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Effect of Replacing PV Module in the String by the Module with Different Power

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This work deals with the analyses of a serial connected photovoltaic modules and its electrical behavior. The modules are different in their nominal power. The aim is to first theoretically analyze the situation, which most often arises in the repair of photovoltaic plants and determine what electrical, respectively. the energy consequences will allow these higher rated modules to be integrated into a chain of lower power types. The theoretical part is supplemented by computer simulation of simplified wiring, simulation of power effect followed by practical measurement. The result of the work is the recognition that it is possible to observe the above conditions to replace the module with higher performance. For non-standard types of module replacement or wiring it is recommended to carry out measurements by an authorized test facility supplemented by an energy assessment.

Introduction

At present, any small or larger repair of the power plant, its source or its components, is a nightmare of all decentralized renewable energy sources operating in the Czech Republic. Although this is not a small number of sources of energy (sun, wind, water) and is increasing, legislators have not had time to adopt and define legal or sub-statutory measures, explaining, supplementing or regulating this area of small energy. In the past, the Energy Regulatory Office proceeded very hard, incorrectly, and interpreted the repair of the plant according to what the client said about the repair. Decision making was at odds with operators' expectations.

Repair power plant due to common defects, wear and tear, damage, natural disasters could not be canceled, so their practical solutions almost always ended up unofficially, without accounting documents in the repair accounts, fearing loss of entitlement to operating financial support. This is very unfavorable in the increased annual profits of the power plants, which pay more taxes than they would have and achieve a better economic return than they should actually achieve.

In November 2018, a draft amendment to the Energy Act and the Act on Supported Energy Sources was issued for interdepartmental comment procedure. Unfortunately, the prepared proposals are not constructively prepared (in the light of the practice) and final adoption is expected by 2020 at the earliest, with effect from 2021. Meanwhile, electricity generators are aging and cannot rely on any legislative adjustment. One of the most frequently discussed repairing is replacing a malfunctioning, damaged, or otherwise unsuitable module.

After more than 15 months' postponement of its issuance (the original date was promised in autumn 2017), the Energy Regulatory Office clarified the conditions under which it is possible to carry out repair or maintenance at the electricity production plant by its interpretative opinion No.10 / 2018 of 18.12.2018. In the final summary, ERO informs that it is possible to carry out the repair by replacement in the case of module or other defect of the module, natural or harmful event or termination of the service life, but the installed capacity of the production plant must not be exceeded, at the same time that the technological and ecological level of the production must not be increased up to the level of the newly established plants.

Goal of Work

For reasons of legislative disagreement, it is important to find out how the module replacement is influenced by the module replacement for a module with a higher output. This is one of the most frequent interventions (in the form of repair in exchange) into a non-functional part of the production plant, where a certain part of the plant is totally or partially non-functional - with a reason for a physical or mechanical failure of the module, which in time becomes a production defect or a consequence of natural or other elements.

In 99.999% of the systems, the modules are connected in series strings, so our goal was to find out if the exchange of the photovoltaic module involved in the string (string) affects the subsequent positive or negative electrical power of the chain, respectively. nominal system performance and, as a result, the total annual energy yield.

Problems of Serially Connected Modules

The photovoltaic modules have a very limited voltage and current output range. The applications where we can use the power of the standalone module are mostly determined by the maximum voltage size, which makes its use for charging purposes for 12 V or 24 V batteries, which was most apparent at the very beginning of the photovoltaics. Today, for most applications, it is necessary to increase the voltage to a certain minimum level, so it is advisable to connect the modules in series to electrically larger units, so-called strings.

Identical PV Cells and Modules Connected to the String

The criterion for connecting modules into string is the energy aspect of losses. In the case of an increase in the total string voltage to twice, the current is then equivalently halved (assuming a constant power), and the total losses in the PV wiring fall according to the equation

$$P = R\,I^2 \qquad [1]$$

to their quarter. This is why most of the world's module and inverter producers push the maximum voltage of string from today's 1000 V to 1500 V.

