LOW COST MAXIMUM POWER POINT TRACKER REPLACES BYPASS DIODE

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ABSTRACT: Photovoltaic strings are sensitive to partly shades. In order to prevent power losses due to limitation of string current, string inverters activate bypass diodes and short circuit shaded modules and the power of partly shaded module becomes lost. Using power optimizers or module inverters rises number of devices and increases costs and failure probability. The paper presents the Low Cost Module Maximum Power Point Tracker (LCMPPT). The low cost maximum power point tracker only operates in case of the module is shaded, without shade the device is inactive and prevents losses. Therefore, only modules which potentially became shaded need the LCMPPT, modules without potential shade do not need the LCMPPT. The LCMPPT does not need any communication, and its activated by global maximum power point search of string inverters. When the shade disappears the LCMPPT stops operation and the module directly provides its power to the string without losses due to limited efficiency of the LCMPPT.

Keywords: module maximum power point tracker, partly shade, photovoltaic string, bypass diode, string loss

1 INTRODUCTION

Globally, the installed photovoltaic (PV) capacity rises by about 40 - 50 GWp/a the last years [1]. Usually a PV-system consists of a number N_M of modules connected in series, forming a PV-string. Additionally, a number N_{ST} of strings connected in parallel rises the output power of a PV-system. A partial shade by objects in the near environment lowers the current I_{MY} of a number N_Y of shaded modules M_Y ($1 \leq Y \leq N_M$). Due to the series connection of PV-modules, shaded modules limit the current of all N_M modules of the string. The module with the lowest current $I_{MY,MIN}$ limits the string current $I_{St} = I_{MY,MIN}$. The limitation of the string current prohibits to operate the number N_Z ($Z = 1 \ldots N, Z \neq Y$) of non-shaded modules at their maximum power point and results in significant power losses of the whole string.

In order to minimize power losses due to partial shades, every module uses up to three bypass diodes (BP) connected in parallel to a typical number $N_{CBP} = 20$ of solar cells. In case of partial shades, the diodes short circuit the number N_{CBP} of solar cells in order to rise the string current $I_{St} > I_{MX,MIN}$ [2].

Modern technologies like maximum power point (MPP) tracker (MPPT) or module inverter at each module are able to operate each module M_N at its individual MPP_{MN}. Unfortunately, module MPPTs or inverters at each module rise system costs and failure probability due to the huge number N_M of devices [3]. Additionally state of the art devices need some communication in order to control the PV-String.

This contribution presents the Low Cost Maximum Power Point Tracker (LCMPPT), which individually operates the shaded module at the MPP only if the module limits the string current and rises the current of the string to the MPP current $I_{MZ,MPP}$ of non-shaded modules. In order to rise lifetime and to reduce power losses, the LCMPPT is inactive without any shade. Additionally, only for modules which potentially become shaded, the LCMPPT replaces the bypass diode. Modules, known from shadow simulation of the near environment, without the possibility to become shaded, do not need a LCMPPT device and the number of devices is as low as the number of potentially shaded modules N_Y of the string. Therefore, the use of LCMPPT will rise the annual energy yield of PV-systems with partial shades compared to bypass diodes. Compared to the use of a number N_M of state of the art module MPPTs or module inverters, using a number $N_Y < N_M$ of LCMPPT saves costs.

First chapter 2 analyses shading effects to output power of PV-strings and chapter 3 introduces the LCMPPT and proves that modules without probability to become shaded do not need an additionally LCMPPT, and are protected only by bypass diodes. Chapter 4 presents an experimental proof of concept and compares the gain of output power P_{ST} using LCMPPT of a string of two modules without shade and one module equipped with a LCMPPT device.

2 PV-STRING WITH SHADED MODULES

2.1 Shaded and unshaded modules

The current I_{MX} of PV-modules M_X significantly depends on irradiation compared to voltage V_M. Objects in near environment result partly shades, and limit I_{MX}.

