PV-WIREFREE:
REDESIGNING AND INNOVATING GRID-CONNECTED PV-SYSTEMS

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ABSTRACT: In this paper a new concept for designing grid-connected PV-systems is presented: PV-wirefree, aiming at minimizing PV BOS costs – Balance of System costs - and inherently safe PV-systems. The guiding design principles used are: minimize dc-voltage, minimize components and material, integrate functions, simplify the PV-system and design for easy installation. Only one solution appeared to meet the goals: the PV-modules have to be connected in parallel to keep the dc-voltage as low as possible. The low dc-voltage also allows omitting many of the safety components used in series connected PV-system. To minimize the number of components even more two new PV-wirefree components are designed in which different functions are integrated. The most innovative new component is the PV-wirefree mounting bus, a current carrying mounting frame. So, a PV-wirefree system does not include expensive dc-wiring anymore, whereas the number of connectors is reduced considerably. In this paper the new PV-wirefree components are presented and safety issues related to paralleling PV-modules are discussed, as well as the additional advantages of PV-wirefree regarding reliability and efficiency.
Keywords: cost reduction, safety, grid-connected

1 REINVENTING PV-SYSTEMS

With PV-wirefree we aim at minimizing PV BOS costs and inherently safe PV-systems, as illustrated in Figure 1. The PV-wirefree partners started with a blank mind - trying not to think about how current PV-systems are designed and which components are being used. The assignment was to design a simple system - with as few components as possible - which is at the same time inherently safe.

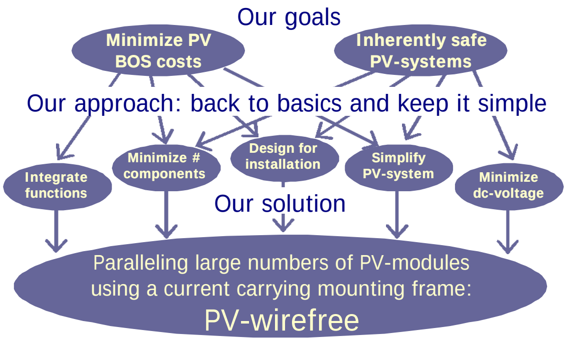

Figure 1: Goals, approach, solution PV-wirefree

2 MINIMIZING NUMBER OF COMPONENTS

2.1 Omission of components

In a PV-string system many components are added only for safety reasons to avoid fire hazard and to guarantee touch safety caused by the high dc-system voltage. In a PV-wirefree system the dc-system voltage always remains below 21 volts. So, numerous PV-string components become redundant by using PV-wirefree, just because of the low system dc-voltage (see also section 4.). The PV-string components that can be omitted are: class II isolation, bypass diodes, wiring of bypass diodes, high-voltage dc-connector, high-voltage dc-wiring, blocking diodes, dc-fuses, overvoltage protection, dc-isolation monitoring, system grounding.

2.2 Integration of functions

The remaining components are replaced by only two new PV-wirefree components, next to the PV-laminate. The module connector and mounting bus are designed to fully integrate mechanical and electrical functions.

2.2.1 PV-wirefree laminate

To enable the use of a 4-points connection instead of a frame, without using thicker glass, the cells in a PV-wirefree laminate are arranged in 5 columns of 7 cells, resulting in a significantly lower tensile stress on the glass as illustrated in Figure 2.

The distance between the connection points is 0.7 m (in both directions). The PV-wirefree module connectors are positioned on the diagonal angles of the laminates. Except for the cell-to-cell connections no internal wiring is required. The electrical outputs are located directly under the first and last cell of the PV-laminate, which eliminates the risk of an internal or external short circuit.

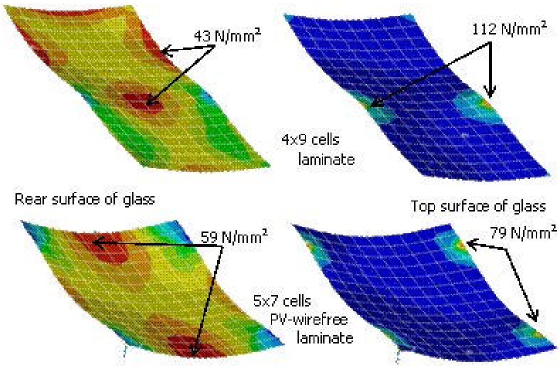

Figure 2: Comparison of tensile stress at a pressure of 2400 Pa of a commercially available 4x9 cell laminate with 6-points connection and a 5x7 PV-wirefree laminate with 4-points connection. The peak tensile stress occurs at the connection points at the top surface of the glass. The 6-points connection has a maximum tensile stress of 112 N/mm^2, the 4-points connection a maximum tensile stress of 79 N/mm^2.