The serial connection of the three modules and cells in series is shown in Fig. 1 and 2.

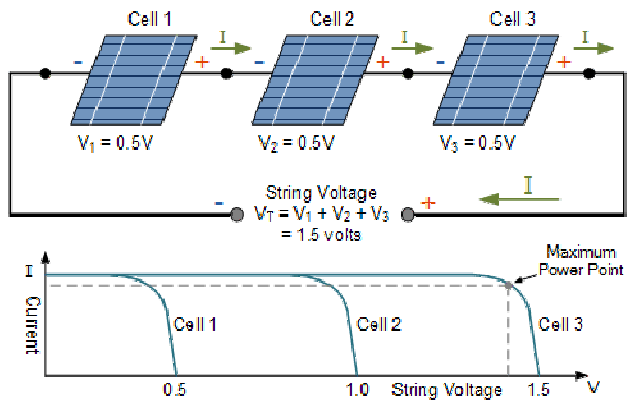

Figure 1: Serial connection of three photovoltaic cells (1)

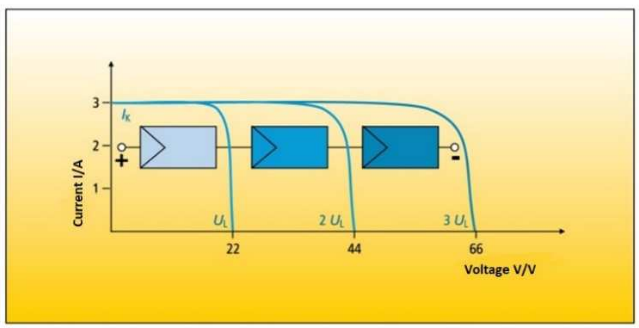

Figure. 2: Serial connection of three photovoltaic modules by 36 cells in module (5)

Figure 1 shows the total voltage and current parameters in a series of three completely identical photovoltaic cells. Volt-ampere characteristic of one module due to connecting in series is graphically added according to voltage. The result is a sum of open-circuit voltages while leaving the short-circuit current. The result of the serial connection and the resulting behavior is therefore identical for the cell and the module as shown in Fig. 2.

From the above it can be deduced that if the measurements and subsequent computer simulation are carried out principally on the modules, the detected character of the serial behavior of the modules will also be applicable to the behavior of the series connected cells and vice versa.

Graphical Simulation

Based on the measured values of the PV modules, a simulation of the graphical sum of the volt-ampere characteristics for the modules connected in series was compiled. The necessary sums of currents, based on the selected set of voltages, were created in

Microsoft Office Excel by the sum of currents of individual modules and the result is shown in Figure 3.

TABLE I: Simulation result of three series-connected modules

Module no.	Nominal Output Power [W]	Real Output Power [W]	Combinated output power (1+2+3) [W]	Combinated output power per module [W]	Nominal Performance deviation[%]	Real Performance deviation
1	85	82.16		46.32	45.51	43.62
2	50	44.69	138.96	46.32	7.36	-3.64
3	50	42.57		46.32	7.36	-8.81

The maximum power point was found with a simulation of 138.96 W, converted to three modules, representing 46.32 W per module. When the nominal power is increased from 50 W to 85 W, which is 70%, the highest deviation from the measured power was recorded by an increase of 8.81% (causing an increase in performance) but due to the nominal power the deviation is 7.36% (reserve to real power is 3.68 W).

