV-string. Figure 1a) depicts such a PV-module M_Y consisting of $j = 3$ substrings S_1, S_2 and S_3, with bypass

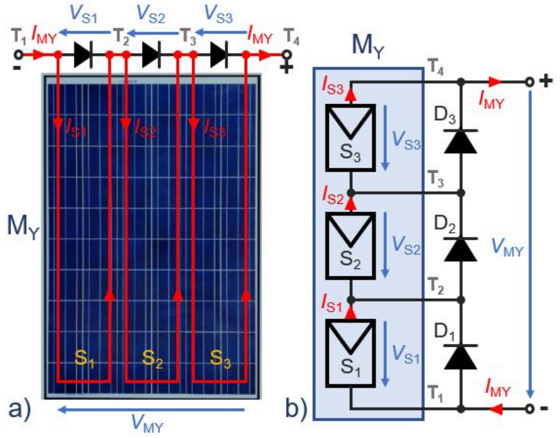

Figure 1: a) Serial connection of substrings S_x in a standard 4-terminal PV-module b) M_Y with protection diodes D_x result in a module voltage $V_{MY}=V_{S1}+V_{S2}+V_{S3}$ and a common module current $I_{MY} = I_{S1} + I_{S3} + I_{S3}$ for homogeneous irradiance.

diodes D_x anti-parallel to each individual substring terminal T_x and T_{x+1} to prevent power losses of unshaded substrings. The serial connection of substrings S_x with substring voltage V_{Sx} results in a total module voltage $V_{MY} = \sum V_{Sx}$ and a common module current I_{MY}. Figure 1b) shows the PV-modules electrical schematic with inactive diodes D_x and the current through each substring I_{Sx} results in $I_{S1} = I_{S2} = I_{S3} = I_{MY}$. String inverters with efficiency $\eta_{ST\_MPPT} \leq 99$ % operate strings at maximum power point (MPP). The serial connection of i PV-modules in a string results in a maximum power $P_{ST,MPP} = \sum V_{MY}\, I_{ST,MPP}$ for all i modules.

Activated bypass diodes D_z short circuit shaded substrings S_z ($z = 1\ldots j$) and allow the string current I_{ST} to match MPP current of unshaded modules in the string. Depending on the severity of the shading string power may increase. Unfortunately, short circuiting of partially shaded substrings via activated bypass diodes results in $V_{Sz} < 0$ and thereby $P_{Sz} < 0$. Consequently, bypassed substrings do not contribute to the string power. Module-based power optimizers (MPO) provide individual operation for each module M_Y at its MPP_{MY} and reduce mismatch losses of the PV-system in case of partially shaded PV-strings. Common MPOs limit the current I_{Sx} of all substrings S_x to the lowest current I_{Sz} of a shaded substring S_z in a module M_Y and translate the limited module current $I_{MY} = I_{Sz} < I_{ST}$ to the string current I_{ST}. Therefore, MPOs result in mismatch losses within partially shaded PV-modules [1]. Available substring MPPT need a number $u = 2x$ Terminals and are incompatible to state of the art Modules with a number of $w = x + 1$ terminals, consequently leading to time consuming and expensive changes in module production. Here we present a substring maximum power point tracker compatible to state-of-the-art modules with w terminals [2].

2 PURPOSE

PV-cells in a substring S_x allow the generation of a current I_{Sx} proportional to solar irradiance $E_{e,x}$. Each substring S_x is composed of k PV-cells connected in series producing a substring current I_{Sx} which can be physically described using an approximated single diode model [3] with $I_{Sx} \approx I_{SC,x} - I_0\,(\exp(V_{Sx} / (k\,V_T)) - 1)$ with $I_{SC,x}$ being the short circuit current of the substring, I_0 the diode reverse saturation current and, V_T the temperature voltage. Therefore, a substring S_x provides an output power $P_{Sx} = V_{Sx}\, I_{Sx} = V_{Sx}\,(I_{SC,x} - I_0(\exp(V_{Sx} / (k\,V_T)) -1))$ with an MPP of $P_{Sx,MPP} = V_{Sx,MPP}\, I_{Sx,MPP} = \max(P_{Sx})$.