Figure 1 compares the output currents of ideally modeled modules with and without bypass diodes in respect to their output voltage V_{MX} for two different illuminations. The current I_{M50BP} represents a module M_{50BP} with commonly used bypass diodes in parallel to all the number $N_{CBP} = 60$ cells and its shaded by 50% compared to the current I_{M100BP} of a module M_{100BP} without shade. The current I_{M100} represents a 100 % illuminated module and I_{M50} a module, which is shaded by 50 % without bypass diodes. The reduced illumination results in current $I_{M50BP} = 50\ \%\ I_{M100BP}$ and $I_{M50} = 50\ \%\ I_{M100}$ compared to the 100 % illuminated module. Due to the ideal model neglecting series and parallel resistance and breakdown voltage, the short circuit currents $I_{M50,SC}$ and $I_{M100,SC}$ limit the current $I_{M50}(V_M < 0\ V) = I_{M50,SC}$ and $I_{M100}(V_M < 0\ V) = I_{M100,SC}$ also for reverse voltage $V_M < 0$ V. Adding bypass diodes to the modules results in the currents I_{M50BP} for a 50 % shaded module and I_{M100BP} for a module without shade. At module voltages $V_M > 0$ V the bypass diodes are inactive. Operating the module at voltages $V_M < 0$ V the bypass diode becomes active and limits the reverse voltage $V_M > -1$ V. Commonly PV-modules are equipped with bypass diodes in order to prevent hot spot effects due to break down voltage $-30\ V < V_B < -5\ V$ of solar cells [4].

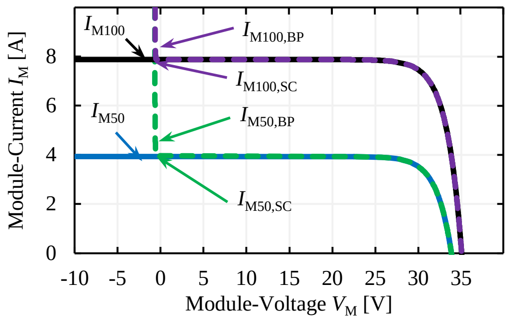

Figure 1: Module current I_{M50} of 50 % illuminated module without and I_{M50} with bypass diode. I_{M100} 100 % illuminated module without and I_{M100BP} with bypass diode. Without bypass diode short circuit currents $I_{SC,50}$ and $I_{SC,100}$ limit $I_{M50} \leq I_{SC50}$ and $I_{M100} \leq I_{SC100}$. With bypass diodes there is no limit.

2.2 Module string without bypass diode

Figure 2a and 2b draw the schematic of PV-strings with a number $N = 3$ of modules M_N in series. The series connection of modules forces the module current $I_{MX} = I_{ST}$ of the module X ($1 \leq X \leq N$) to match the string current I_{ST} and the string voltage $V_{ST} = V_{M1} + \ldots + V_N$ increases with number N of modules. In order to maximize the string power, commonly a string MPPT will adjust $I_{ST} = I_{X,\,MPP}$ to operate the modules M_X at their common MPP-current $I_{ST} = I_{X,MPP} = I_{ST,MPP}$.

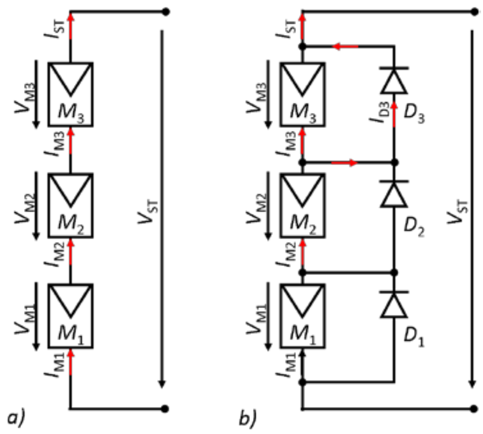

Figure 2: a) Three PV-modules M_X (X = 1..3) connected in series forming a string with voltage $V_{ST} = V_{M1} + V_{M2} + V_{M3}$. Currents $I_{MX} = I_{ST}$ match string current I_{ST} b) Three PV-modules with antiparallel bypass diodes D_X in series connection. Bypass diodes D_X prevent limit of string current $I_{ST} = I_{M3} + I_{D3}$ in case M_3 becomes partly shaded.