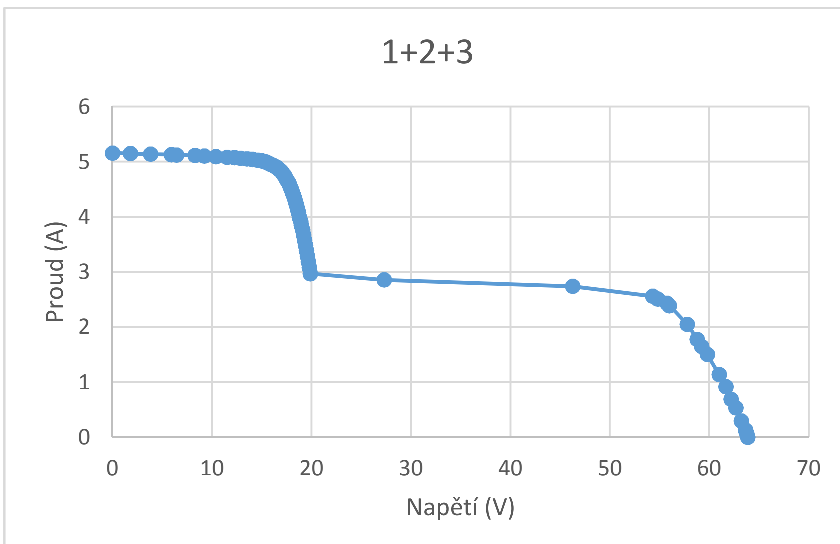

Figure 3: VA simulation of three series-connected modules

The photovoltaic modules under consideration are about 10 years old, with various experiments being carried out on them, and therefore there is a noticeable difference between nominal and actual measured (real) power. Therefore, the maximum nominal power is not exceeded.

TABLE II: Dependence of power deviation on number of modules no.

	Quantity of module no. 2								
	1	2	3	4	5	10	15	20	40
Deviation [%]	-11.4	-7.04	-5.03	-3.3	-3.03	-1.43	-0.98	-0.75	-0.38

If only two modules are connected (number = 1), the maximum rated power increases by 11% relative to module 2. The nominal power will always increase if module 1 is larger than module 2. If string contain sixteen modules (1 + 15), the total nominal power increase will be up to 1% against module no. 2.

Experiment

The verification experiment was carried out in the accredited testing laboratory No. 1657 at the CVV RES department, VUT FEKT Brno. The first image (Fig. 4) from the measuring station shows the arrangement of the measurements of three PV modules that are different in power and size. The second picture (Fig. 5) shows the back of the modules and their attachment to the mounting frame, between them and the connection of the output to the measuring probe.

Figure 4: Image of the experimental design of the measurements performed at the accredited workplace of BUT FEEC, CVV RES

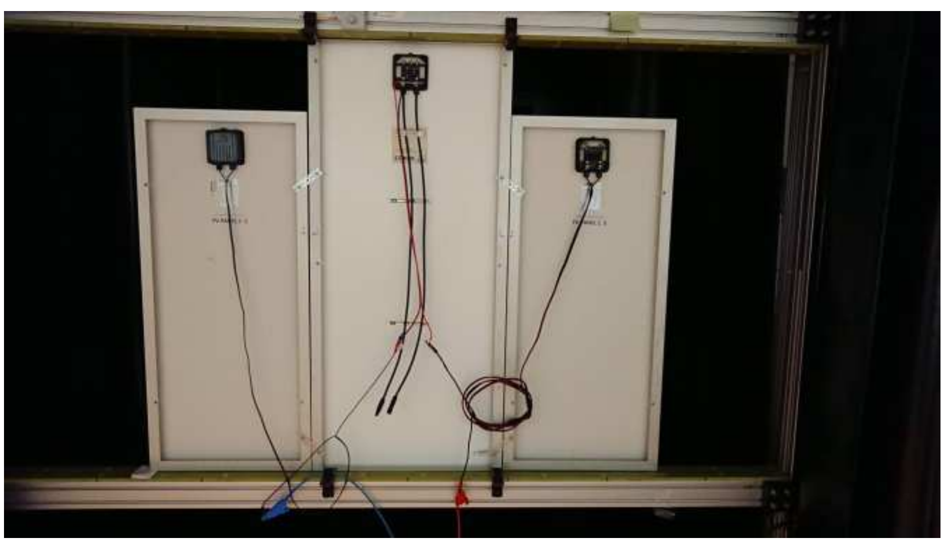

Figure 5: A snapshot of the back of the tested modules from the measurements performed at the accredited workplace of BUT FEEC, CVV RES

TABLE III: Measurement results of connected sample modules No. 1, No. 2 and No. 3 and their serial combinations

