Design of a Cell String Level Maximum Power Point Tracking Converter connected to a DC Grid

Lukas Irazusta Gorostidi
DC Opportunities R&D BV
Delft, Netherlands
lukas.irazusta@dc-opportunities.com

Jesse Echeverry
DC Opportunities R&D BV
Delft, Netherlands
jesse.echeverry@dc-opportunities.com

Hidde L. Moens
DC Opportunities R&D BV
Delft, Netherlands
hidde.moens@dc-opportunities.com

Bob van Someren
Elf Software Development
Rotterdam, Netherlands
b.vansomeren@elfsoftware.eu

Laurens Mackay
DC Opportunities R&D BV
Delft, Netherlands
laurens.mackay@dc-opportunities.com

***Abstract*—The presented research focuses on the design and implementation of a maximum power point tracking (MPPT) system for photovoltaic (PV) panels installed on a sailing yacht. This yacht relies solely on renewable energy sources, particularly solar energy when anchored. The unique challenge addressed is the impact of partial shading on the PV panels due to the yacht's masts and sails. A two-step conversion system is developed, where string-level converters adjust to shading conditions to maintain optimal power output. The isolated converter then steps up the voltage for integration into a bipolar DC grid. Experimental results demonstrate that this system significantly enhances energy yield under varying shading conditions.**

***Index Terms*—Maximum Power Point Tracking (MPPT), Photovoltaic (PV) Systems, Partial Shading, String-Level Converters, Bipolar DC Grid, GaN Transistors, and Zero Voltage Switching (ZVS).**

I. INTRODUCTION

Renewable energy solutions are increasingly essential for sustainable marine transportation. Solar energy, in particular, offers a viable solution for powering yachts when they are stationary. However, the efficiency of solar panels is drastically affected by partial shading, a common issue on yachts due to the presence of masts and sails. Traditional series-connected PV cells suffer from reduced output when even a single cell is shaded, as all cells share the same current. This research addresses this challenge by developing an MPPT system that optimizes the power output of each string of cells within the panels.

A widely used solution to mitigate the effects of partial shading are bypass diodes [2]. When a section of the PV panel is shaded, the shaded cells produce less current, creating a bottleneck that can significantly reduce the power output of the entire module [1] [4]. Bypass diodes provide an alternative current path around the shaded cells, preventing these cells from becoming hot spots and allowing the unshaded sections of the panel to continue operating efficiently. This helps maintain overall module performance and protects the cells from potential damage [6] [3].

The system designed for this study includes MPPT converters connected to the PV panels on a sailing yacht, operating under conditions where shading patterns are unpredictable. Each panel, comprising 48 cells in strings of 8, is capable of both electrical and thermal energy harvesting. A novel two-step conversion process is implemented, where string-level converters manage individual strings' outputs, and an isolated converter integrates the power into a DC grid. One of the biggest challenges to tackle is the wide input range voltage of this converter. This study explores the design requirements, topology selections, and operational principles of these converters, highlighting the advancements in managing partial shading and improving overall energy efficiency.

There are existing solutions in the market that employ cell string level MPPT technology such as Taylor Solar [7] or SolarEdge [5] for example. On top of integrating this technology, the research focuses on interfacing it with a bipolar DC grid. In order to accomplish a higher efficiency, a topology morphing control has been integrated on the second converter to adapt its topology depending on the operating conditions.

II. SYSTEM DESIGN

This chapter introduces an overview of the system as well as the use-case. The MPPT converters are connected to the solar panels installed on the deck and rooftops of a sailing yacht. This sailing yacht is solely powered by renewable sources: while sailing, it is possible to charge the batteries located inside the yacht given the regenerative nature of the screw. However, when in anchor all generation comes from solar energy. The yacht still needs to supply loads even when it is not moving. Therefore, maximizing the energy yield generated by the panels is of high importance.