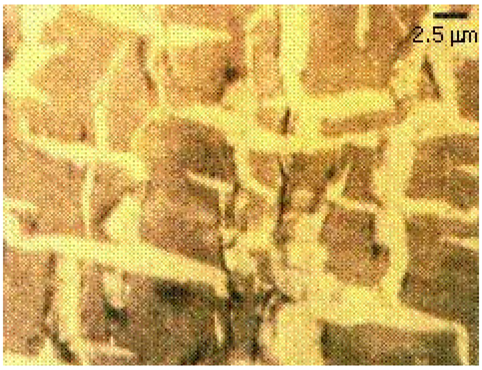

Figure 3: Aluminium-oxide layer crushed under the high pressure of a contact force. The darker areas are oxide, the lighter are metallic aluminium

2.2.2 PV-wirefree module connector

The PV-wirefree module connector replaces the aluminium frame, the junction box and the high-voltage dc-connector. Four connectors secure the module in place. Two of these also take care of the electrical connection, a gas-tight aluminium-to-aluminium connection. To ensure a reliable performance of over at least 20 years, the stabilized normal contact force is 100 N, ten times what is usual for copper. The high pressure employed in the connection is required to crush the thin aluminium-oxide layer as shown in Figure 3.

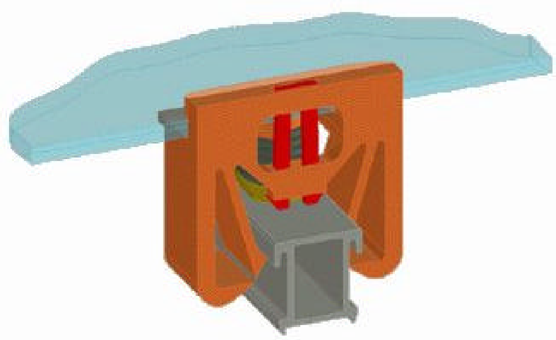

Figure 4: PV-wirefree module connector

2.2.3 PV-wirefree mounting bus

The mounting bus – short for current carrying mounting frame – replaces the high voltage dc-wiring and part of the support structure. The cross section of approximately 120 mm^2 aluminium is strong enough to hold the PV modules and thick enough to safely conduct hundreds of amperes.

Moreover, installing a PV-wirefree system has become rather simple, not requiring special skills: just click the module connector onto the mounting bus, and mechanical and electrical installation is complete.

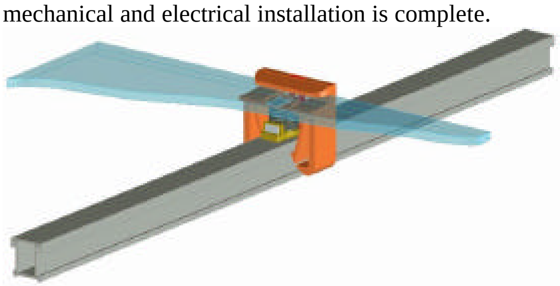

Figure 5: PV-wirefree mounting bus

3 INHERENT SAFETY

3.1 Important exceptions

A feasibility study into PV-wirefree learned that the following important, basic assumptions related to safety issues **do not apply to PV-wirefree systems** since the voltage of a PV-wirefree system – when using the PV-wirefree laminate (section 2.2.1) - always remains below 21 volts:

1. Interruption of high dc-currents is dangerous since it can cause continuous arcing. Since arcing requires a minimum voltage of approximately 30 volts, continuous arcing will not occur in a PV-wirefree system, because the dc-system voltage will never exceed 21 volts. Also laboratory and field measurements have shown that during the transient of interrupting a short circuit-current of about 200 amperes in a PV-wirefree system, no voltages above 21 volts occurred.

2. More than three PV-modules connected in parallel represent a fire hazard due to possible large back-feeding currents. With an increasing number of PV-modules in parallel the worst-case back-feeding current will stabilize at a value less than 0.2 I_{sc} as shown in figure 6. Provided that the internal wiring can never cause short-circuits within the laminate and blocking diodes are omitted the current is limited to values dictated by the physics of the cells. Because of the cell characteristics, even up to six cells in one PV-laminate may become a full short-circuit without causing the current to increase to values above 2 x Isc, a generally accepted safe value.