Sample / Combination Physical quantity			1	2	3	1+2+3
Short current	I_{SC}	A	2.805	2.890	5.155	5.501
Open Circuit Voltage	U_{0C}	V	20.881	21.234	21.894	63.800
Efficiency	Eff.	%	9.41%	9.95%	12.62%	8.87%
Fill Factor	FF	%	72.83%	73.48%	72.80%	39.51%
Maximum power	$\mathbf{P_{mpp}}$	**W**	**42.665**	**45.092**	**82.167**	**138.652**
Voltage in maximum power	U_{mpp}	V	16.128	17.014	17.275	53.068
Current in maximum power	I_{mpp}	A	2.645	2.650	4.756	2.613
Serial resistance	R_{ser}	Ω	1.1	0.9	0.6	2.6
Paralel resistance	R_{sh}	Ω	183.9	185.7	210.8	8.2

Three photovoltaic modules with different peak power, each with 36 cells, were selected for measurement. Accredited workplace CVV OZE, VUT FEKT is set up for measurement of modules under STC conditions: AM = 1.5, t = 25˚C, G = 1000 Wm^{-2}.

First, the VA characteristics of the modules themselves were measured - sample 1, 2, and 3. Then a serial triple combination of sample modules No. 1 + 2 + 3 was measured. The measured data of the experiment were taken from the official outputs of the accredited technical equipment and thus Table 3 was compiled.

The following three figures show the volt-ampere characteristics of the separately connected modules. Each measurement consists of 500 quick measurements, in a 20 μs time interval, with a total measurement time of 10 ms. For such a short measuring time, a constant (non-elevated) temperature of the module and the individual cells in the module is guaranteed, and therefore the measured values of the individual voltage and current quantities.

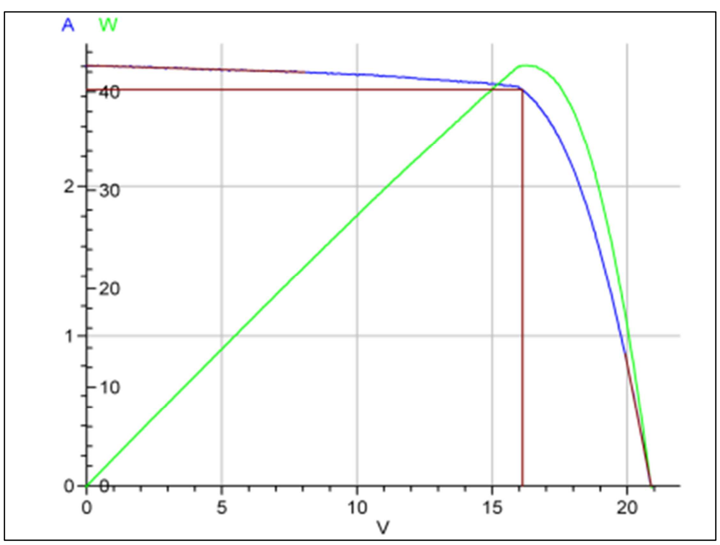

Figure 6: Volt-Ampere Characteristics and Waveform No. 1 (Power 50Wp)