In a standard photovoltaic panel, its cells are connected in series. As a result all cells share the same current. When a cell is shaded, the current it generates reduces affecting the rest of the panel, regardless of whether they are shaded as well, or not. Shading therefore, significantly affects the power output of solar generation. This has a negative impact in stationary applications such as building rooftops or solar parks but is specifically detrimental in mobile applications such a sailing yacht since it is surrounded by masts and sails that create

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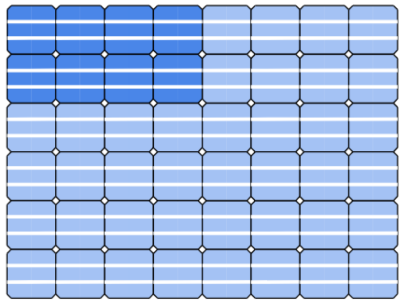

Fig. 1. Drawing of a 48 cell solar panel with one highlighted string. Each sting consists of 8 solar cells and each panel consists of 6 strings.

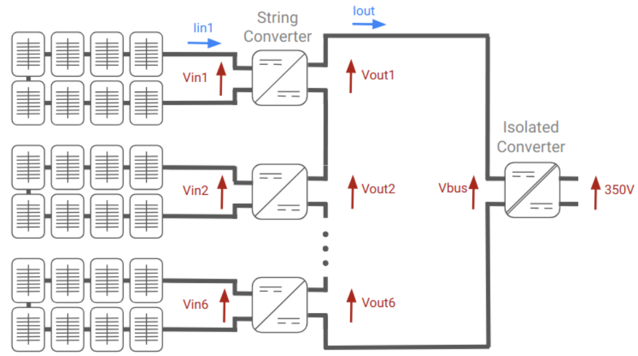

Fig. 2. System Overview Diagram.The system consists of a 2 step conversion. Each string of photovoltaic cells consists of 8 units connected to a string converter. Each system consists of 6 of these and their outputs are connected in series. The second conversion occurs at the isolated converter which connects to the DC grid on the output.

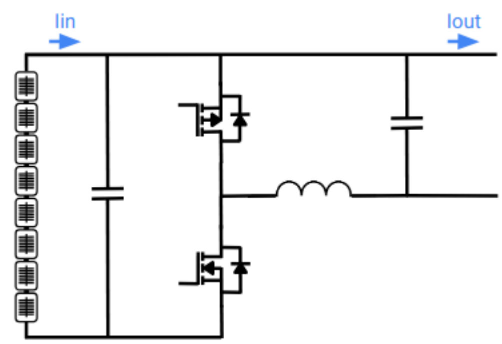

Fig. 3. Low-side-switch step-down converter. Contrary to the conventional step-down converter, this topology utilizes a N-type MOSFET on the low-side switch and a P-type MOSFET on the top-side switch. When the duty cycle is above 50%, the current will flow through the low-side switch most of the time. N type MOSFETs offer better electrical characteristics than P-type MOSFETs.

unpredictable patterns of shading onto the surfaces of the solar panels.

Each photovoltaic panel consists of 48 cells grouped in strings of 8 cells each as depicted in Fig. 1. These panels are designs to also harvest thermal energy from the sun by transferring heat to a fluid that is circulating underneath the panel.

The output of the MPPT optimizer is connected to a bipolar DC grid. This consists of 3 lines: positive, neutral and negative. The nominal voltage between positive-and-neutral and neutral-and-negative is 350V whereas the line to line voltage is 700V. Depending on the load it will be connected to a single line of line-to-line. The converters are connected in an interleaved manner in order to keep the 2 lines of the grid balanced. This way, there will be no current flowing through the neutral line.

The MPPT consists of a 2-step conversion as depicted in Fig. 2. Each of the photovoltaic strings is connected to a step-down string converter. In one panel, there are 6 of these and their outputs are connected in series, hence they share the same current. When a panel is not shaded, all string converters have a duty cycle of 100%. When a string is shaded, its operating point is adjusted to maintain the same output current so that the rest of the strings can operate at MPP. The output of these converters is taken to the second-stage converter that steps the voltage up and feeds power into the DC grid. The topology of this second converter is isolated in order to provide fault tolerance. As a result, in case of failure of a panel the rest of the panels can continue operating under normal conditions.