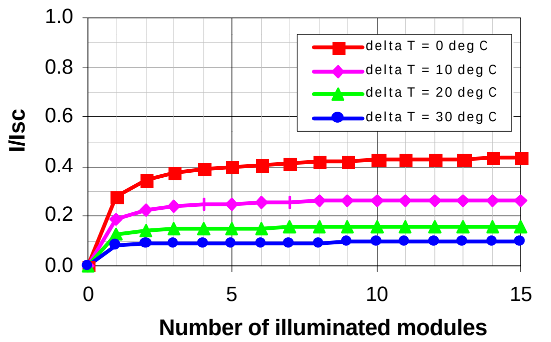

Figure 6: Normalized back-feeding current in one shaded PV-module versus the number of parallel connected PV-modules under standard illumination conditions, at various temperature differences between illuminated and unilluminated modules.

3. Bypass diodes are needed to avoid hot spots in case of partial shading. This assumption only applies to PV-string systems. Because of the low difference between de Voc and Vmpp the voltage across one shaded cell in a PV-wirefree system will not exceed 4 volts. So, significant reverse current in this cell cannot occur, avoiding hot spots.

3.3 Touch safety

A PV-wirefree system is fully touch safe during installation and operation. Moreover, in case system faults occur, it will not lead to unsafe situations:

- **During installation** all parts can be touched safely since the dc-system voltage will never exceed 21 volts.

- **During operation** the dc-voltage drops to an even safer value of approximately 16 volts. Moreover, the mounting bus, which carries the current, is covered by the PV-laminates and is therefore hardly accessible.
- **Accidental short-circuits** will not lead to unsafe situations, since interrupting the current in a PV-wirefree system will not cause voltages above 21 volts.

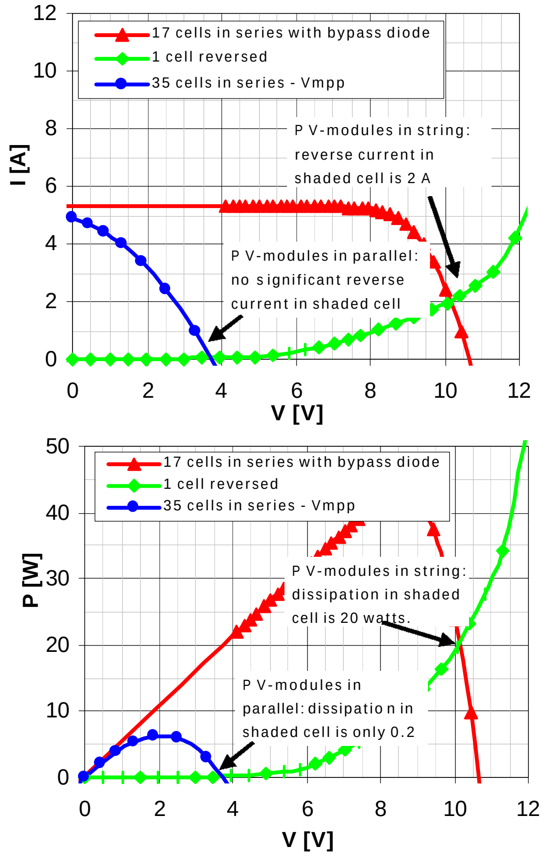

Figure 7: Dissipation caused by partial shading of one cell in a fully illuminated PV-wirefree system will only be 0.2 watt, in a PV-string it will be 20 watts.

3.4 Elimination of fire hazard

The risk of fire hazard is eliminated by using a PV-wirefree system, just by simply paralleling the PV-modules resulting in a dc-system voltage which will remain below 21 volts:

- **No local overheating or continuous arcing in malfunctioning electronic connections.** In a PV-string system malfunctioning of connectors, damaged wiring or a failure in one of the PV-modules causes a fire hazard since a substantial part of power of the total string will be dissipated locally. In a PV-wirefree system this phenomenon is limited to the power of one PV-laminate only, which is not enough to cause a fire hazard. Moreover the voltage is too low to cause continuous arcing. In comparison with common dc-wiring the rugged mounting bus is unlikely to break or be damaged.
- **No over-current due to back-feeding**. Careful design of the PV-wirefree laminate eliminates the risk of over-current caused by back-feeding.
- **No hot spots due to partial shading.** As explained in section 3.1 and illustrated in figure 7 partial shading cannot cause hot spots in PV-wirefree systems.