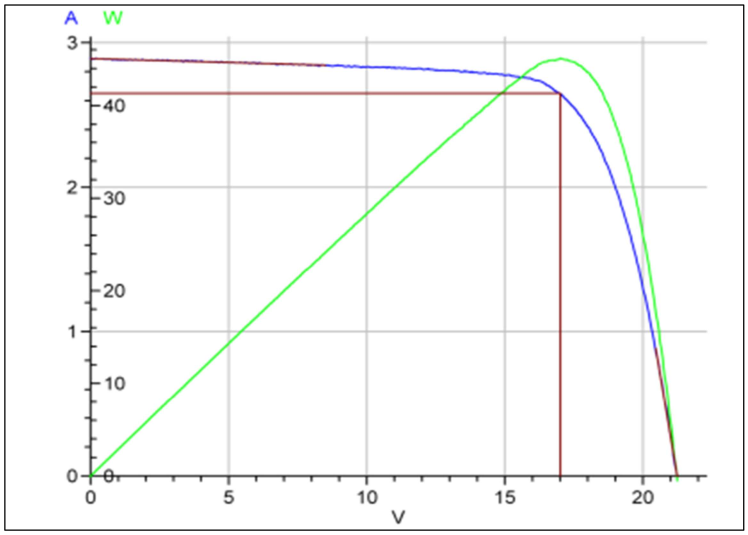

Figure 7: Volt-Ampere Characteristics and Waveform No. 1 (Power 50Wp)

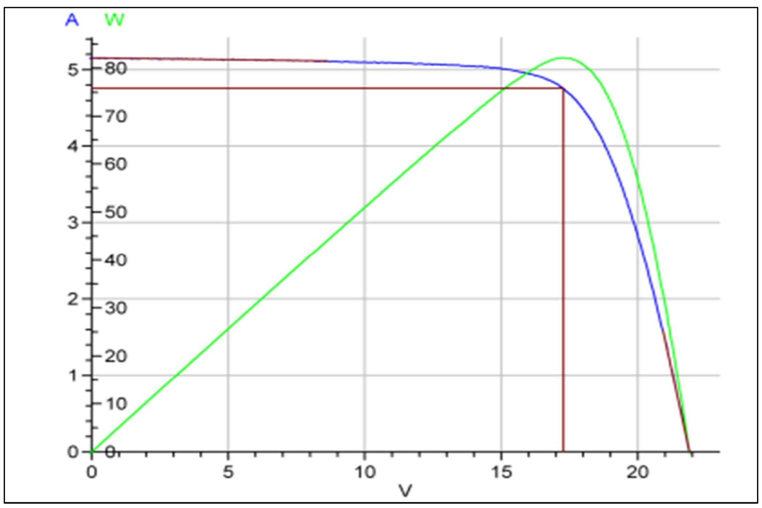

Figure 8: Volt-Ampere Characteristics and Waveform No. 1 (Power 85Wp)

The VA characteristic in Fig. 9 is extended to 64 V of open circuit voltage, which corresponds to the total of three modules connected in series, each of 36 cells. The forms of each VA characteristics are identical and differ only by the change in the current axis. The more power the new module, the more value of initial short-circuit current of whole characteristic.