III. String Level Converter

The first of the 2-step conversion occurs in the string level converter. The purpose of this converter is to collect the power generated by the photovoltaic string connected to it and adjust its operating point when shaded. The topology selected for this converter is a synchronous low-side Buck converter as shown in Fig. 3.

In a step-down topology, the duty cycle can be kept at 100% when the panel is homogeneously illuminated. The input current can bypass the first conversion step as depicted in Fig. 4. In this operating condition, switching losses are eliminated and the 2 elements generating conduction losses are the equivalent series resistance of the inductor and the drain-source on-resistance of the low-side switch. In a low-switch topology, it is possible to use a N type FET on the low-side. N type MOSFETs offer better electrical characteristics resulting in lower conduction and switching losses. Furthermore, the reference point to drive the gate of the low-side switch is connected to the ground of the input, hence eliminating the need to use a level shift driver. The synchronous topology increases the efficiency of the conversion by having a second MOSFET instead of a diode.

When shading occurs in a string its operating point is adjusted by decreasing the output voltage to maintain the same output current as the rest of the strings, allowing these to operate at MPP. Since the outputs of the string converters share the same current, this can measured by the isolated converter. By doing this, it is not required to place current sensors on each of the string converters and hence, reducing the conduction losses.

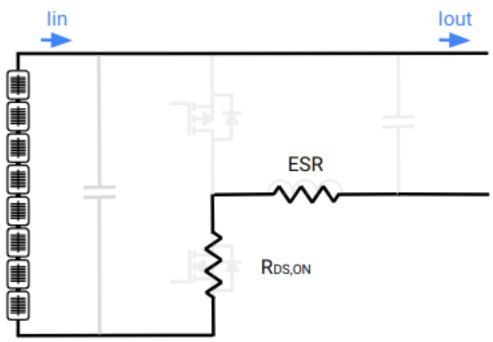

Fig. 4. Current flow at 100% duty cycle. When shading does not occur, switching losses are eliminated and conduction losses occur at the ESR of the inductor and Rds,on of the N type MOSFET.

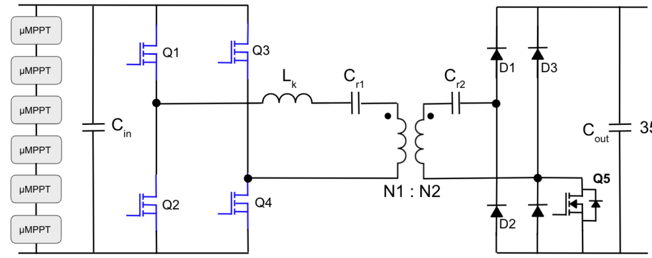

Fig. 5. Schematic of CLLC Isolated Converter. C_{r1} and C_{r2} are the resonant series capacitance of the primary and secondary, respectively. C_{r2} can also be used as a DC blocking capacitor if Q5 is permanently closed. Q1-Q4 are shown in blue because they are 80V rated GaN high electron mobility transistors (HEMTs)

IV. Isolated Converter

A. Design Requirements

The string level converter forms an output bus voltage that ranges from 10-30 V. This bus is comprised of the string outputs of an entire panel. In order to form a connection to the 320-380 V DC microgrid, a step up converter with galvanic isolation is required. Isolation between the DC microgrid and low voltage PV is a safety requirement to prevent human contact exposure to leakage currents and allow for safe interaction with the low voltage PV side. The PV panels in this project were specifically designed to meet various mechanical, electrical, and thermal requirements for the solar yacht. The maximum power of a single panel was determined to be 180W and due to this, gallium nitride (GaN) transistors became advantageous to integrate into the design. The lower power level in combination with GaN technology allows for smaller passive components, higher frequency operation, wider ZVS range (because of low parasitic capacitance in GaN) and overall higher efficiencies.