Figure 2a) does not use bypass diodes. If one module M_Y ($1 \leq Y \leq N = 3$) becomes shaded and limits the current I_{ST}, the modules M_Z ($Z = 1 \ldots N$, $Z \neq Y$) without shade are not able to operate at their maximum power point current $I_{Z,MPP}$ or voltage $V_{MPP,Z}$. Figure 2b) uses bypass diodes D_N connected parallel to each module in reverse direction. As long as the module voltages $V_{MX} > 0$ V, the bypass diodes D_X of the modules operate in reverse direction. Neglecting the saturation currents of the bypass diodes, the current I_{MX} matches the string current I_{ST}. If one module e.g. M_3 becomes shaded and the voltage $V_{M3} > 0$ V prevents a current $I_{BP3} \approx 0$ A, I_{M3} limits the current $I_{ST} = I_{M3}$. If the module voltage $V_{M3} < 0$ V drops, the diode D_3 operates in forward direction and the current $I_{D3} + I_{M3} = I_{ST}$ allows $I_{ST} = I_{MZ}$ to match the maximum power point current $I_{MZ} = I_{Z,MPP}$ of the non-shaded modules M_Z.

2.3 String power

Figure 3 compares the output power P_{M50} of modules M_Y shaded by 50% to the output power P_{M100} of modules M_Z without shade. In matters of fig 2a a string of three non-shaded modules result in a string power P_{ST100} providing a maximum output power $P_{ST100,MPP}$. If one module is shaded by 50% the string power P_{ST50} significantly drops and the possible maximum string power $P_{ST50,MPP} \approx 50$ % $P_{ST100,MPP}$ is as low as the whole string would be shaded by 50%.

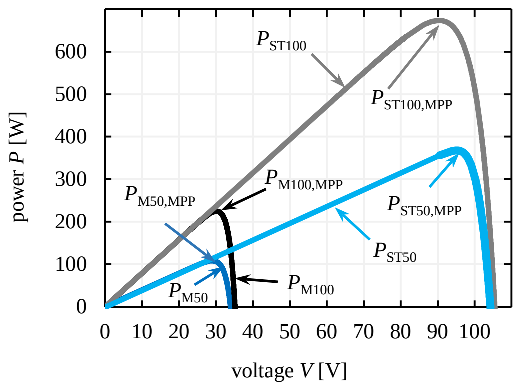

Figure 3: Power P_{M100}, with maximum $P_{M100,MPP}$, of 100 % and P_{M50}, with maximum $P_{M50,MPP}$, 50 % illuminated module. Three modules in series, P_{ST100}, with maximum $P_{ST100,MPP}$, all modules 100 % illuminated and $P_{ST,50}$, with maximum $P_{ST100,MPP}$ two modules 100 % and one module 50 % illumination.

Figure 4 calculates the module power P_{M50BP} of shaded modules $M_{Y,BP}$, equipped with bypass diodes D_Y and P_{M100BP} of non-shaded modules $M_{Z,BP}$ with bypass diodes D_Z. Referring to fig 1) in case of module voltages $V_{MN} > 0$ V, the modules $M_{Y,BP}$ and $M_{Z,BP}$ with bypass diodes do not affect the output power P_{M50BP} and P_{M100BP} of the modules. In matters of fig 2b connecting three modules in series results in an output power $P_{ST100BP}$. When no module is shaded, the bypass diodes do not limit the maximum power $P_{100BP,MPP} = P_{M100MPP}$. In case one module M_Y (Y = 3) becomes shaded, while $V_{MY} > 0$ V, the current $I_{MY} = I_{ST}$ limits the string current and limits the string power to $P_{LOCAL,MPP}$. Reducing the string voltage V_{ST} reduces the module voltage $V_{MY} < 0$ V and the current I_{DY} of the bypass diode D_Y rises the string current $I_{ST} = I_{MY} + I_{DY}$ and the power of the string increases to $P_{ST50BP,MPP} > P_{LOCAL,MPP}$.