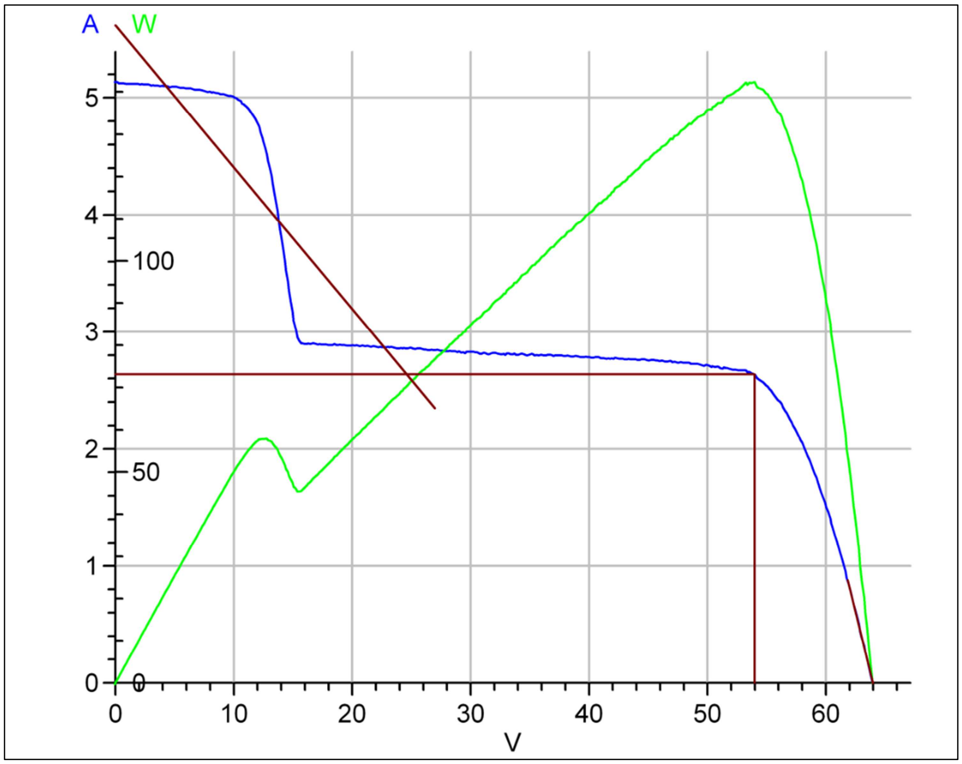

Figure 9: Resultant volt-ampere characteristic and power curve of three in series of connected samples No. 1, No. 2 and No. 3 (1 + 2 + 3)

At low loads, the current is at the short-circuit level of the highest power module and may exceed the maximum current value of the remaining lower power modules. Due to the low voltage, the generated power and power losses are small and should not damage modules with lower power. If bypass diodes are included in the lower power modules, these diodes are activated and thus the modules are protected against a larger current flow.

The volt-ampere characteristic forms are closest to those seen in the shaded several modules characteristic involved in the chain. In the module chain, the current drops from the initial (short-circuit) value of the current to the value of the shaded modules, which will be only 10 - 20% of this value compared to the measured values.

From the overall performance characteristics of the 1 + 2 + 3 series combination, we can see that instead of one power maximum we find two maxima in Figure 9, instead of the expected three maxima, due to three different power modules. The absence of the third power maximum is obviously due to a damaged (burnt) bypass diode on one of the lower power modules, because at a power difference of about 5%, the inflection point can be expected to progress. For the lower maximum we talk about the local maximum (LMPP), for the total maximum we talk about the global maximum (GMPP). In the case of modules with different powers, the number of local power peaks will increase equally. In practice, therefore, it is important that the modules are connected to a modern type of inverter that can quickly search the entire VA characteristic curve and detect GMPP.

Examination of the measured values revealed that the recorded data on the parallel resistance value of the serial triple combination R_{sh} did not correspond to reality, in the order of magnitude. This is due to the fixed software routine of the device that determines the guideline ΔU / ΔI slope, which does not allow for such a rapid time drop relative to the measurement time. The manual calculation of the slope has revealed a parallel resistance in the range of 90 - 120 Ω, which is already expected.

From the measured values of the serial combination 1 + 2 + 3, we also found in Table 3 incorrectly calculated short-circuit current ISC. The stated value of 5.501 A is higher by 0.346 A, the correct value is 5.155 A from a separate module measurement. The value of the short-circuit current is evaluated on the basis of a long derivative measurement of the current change, which is unsuitable for the measurement of series combinations.

Results

Table IV summarizes the results of the rated power of the series combination and the expected peak power according to the theory. The resulting difference is further compared with the accuracy of the measuring device, the corrected positioning mistake, and from there the calculated divergence of the measurement, which is 2.4% for the measured triple combination, is calculated.

TABLE IV: Measurement results of module performance in series connection

Sample / combination	Measured value P_{mpp} W	Expecteded value P_{mpp} W	Diference %	Accuracy of measurement %	Divergence %
1	42.665	42.665	0	6	0
2	45.092	45.092	0	6	0
3	82.167	82.167	0	6	0
1+2+3	138.652	127.995	8.3	6	2.4

Conclusion

The aim of this work was to find out by measuring that the replacement of the old, damaged or otherwise inoperative module in the connected module chain can be done by replacing the module with the higher peak power, which does not increase the overall rated power of the system. The replaced module has a peak power exceeding the original peak power of the old module, but by plugging it into a modular string the power of the string is result of serial combination influenced by the output current of the weakest module. This was confirmed by both computer and graphical simulation and was verified by measurement.

Acknowledgments

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