B. Topology Selection

The CLLC with a step up planar transformer was the selected topology in order to compensate for the converter design requirements. The CLLC with frequency modulation (FM) and dual active half bridge (DAB) with single phase shift control were the two topologies of interest and after evaluation, the CLLC with FM was determined to be the better fit due to the following: no need for active switches on secondary (350 V) side, wider ZVS range at various operation points, output voltage control during no-load scenario, the flexibility / simplicity of FM, and, lastly, operating at higher frequencies required in FM is achievable with GaN transistors. However, the issues pertaining to wide input voltage range, the variable nature of a DC microgrid between 320-380 V, and maintaining efficient operation with zero voltage switching (ZVS) under all conditions, remained unsolved with a basic CLLC topology solution.

C. Operation Principles

In order to solve the issues related to the loss of soft switching and wide input /output voltage range, a novel control strategy, based on the control presented in [8], [9], [10], was used. The isolated converter was designed with various operation or topology modes in order to utilize the topology morphing control. Referring to fig. 5, can help illustrate that there are 4 different operation modes that can be used. The primary side can be operated in full bridge mode or half bridge mode (Q3 open and Q4 closed) which produces a gain factor of 1 or ½, respectively. The secondary side (operating between 320-380 V) can be configured in full bridge rectification mode or voltage doubler with DC bias capacitor mode (by turning on Q5) in order to produce a gain factor of 1 or 2, respectively. This is beneficial in order to take stress off the operational frequency range of the converter by keeping the input-to-output voltage ratio required from the FM closer to 1 or f_{r1} at 225 kHz. This provides the additional benefit of maintaining zero-voltage switching (ZVS) operation over a wide input voltage range. Operating at frequency above f_{r1} keeps the resonant take with a more inductive impedance characteristic thereby providing a lagging current with respect to voltage and less circulating current in the resonant tank. This lagging current is what is used to discharge the parasitic capacitance of the transistor during the "dead time" between switching instances and low circulating current can reduce transformer losses. For these reasons, it was determined more efficient to operate at the resonant frequency or at higher frequencies up to 400kHz. Fig. 7 shows how the control keeps the operational frequency in the desired regions by switching between different topology modes.

D. Planar Transformer

A planar transformer was chosen because of its large inherent surface area, low profile and reduced skin effect or AC loss component at higher switching frequencies. These benefits were exploited in both the mechanical and thermal design by pressing the core to the aluminium enclosure, maintaining a low-height enclosure, and allowing for a more efficient transformer. The planar transformer was designed with a low leakage inductance or series inductance component

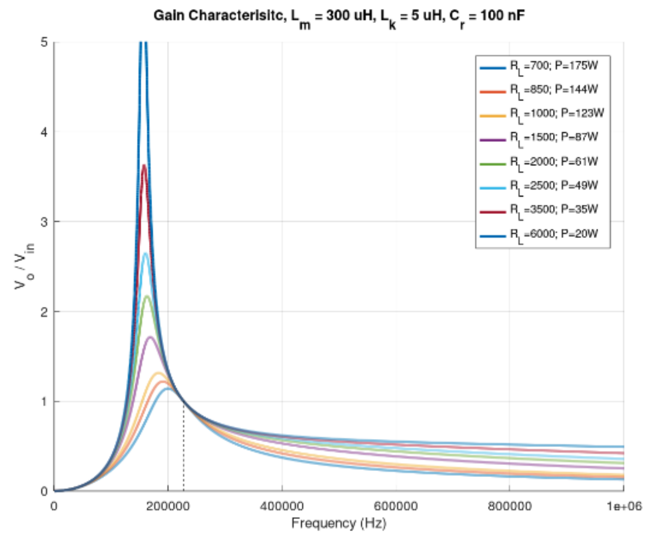

Fig. 6. Gain characteristic of resonant tank where $f_{r1} = 225kHz$ (labeled with dotted black line). The different color curves show the frequency vs. gain behavior under various load conditions