Figure 2 shows a mismatch in currents $I_{S1} \neq I_{S2} \neq I_{S3}$ of each of $j = 3$ substrings, with $n = 20$ cells each, individually proportional to inhomogeneous irradiances $E_{e,1} \neq E_{e,2} \neq E_{e,3}$ due to dirt or shading. This results in individual power P_{Sx} with each an individual substring MPP $P_{S1,MPP} = V_{S1,MPP}\, I_{S1,MPP}$, $P_{S2,MPP} = V_{S2,MPP}\, I_{S2,MPP}$ and $P_{S3,MPP} = V_{S3,MPP}\, I_{S3,MPP}$, with the power mismatch $P_{S1,MPP} \neq P_{S2,MPP} \neq P_{S3,MPP}$. The differences to the power points $P_{Sx,MY}$ which each substring S_x contributes to the maximum module power $P_{MY,MPP} = \sum V_{Sx,MY}(I_{Sx})I_{,MY,MPP}$ at $I_{Sx} = I_{MY,MPP}$ show the potential power increase $\Delta P_{Sx} = P_{Sx,MPP} - P_{Sx,MY}$ using individual substring MPP tracking. When considering a standard PV-module M_Y slight differences in irradiance or substring mismatch result in a common module current I_{MY} with a maximum power $P_{MY,MPP} = V_{MY,MPP}\, I_{MY,MPP} < \sum P_{Sx,MPP}$. Larger

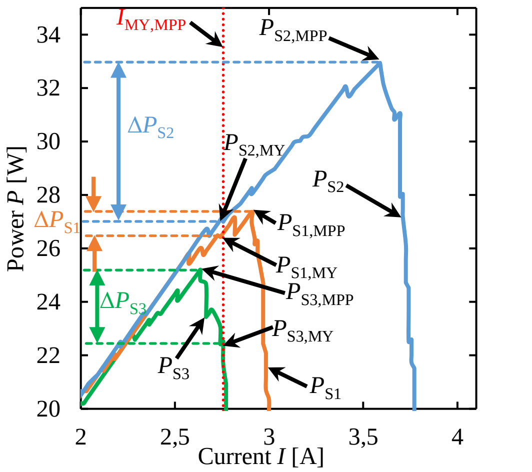

Figure 2: Mismatch of substrings S_x in a standard 4-terminal module M_Y due to unequal irradiance show the potential power output increase $\Delta P_{Sx} = P_{Sx,MPP} - P_{Sx,MY}$ by tracking each substrings MPP $P_{Sx,MPP}$ individually instead of the module MPP with substring power contribution $P_{Sx,MY}$.

differences in irradiance ΔE_e in a PV-string cause the activation of diodes D_z bypassing the shaded substrings S_z with $P_{Sz} < 0$, resulting in a larger module current I_{MY} to achieve I_{ST}, but with a greater power loss of an affected module M_Y. Furthermore, these differences in irradiance on individual modules in a PV-string due to partial shading can result in a complete bypass and zero power generation $P_{MZ,bypass} = 0$ of the affected modules M_Z to achieve I_{ST}, although the shaded modules power $P_{MZ} > 0$ with MPP_Z $P_{MZ,MPP} = V_{MZ,MPP}\, I_{MZ,MPP}$, $I_{MZ,MPP} < I_{ST}$ can still be harvested. To harvest maximum energy from shaded substrings S_z and unshaded substrings S_x ($x \neq z$) in a PV-module M_Y, MPP trackers (MPPT) attached to terminals T_x and T_{x+1} of each substring S_x operate all substrings independently from each other. A first prototype of substring-MPPTs $MPPT_x$, designed for standard 4-terminal PV-modules, prove independent operation of series connected substrings and harvests shaded substrings power P_{Sz}.

3 APPROACH

Figure 3 replaces the protection diodes D_x connected between terminals T_x and T_{x+1} with individual substring maximum power point trackers $MPPT_x$ in parallel to each serially connected substring S_x in a junction box of a standard 4-terminal PV-module M_Y with $j = 3$ substrings. For a shaded substring S_z, $MPPT_z$ adjusts the voltage V_{Sz} to the MPP voltage $V_{Sz,MPP} \approx 1/3\ V_{MY}$ and the current I_{Sz} to the MPP current $I_{Sz,MPP} < I_{MY}$. The power balancing and MPP tracking (PBM) provides the power $P_{z,MPP} = V_{Sz,MPP} I_{Bz,MPP}$ to $MPPT_z$ attached to the shaded substring S_z, allowing $I_{Sz,MPP} + I_{Bz,MPP} = I'_{MY}$ and the power $P_{PBM} = V_{MY} I_Q$ lowers the current $I_{MY} = (I_{Sz} + I_{Bz}) - I_Q < I'_{MY}$ if one or more substrings S_z are shaded. Therefore, in case of shaded substrings S_z, a current interface fits the current I_{MY} to the current I_{ST}.