To reduce power losses due to the shaded modules, state of the art modules use bypass diodes connected in parallel to the modules as described in fig 2b. The string inverter activates the bypass diodes of shaded modules, like module M_3, by doing a sweep measurement of the power voltage characteristic of the string [5,6,7]. Unfortunately, active bypass diodes operate modules at short circuit conditions and they provide no power to the string.

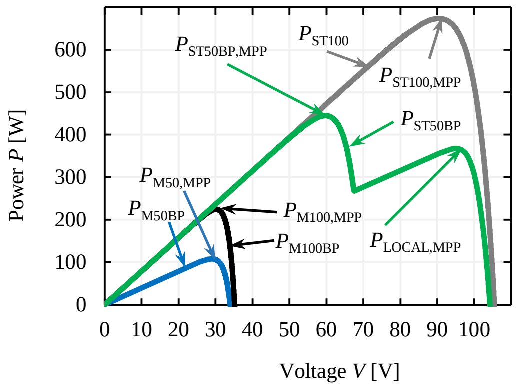

Figure 4: Power P_{M100BP}, with maximum $P_{M100BP,MPP}$, of 100 % illuminated module with bypass diode D, and P_{M50BP}, with maximum $P_{M100,MPP}$, 50 % illuminated with bypass diode D. Three modules in series, $P_{ST100BP}$, with maximum $P_{ST100,MPP}$, all modules 100 % illuminated and $P_{LOCAL,MPP}$ local maximum $P_{ST,MPP50}$ and global maximum $P_{ST50BP,MPP}$ with bypass diode active for two modules 100 % and one module 50 % illumination.

3 OPERATION OF THE LCMPPT

In order to prevent short circuit conditions of partly shaded modules the local maximum power point tracker operates partly shaded modules at their individual MPP. Without shade the LCMPPT is in standby mode and the module current $I_{MY} = I_{ST}$ matches the string current I_{ST}. In case of a shade, the string inverter activates the LCMPPT during Global MPP Tracking Sweep Measurement (GSM). The LCMPPT automatically will turn OFF when the shade disappears. Due to the LCMPPT only operates during partly shading conditions, without the need of communication, it is possible to add the LCMPPT only to modules M_Y which are potentially become shaded. In order to save costs modules M_Z without possibility to become partly shaded by the environment, are protected by common used bypass diodes D_Z.

3.1 Local maximum power point tracker

Figure 5 draws the schematic of the LCMPPT, which bases on the topology of a buck converter. The switch S_1, the diode D and the inductor L_1 form the buck converter. A buck converter adjusts an output voltage $V_{OUT} = dV_{MY}$ in respect to its input voltage V_{MY} varying the duty cycle $d = T_{ON}/(T_{ON}+T_{OFF})$ of a pulse width modulated (PWM) signal. Due to the PWM signal the switch S_1 turns ON for a period of time T_{ON} or OFF for the period of time T_{OFF}. Capacitor C_1 buffers the input voltage V_{MY} and C_2 the output voltage V_{OUT}. Without any shade the currents I_{MY} of modules equipped with a LCMPPT match the direct current (DC) $I_{OUT} = I_{ST}$. In this case the duty cycle $d = 100$ % turns switch S_1 continuously ON and the diode D_1 operates in same way as bypass diodes as described in fig 2b. The closed switch S_1 applies the voltage V_{MY} of the PV-module to the diode D and prevents a current I_D. Due to direct current (DC) conditions $I_{MY} = I_{ST}$, and neglecting the series resistance R_L of L_1, the inductor L_1 does not affect the module current I_{MY} or voltage V_{MY}. In case the module becomes shaded and the string inverter activates the diode D, the voltage $V_{OUT} < 0$ V $< V_{TH}$ drops below a threshold voltage V_{TH} and activates the MPPT of the LCMPPT.