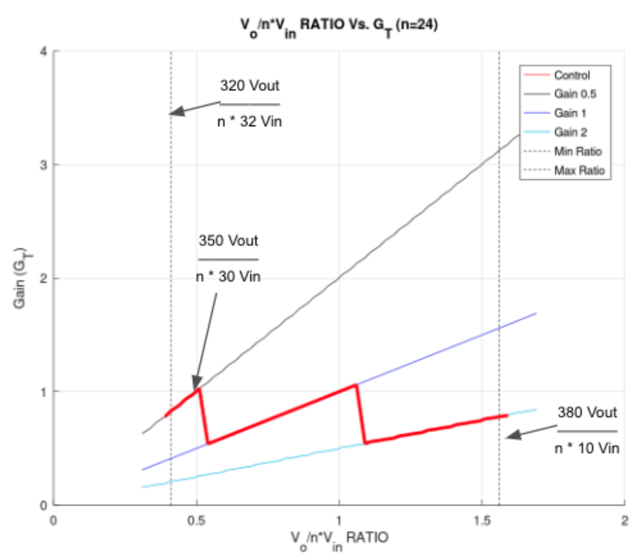

Fig. 7. CLLC gain vs. $V_o/N * V_{in}$ ratio. The topology morphing control is visualized by use of the red line. The 3 lines (black, blue, cyan) represent the 3 topology modes (half-bridge, full-bridge, voltage doubler). The red line traverses through all of the topology modes throughout the full input / output voltage range. The extreme cases are shown by the vertical dotted black lines marking the beginning and end of the red line. It can be seen that the Gain value stays between 1 and 0.5 through out the entire operational range of the converter. Only using one of the line (or a single topology) increases the loss of soft switching and the switching frequency range on the converter.

(l_k) in the range of $5uH$ and a turns ratio (N) of 20 (3 primary turns and 60 secondary). Parasitic capacitance was a factor in the design due to the nature of planar when interleaving windings but it was somewhat mitigated by skipping PCB layers between adjacent windings and reducing the area of overlap between primary and secondary windings. The design was effective but the low leakage component was an issue. This CLLC converter is to be operated as a step up converter which signifies that the secondary side provides the high winding inductance however, when the secondary component of the total equivalent inductance transfers over to the primary side, it is decreased by a factor of N^2. As previously mentioned, some inductance is necessary in order to provide enough lagging current to achieve ZVS. It was determined that a higher primary referred l_k is preferred to maintain ZVS over all input / output voltage conditions.

V. Controls

A. MPPT Control

The maximum power point tracking control is implemented in the switches of the string level converters. However, the control loops of this algorithm are divided into the processor of the isolated converter, which runs the centralized control; and the processors of each string level converter, which run the decentralized control loops.

There is a bidirectional information exchange communication line between the 2 processors. The string level converters send the following parameters to the isolated converter:Duty cycle, input voltage, output voltage and temperature of the processor.

Having the current measured at the input of the isolated converter as opposed to at the input of each string level converter reduces the amount of shunt resistors by a factor of 6 hence reducing conduction losses.

As depicted in Fig. 8 the centralized control of the isolated converter runs a MPPT algorithm and calculates input voltage setpoint for each of the string level converters based on voltage and current measurements. This setpoint is sent to the string level processor and executed in the local processor. In case of communication failure, the string level converters have been programmed to operate independently and approximate the MPPT point until the bus communication is back.

B. Shading Control

When the photovoltaic panel is homogeneously illuminated, the duty cycle of the string level converters is kept at 100% to eliminate switching losses. Under these conditions, the input voltage setpoint of the isolated converter is 6*V_{MPPT}. When one of the strings is shaded, its output voltage is reduced by decreasing the duty cycle of the string level converter. This way the output current remains constant and the rest of the strings can maintain the same operating point.