Homogeneous irradiance on the PV-string with $I_{Sx} = I_{MY} = I_{ST}$ results in $I_{Bx} = I_Q = 0$ A, leading to a true serial connection solely composed of the substrings S_x, and the PBM sets $MPPT_x$ and current interface to standby for maximum energy yield. Standby operation with

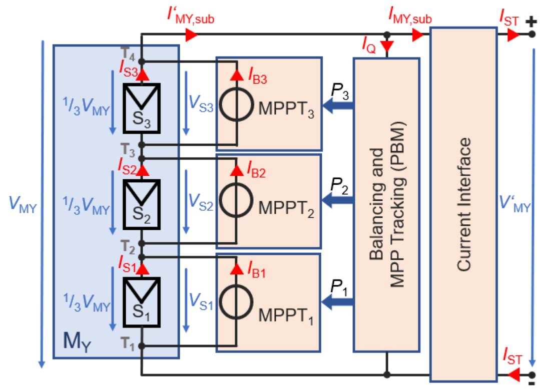

Figure 3: Substring-MPPT for independent I_{Sx} and V_{Sx} of serial substrings S_x. Power balancing sets V_{Sx}=1/3 $V_{MY} \approx V_{Sx,MPP}$ and current interface fits I_{MY} to I_{ST} and V_{MY} to $V_{MY'}$.

$V_{MY} = V'_{MY}$ prevents switching losses in same way the Low Cost MPPT (LCMPPT) increases its efficiency η_{LCMPPT} [4]. The target efficiency $\eta_{SUB} = \eta_{LCMPPT} > 99.5$ % of the inactive $MPPT_x$ without shading represents DC losses $P_{VDC} = (R_{DSon} + R_{LDC})\ (I_{ST})^2$ due to the resistance R_{DSon} of non-switching metal-oxide-semiconductor field-effect transistors and R_{LDC} of inductors integrated in the current interface [5]. In case of partial shading, global MPP tracking of the string inverter activates the current interface to adjust the module current I_{MY} to the string current I_{ST}, resulting in an operation of all modules M_Y of the PV-string at MPP conditions.

4 EXPERIMENTAL RESULTS

First conducted laboratory measurements of a shaded module M_Y fitted with the prototype of the Substring-MPPT regulate $V_{Sx} = 1/3\ V_{MY}$ and provide proof-of-concept curves with a comparison to the same shaded module M_Y with the standard bypass diodes D_x.

Figure 4 shows the current $I_{MY,sub}$ and the power $P_{MY,sub}$ depending on the voltage V_{MY} of a measured module M_Y with substring S_2 shaded by roughly 60 %. The equipped prototype of the Substring-MPPT harvests the individual substring powers P_{S1}, P_{S2} and P_{S3} of the unshaded substrings S_1 and S_3 and shaded substring S_2 with voltages $V_{Sx} > 0$. The individual $MPPT_x$ adapts each

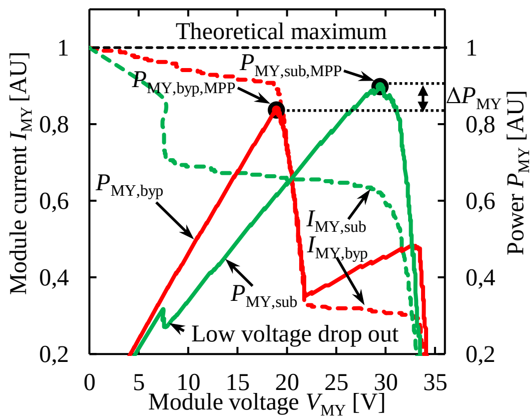

Figure 4: Module M_Y using the Substring-MPPT prototype results in a higher MPP output $P_{MY,sub,MPP}$ than $P_{MY,byp,MPP}$ which uses diode D_2 to bypass the shaded substring S_2.