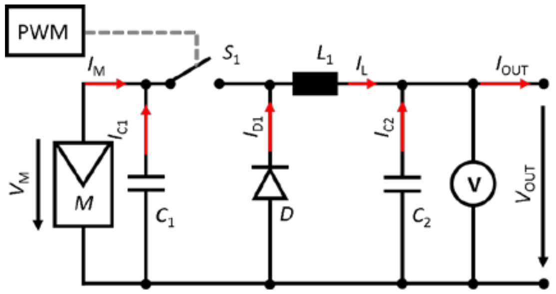

Figure 5: Schematic of LCMPPT. C_1 and C_2 stabilize V_M and V_{OUT}. S_1, L_1 and D forming a buck converter. A PWM signal with duty cycle d boosts I_M to I_{OUT}. Voltage measurement for MPPT

Figure 6 explains the state machine of the LCMPPT. For $V_{OUT} < V_{TH}$ the LCMPPT first switches S_1 OFF and sets the duty cycle $d = d_{MIN}$ to an initial minimum $d_{MIN} << 1$ and the current $I_M = -I_{C1}$ charges C_1. Charging C_1 increases the voltage V_{MY} and buffers the output power $P_{MY} = V_{MY}I_{MY}$ of the module M_Y. During S_1 is switched OFF, the current $I_{D1} = I_L = I_{ST}$ of diode D matches the current I_L of the inductor L_1 and the string current I_{ST}. Controlled by the duty cycle $d = T_{ON}/(T_{ON}+T_{OFF})$ of PWM signal, after a period of time T_{OFF} the switch S_1 turns ON again. During the period of time T_{ON}, the voltage $V_{MY} = V_{D1}$ turns OFF the diode D and the current $I_L = I_{C1} + I_{MY}$ discharges C_1.

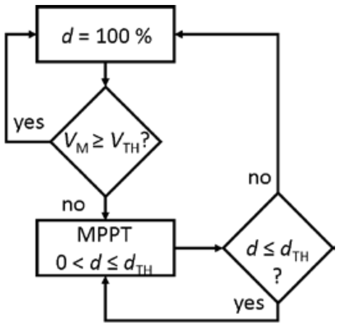

Figure 6: Activation algorithm of MPP tracking. If $V_{MY} < V_{TH}$, MPPT activates. When the shade disappears $d > d_{TH}$ disables the MPPT and $d = 100$ connects MY in series to the modules M_Z.

The transfer function $V_{OUT}(V_{MY})^{-1} = I_{MY}(I_{ST})^{-1} = d$ of the buck converter offers the possibility, that a maximum power point tracker algorithm adjusts the duty cycle d to $d = d_{MPP} = V_{OUT}/V_{MY,MPP}$ to the optimum duty cycle d_{MPP} in order to operate the module M_Y at its individual maximum power point current $I_{MY,MPP} = dI_{ST}$. Neglecting the efficiency $\eta_{LCMPPT} < 1$of the LCMPP, the modules M_Y add their MPP power $P_{MY,MPP}$ to the string power P_{ST}. In order to maximize the string power, $P_{ST} = \Sigma P_{MY,MPP} + \Sigma P_{MZ,MPP}$ the MPPT of the string inverter adjusts the string current $I_{ST} = I_{MZ,MPP}$ to the maximum power point current $I_{MZ,MPP}$ of the non-shaded modules. Once the MPPT of the LCMPPT operates partly shaded modules at their individual MPP, the LCMPPT continuously proves, if the shadows disappeared. In case the shade disappears the current $I_{MY} \cong I_{ST}$ of the partly shaded module increases and matches the string current I_{ST} provided by the non-shaded modules M_Z. For $I_{MY,MPP} = I_{ST,MPP}$ the MPPT increases the duty cycle

$d = I_{MY}(I_{ST})^{-1} \cong 1$. Detecting a duty cycle $d > d_{TH}$ close to 100 %, the MPPT of the LCMPPT stops operation and sets $d = 100$ % in order to permanently connect the module M_Y in series to the modules M_Z of the string.

Figure 7 depicts the series connection of potentially be shaded modules M_Y (Y=3), equipped with a LCMPPT introduced by fig. 5, in series with two non-shaded modules M_Z (Z = 1, 2) protected by commonly used bypass diodes D_1 and D_2.