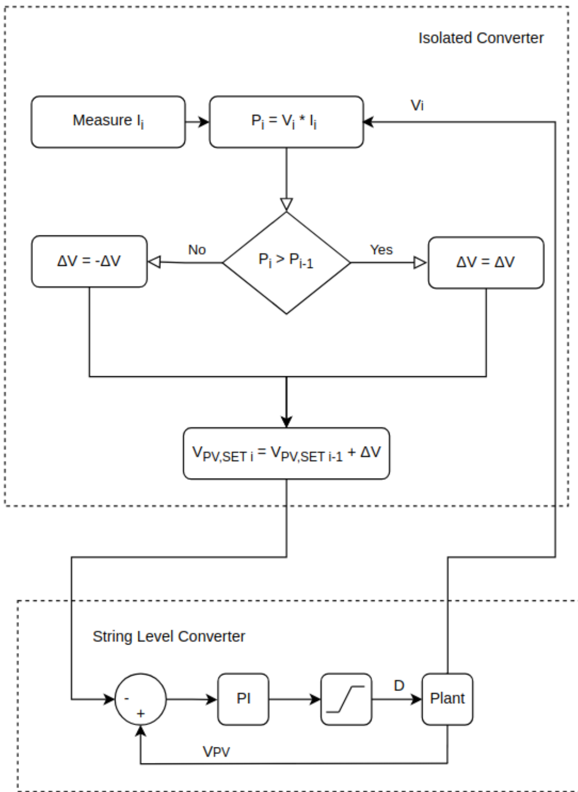

Fig. 8. Control Diagram.The output voltage of each string level converter is measured and sent to the isolated converter. This is multiplied by the current measured at the input of the isolated converter to obtain the instantaneous power. This power is compared to the power calculated in the previous measurement. If the power has increased, ΔV will maintain its previous value whereas if the power has decreased, this means that the control is moving away from the maximum power point. thus this parameter will be assigned the opposite sign. This change in the input voltage is added to the setpoint of the previous iteration and fed as an input for the decentralized control loop.

C. Embedded Protection

The isolated converter will stop switching if either of the following conditions are met:

- Input overcurrent of the string converter: if a short circuit or a fault occurs on the PV panel side.
- Output overvoltage of the isolated converter: if a voltage threshold is exceeded on the DC grid side, the string level converters will adjust their power generation by shifting the operating point of the photovoltaic panels away from the MPP . If an absolute maximum voltage is exceeded, switching will be stopped.
- Input under voltage lockout of the string converter: when the sun irradiation is low it is prioritized maintaining communication active rather than drawing current and collapsing the voltage resulting in constant resetting.

VI. Results

A. Prototype Development

Fig. 9 shows the physical prototype of the converter developed based on the topologies presented in chapters III and IV. The prototype consists of 2 PCBs: the circuit mounted on the upper level contains 6 identical modules with string level converters in them and the lower level board contains the isolated converter.

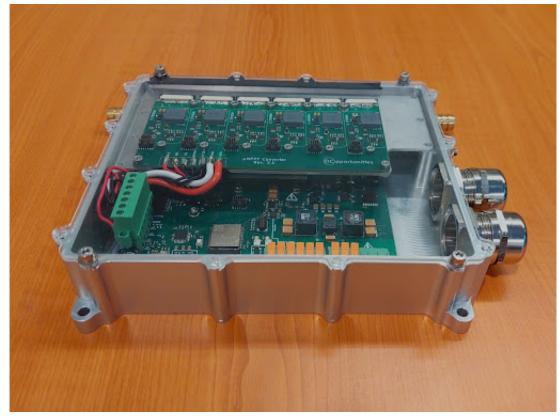

Fig. 9. Physical prototype. The isolated converter is mounted on the lower level and the string level converters are on the top level. The boards are mounted in a watertight metal enclosure.

The prototype is mounted inside a metal enclosure which serves 2 main purposes. On the one hand, the metal enclosures acts as a heat-sink to dissipate the losses generated at the isolated converter. On the other hand, the case has been designed to be watertight. The enclosures will be installed on the back of a photovoltaic panel which will sit on the deck of a sailing yacht.

B. Test Setup

The aforementioned prototype has been connected to the test setup depicted in Fig. 10. In this setup a photovoltaic panel with 48 solar cells is placed behind a tree casting a vertical shadow onto the surface of the panel. The cells of the panel are divided into 6 strings of 8 cells each. Each string constitutes a column of the panel and at the instance of the picture. For better understanding of the collected data, the picture was taken at 10:35AM. The most right column has been designated as string 0 and this enumeration progressively increases until the most left string. which is given number 5. The test lasted roughly 3 hours and during this time frame the shadow of the tree moved from right to left.