substring current I_{Sx} to fit the current $I_{MY,sub} = I_{S1} - I_Q = I_{S2} + I_{B2} = I_{S3} - I_Q$ to achieve $P_{MY,sub,MPP} = V_{MY,sub,MPP} I_{MY,sub,MPP} = \sum V_{Sx} I_{MY,sub,MPP}$. Diode D_2 bypasses S_2 with $P_{S2} < 0$ to achieve $P_{MY,byp,MPP} = V_{MY,byp,MPP} I_{MY,byp,MPP}$. Experimental results prove $P_{MY,sub,MPP} > P_{MY,byp,MPP}$ and show an increase in maximum power point from 79.8 % using bypass diode technology to 89.2 % of the theoretical maximum using the Substring-MPPT prototype with one shaded substring. The output power P_{MY} increases by $\Delta P_{MY} \approx 12$ % to $P_{MY,sub,MPP}$ compared to $P_{MY,byp,MPP}$, with potential of an increase of $\Delta P_{MY,max} \approx 25$ % through implementation of an active substring MPP tracking. Use of power electronic components needing certain minimum voltages to function correctly leads to a low voltage drop out of the Substring-MPPT at lower module voltages.

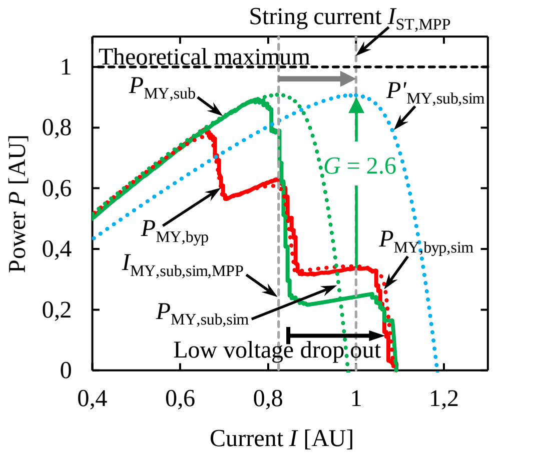

Figure 5: Substring-MPPT reaches a higher module power output MPP $P_{MY,sub}$ by harvesting shaded substring power and the current interface translates $P_{MY,sub}$ to $P'_{MY,sub}$ to adapt to global string MPP current $I_{ST,MPP}$.

Figure 5 shows the module output power $P_{MY,sub}$ depending on I_{MY} of a measured module M_Y with substrings S_2 and S_3 shaded by roughly 25 % and 30 % respectively with the equipped Substring-MPPT prototype. Comparison to $P_{MY,byp}$ of the same module identically shaded with bypass diode technology shows an increase in maximum power output. The power is normalized to the theoretical maximum possible power output of the module with S_2 shaded as above over the current normalized to the global MPP current $I_{ST,MPP}$. The simulated power $P_{MY,sub,sim}$ of the prototype of the substring balancer PBM with ideal components reaches an increase of power by a factor $G = 2.6$ compared to the simulated power output $P_{MY,byp,sim}$ with bypass diodes. The active current interface converts the modules MPP current $I_{MY,sub,sim,MPP}$ to the global MPP current $I_{ST,MPP}$ of the string. The theoretical maximum power output of the module at PV-string global MPP conditions can be achieved by implementing active substring MPP tracking.

5 DISCUSSION AND CONCLUSION

The first prototype of the Substring-MPPT shows proof-of-concept of increasing power performance by regulating the substring voltages $V_{Sx} = 1/3\, V_{MY}$ in respect to the voltage V_{MY} over the three serial connected substrings. Substring balancing optimizes the power of a shaded or mismatched 4-terminal PV-module M_Y compared to standard bypass diodes. The current interface adapts the MPP current $I_{MY,MPP}$ to the strings global MPP current $I_{ST,MPP}$ allowing a forward biased operation of the individual substrings whilst avoiding hotspots. Experimental shading scenarios show a power gain of 8 % for one substring shaded by 60 %. A comparison of measurement and simulation for two substrings shaded by 25 % and 30 % allow an increase in module output power from 34 % of the theoretical maximum power to 90 % by a factor $G = 2.6$ when integrated into a PV-system with the current interface converting the module output current to a global MPP current. The implementation of an active substring MPP tracking and optimization of the Substring-MPPT can provide an additional potential power output increase to the theoretical maximum. For unshaded modules the Substring-MPPT reduces all power losses to minimal DC losses over the integrated non-switching metal-oxide-semiconductor field-effect transistor and inductors. In case of shading, global MPP tracking of the string inverter activates the Substring-MPPTs current interface translating the lower module MPP current $I_{MY,MPP}$ to the higher PV-string MPP current $I_{ST,MPP}$.

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