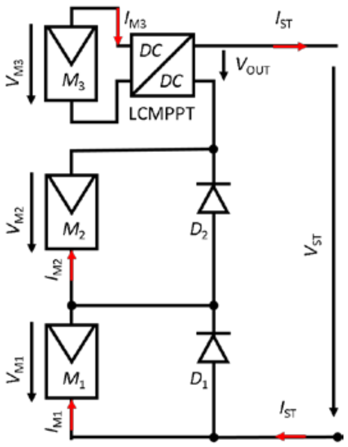

Figure 7: Module M_3 equipped with LCMPPT connected in series to M_1 and M_2 with bypass diodes D_1 and D_2 result in String voltage V_{ST}. In case of shade LCMPPT bucks V_{M3} to V_{OUT} and boosts I_{M3} to match $I_{M1} = I_{M2} = I_{ST}$ of modules M1 and M2, protected by diodes D_1 and D_2.

Due to the MPPT of the LCMPPT stopped operation and the series connection of modules M_Y in series to the modules M_Z, the MPPT of the string inverter adjusts the voltage $V_{ST} = V_{M1} + V_{M2} + V_{OUT} = V_{ST,MPPT}$ and operates the string and also the modules M_Y at MPP. If the party shade of the modules M_Y recurs, the GSM of the string inverter again activates the diode D and the LCMPPT again starts individual maximum power point tracking of module M_Y.

4 EXPERIMENTAL RESULTS

With respect to fig. 7 an experiment proves the use of the LCMPPT technology. The experimental setup uses three modules consisting of 20 solar cells connected in series. Two modules M_1 and M_2 are equipped with bypass diodes D_1 and D_2 and one uses a LCMPPT instead of bypass diodes. Due to laboratory conditions, power LEDs homogeneously illuminate the three modules. A first experiment varies the string voltage V_{ST} without any shade and measures the power $P_{ST,100}$ of the string. A second experiment partly shades module M_3 by 50% In order to reduce the short circuit current $I_{M3,SC} \approx 50$ % $I_{M1,SC} = 50$ % $I_{M1,SC}$ of module M_3 by 50 %.

Figure 8 compares the measured power $P_{ST50,BP}$ of a string using three modules M_1, M_2 and M_3 with bypass diodes to the power P_{LCMPPT} of a string with one module M_3 equipped with the LCMPPT and two modules M_1 and M_2 protected by bypass diodes D_1 and D_2 introduced by fig. 7. Emulation the GSM-measurement of a string inverter the experiment starts measurement at open circuit voltage $V_{ST} = V_{OC} = 32.76$ V. During the sweep measurement to find the MPP of the partly shaded string, the string power P_{LCMPPT} rises to the local-MPP power $P_{LOCAL,MPP} = 10.9$ W. By tracking string voltage V_{ST} in downwards direction, V_{ST} continuously decreases, and the

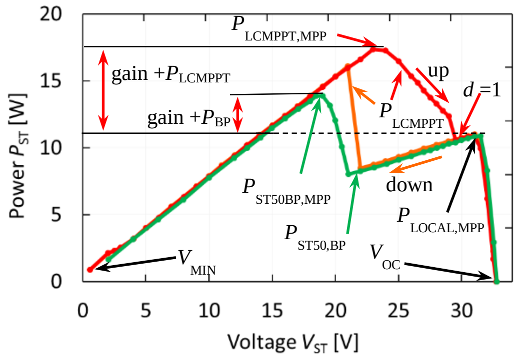

Figure 8: String power $P_{ST50,BP}$ of three modules with bypass diodes, one partly shaded. Bypass diodes rises MPP-power from $P_{MPP,local}$ to $P_{MPP,BP}$ and results power gain $+P_{BP}$. P_{LCMPPT} with LCMPPT during sweep measurement starting at V_{OC}. LCMPPT inactive results $P_{LOCAL,MPP}$, activated string power rises. Starting measurement at V_{MIN} with activated LCMPPT results a continuous power function with maximum power $P_{LCMPPT,MPP}$. LCMPPT rises string performance from $P_{local,MPP}$ to $P_{LCMPPT,MPP}$ and results in power gain $+P_{LCMPP}$ compared to $+P_{BP}$ using bypass diodes to increase power to $P_{ST50BP,MPP}$. $d = 1$ indicates switching OFF of LCMPPT at low string current.