C. Collected Data

The purpose of the aforementioned test setup is to cast a controlled shadow on different strings and collect data to analyze how the control reacts to the partial shading of the panel. The instant of the picture shown in Fig. 10 is represented by a intermittent red. The graph a) in Fig. 11 shows the duty cycle of the cell-strings. When a string is shaded, the converter attached to it reduces its duty cycle to maintain the same output current which is shared with the rest of the strings hence allowing the rest of the strings to operate at their maximum power point at 100 % duty cycle and eliminating switching losses. The graph shows how all converters follow a similar pattern and consecutively adjust

Fig. 10. Testing setup. The photovoltaic panel is placed behind a tree casting a vertical shadow onto it. Each column is composed by a string of 8 cells and at the instant when the picture was taken the 3rd string starting from the left is fully shaded by the tree.

their operating point as they get shaded. At the moment of the picture the orange graph shows the duty cycle at its minimum, this is because the string is fully shaded. As the shadow starts moving away and begins to cast a partial shadow on a new string, the duty cycle of string 3 (depicted in orange) increases while string 4 (depicted in light blue) decreases.

It is of notice that when the duty cycle decreases in string 4, its shape is less smooth than with the rest of the strings. The reason behind this is that during that time clouds came between the sun and the panel. At this point not only is string 4 shaded, but the entire panel is. Therefore all strings are homogeneously illuminated by indirect light. This is also visible on graph b) of Fig. 11, it shows the contribution of each string in percentage of the total power. When the duty cycle of string 3 is minimum, its contribution is significantly smaller than the rest. However, when a cloud comes in between (for instance around 11:10AM) the contribution of each string is equitably distributed.

In order to have a quantitative understanding of the benefits of the string level conversion technique Fig. 12 shows the comparison in power generation between a traditional optimizer performance and the results obtained in the test in graph a). Graph b) illustrates this same difference in percentage. At the moment of the picture being taken the power generation is roughly 3 times higher compared to what the generation would have been if string level conversion was not carried out.

VII. Conclusions

The developed MPPT system demonstrates substantial improvements in managing the power output of PV panels under partial shading conditions. By employing string-level converters in conjunction with an isolated step-up converter, the system ensures that shaded strings do not compromise the

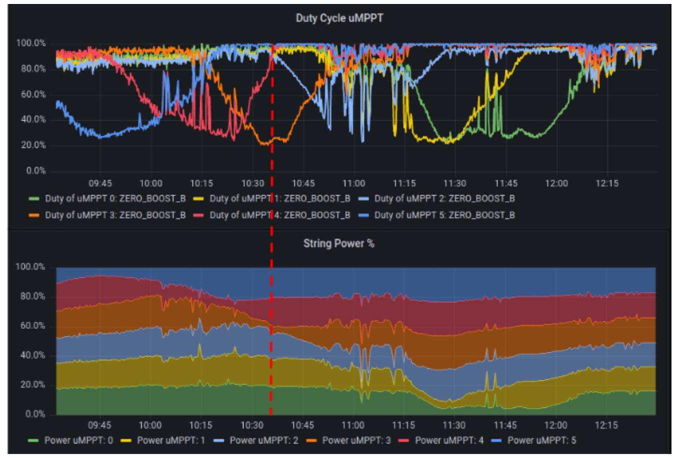

Fig. 11. Test results: a) Duty cycle per string b) Share of total power. When a string is shaded its duty cycle is decreased to maintain the same output current so that the rest of the strings can operate at MPP at 100% duty cycle. When the duty cycle of a string is at its minimum, its contribution to the overall power generation is also minimum.