diode D of the LCMPPT, explained by fig. 5, activates at a voltage $V_{ST} = 22$ V and operates M_3 at short circuit voltage $V_{M3} \leq 0$ V. Triggered by $V_{M3} < V_{TH}$ the LCMPPT starts MPP-tracking and operates the shaded module M_3 at MPP and the string power immediately rises. The GSM of the string inverter decreases V_{ST} to minimum voltage $V_{MIN} = V_{ST} = 0.6$ V. After $V_{ST} = V_{MIN}$ the GSM increases the string voltage V_{ST} in order to emulate the MPPT of a string inverter. Usually now the string inverter adjusts the string voltage $V_{ST} = V_{ST,MPP}$ to the detected maximum power point voltage V_{STMPP} and starts a MPPT algorithm. Due to the active LCMPPT increasing V_{ST} from $V_{ST} = V_{MIN}$ towards V_{OC} the power P_{LCMPPT} of the string continuously increases to $P_{LCMPPT} = 17.4$ W $> P_{ST50,BP,MPP}$. Increasing the string voltage to $V_{ST} > V_{ST,MPP}$ reduces the string current $I_{ST} = I_{M3,SC}$ to match the short circuit current of module M_3. For $I_{ST} = I_{M3,SC}$ the duty cycle $d > d_{TH}$ of the MPPT of the LCMPPT turns of the LCMPPT and sets $d = 100$ %.

Comparing $P_{LOCAL,MPP}$ to $P_{LCMPPT,MPP}$ results in power gain $+P_{LCMPPT} = 6.5$ W compared to the power gain $+P_{BP} = 3$ W of $P_{ST50,BP}$ using bypass diodes. The additional power $+P = P_{LCMPPT,MPP} - P_{ST50BP,MPP}$ proves the for surplus of power using LCMPPTs instead of bypass diodes of the LCMPP. Due to the continuous function of the string power P_{LCMPPT} with activated LCMPPT state of the art MPPT are able to track the string to maximum output power.

5 CONCLUSION

The contribution introduced topology, the operation and the system integration of the Low Cost Maximum Power Point Tracker (LCMPPT). The LCMPPT prevents losses of unshaded modules in a string due to shaded modules. The LCMPPT only operates in case the module equipped with the LCMPPT is shaded, without shade the LCMPPT is inactive. Due to the LCMPPT only operates in case a shadow limits the current of a module, only modules which potentially became shaded need the LCMPPT. Modules without potential shade do not need to use a LCMPPT. In order to activate the LCMPPT in case of a shade at the module, the global MPPT search of the string inverter results a voltage drop and the LCMPPT tracks the shaded module to its individual maximum power point. In case the shade disappears, the LCMPPT detects that the MPP current of the shaded module matches the string current and stops operation. The LCMPPT does not need any communication and operates in combination with state of the art string inverters. First experiments result that the LCMPPT prevents power losses due to bypassing shaded modules and provides a maximum string power close to the theoretical power.

6 REFERENCES

[1] Adrian Whiteman et. al., Renewable Capacity Statistics 2016, (IRENA, 3.2016) p. 29

[2] E. Karatepe, M. Boztepe, M. Colak, Development of a suitable model for characterizing photovoltaic arrays with shaded solar cells, Solar Energy 81, (2007) p. 977–992

[3] S. Harb and R. S. Balog, Reliability of Candidate Photovoltaic Module-Integrated-Inverter (PV-MII) Topologies—A Usage Model Approach, *IEEE Trans. Power Electronics*, 28, 6, (2013) p. 3019 doi:10.1109/TPEL.2012.2222447

[4] M.C. Alonso-García, J.M. Ruíz, Analysis and modelling the reverse characteristic of photovoltaic cells, Solar Energy Materials and Solar Cells 90, (2006) p. 1105-1120 DOI: 10.1016/j.solmat.2005.06.006

[5] COOLCEPT, http://www.steca.com/index.php?coolcept-StecaGrid-1500-4200-de

[6] Datasheed, Fronius Primo3.0-1, www.fronius.com (20.6.2016)

[7] SMA, Keine macht den Schatten, http://www.sma.de/partner/expertenwissen/keine-macht-den-schatten.html