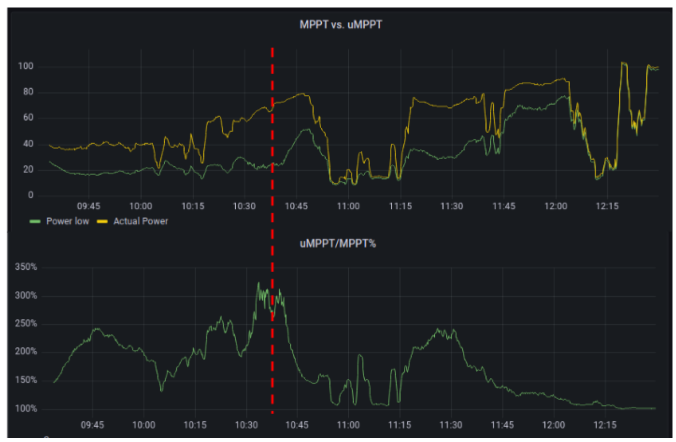

Fig. 12. Test results: a) Comparison of power generation between a traditional optimizer & implementing the string level converter technique b) The aforementioned difference in percentage form. This difference goes up to 300% at the instant of the picture being taken.

performance of the entire panel. Experimental results validate the effectiveness of this approach, showing up to a threefold increase in power generation compared to conventional optimizers. The integration of GaN transistors further enhances the efficiency and performance of the converters.

The findings suggest that such a system can be highly beneficial for renewable energy applications in mobile environments like sailing yachts, where shading patterns are dynamic and unpredictable. Future research could focus on refining the control algorithms to achieve ZVS and implementation of droop control, mechanical integration and exploring the scalability of this system for larger marine vessels or other mobile applications. Additionally, further studies might investigate the long-term reliability and economic feasibility of widespread implementation.

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References

[1] Ahmed Abdelhafez, Ahmed Radwan, and Ehab El-Saadany. "A Novel Hybrid Photovoltaic System Architecture Based on High Voltage Gain DC-DC Microconverters". In: *2015 IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC)* (2015), pp. 1615–1620. DOI: 10.1109/EEEIC.2015.7165326. URL: https://ieeexplore.ieee.org/document/7182327.

[2] T. Esram and P.L. Chapman. "Effects of Partial Shading on Photovoltaic Module and Improving Electrical Parameters via Bypass Diodes". In: *IEEE Transactions on Energy Conversion* 22.4 (2007), pp. 1062–1068.

[3] Nishant Kumar, K. S. Sandhu, and S. S. Chandel. "A review of conventional, modern and hybrid maximum power point tracking techniques for wind energy systems". In: *Applied Energy* 118 (2014), pp. 228–244. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2015.01.057. URL: https://www.sciencedirect.com/science/article/pii/S0306261915001130.

[4] Freddy Pan et al. "Comparative Analysis of Single-Phase Transformerless Photovoltaic Inverters". In: *IEEE Transactions on Industry Applications* 50.2 (2014), pp. 1227–1237. DOI: 10.1109/TIA.2014.2299772. URL: https://ieeexplore.ieee.org/document/6807815.

[5] SolarEdge Technologies. *SolarEdge*. https://www.solaredge.com/nl/. [Accessed: 23-May-2024].

[6] S. Sulaiman et al. "A review on MPPT techniques of PV system under partial shading condition". In: *Renewable and Sustainable Energy Reviews* 78 (2017), pp. 854–867. ISSN: 1364-0321. DOI: 10.1016/j.rser.2017.07.106. URL: https://www.sciencedirect.com/science/article/pii/S1364032117307256.

[7] *Taylor Solar Zonnepanelen*. https://mtsprout.nl/tech-innovatie/taylor-solar-zonnepanelen. [Accessed: 23-May-2024].

[8] A. Chub V. Sidorov and D. Vinnikov. "Topology Morphing Control with Soft Transients for Multimode Series Resonant DC-DC Converter." In: *2021 IEEE 22nd International Conference of Young Professionals in Electron Devices and Material (EDM)* (2021).

[9] D. Vinnikov et al. "Hybrid DC-DC Converters with Topology Morphing Control and Post-fault Operation Capability". In: *IEEE Transactions on Industrial Electronics* (2021).

[10] D. Vinnikov et al. "Topology-Morphing Photovoltaic Microconverter With Wide MPPT Voltage Window and Post-Fault Operation Capability". In: *IEEE Transactions on Power Electronics* 8 (2020), pp. 153941–153955.