4 RELIABILITY

To compare PV-wirefree with a PV-string system we consider malfunctioning of:

- **Connector**. The high-pressure PV-wirefree connector is very robust and with its large gas-tight contact area, it is as reliable as a commonly used dc-connector. But even if one PV-wirefree connector would fail, the reduction in output will remain limited to the potential yield of one PV-module only, since the PV-laminates are connected in parallel.
- **DC-wiring.** In case the relatively thin dc-wiring of a PV-string is damaged, the full PV-system will be out of order. Since the PV-wirefree mounting bus is extremely robust with a cross section of 120mm^2, breaking has become almost impossible.
- **PV-module.** If one PV-module is not functioning properly, the output of the PV-wirefree-system will decrease accordingly, but the other PV-modules will continue delivering power to the grid since these are connected in parallel.
- **Bypass diodes.** Short-circuiting of bypass diodes cannot occur in a PV-wirefree system, since these are omitted. In a PV-string system short-circuiting of the bypass diodes decreases the annual yield of the total PV-system.

Since the PV-modules in a PV-wirefree system are connected in parallel the effect of malfunctioning of a connector, dc-wiring or a PV-module is limited, whereas in PV-strings it affects the performance of the total system. Moreover, in a PV-wirefree system bypass diodes are omitted, and therefore they cannot cause faults anymore. Thus, a PV-wirefree system is more reliable than a PV-string system.

5 EFFICIENCY

To compare PV-wirefree with a PV-string system we consider the following loss categories:

1. Mismatch losses. Since the PV-modules are connected in parallel mismatch losses at system level due to differences in illumination of PV-modules do not occur, resulting in an increase of the annual yield under such conditions with 5-15%, as shown in figure 8.

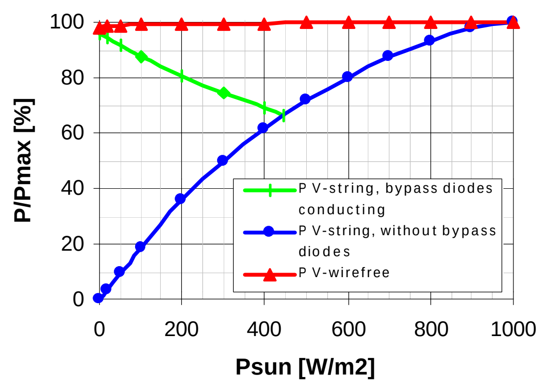

Figure 8: Effect of difference in illumination of two PV-modules in series compared with PV-wirefree system. One PV-module is illuminated with 1000 W/m^2, the illumination of the other PV-module increases from 0 to 1000 W/m^2.

2. Losses due to improper functioning of components. One of the main advantages of connecting PV-modules in parallel is that the PV-modules operate independently from each other, whereas the performance of a PV-system in which the PV-modules are connected in series depends on the operation of all separate PV-modules and components (see also section 5). The latter implies that malfunctioning of only one component immediately affects the output of the total PV-string. Hence, the annual yield of a comparable PV-wirefree system will always be higher.

3. Conduction losses. To limit the conduction losses of a PV-system in which PV-modules are connected in parallel, thick dc-wiring is required. By using the PV-wirefree mounting bus with a cross section of 120 mm^2, this disadvantage is mainly overcome. As shown in the graphs below the conduction losses in PV-wirefree systems of up to 15 PV-laminates remain well below those in a comparable PV-string system. Conduction losses in PV-wirefree systems of more than 15 PV-laminates become higher but the increase in losses compared with PV-string systems is still below 1%.

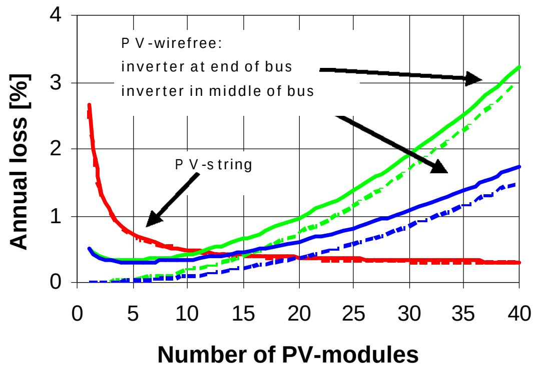

Figure 9: Conductor losses in a PV-string and a PV-wirefree system versus the number of PV-modules. The dashed lines show the conduction loss (I^2R), the solid lines represent the conduction losses plus the contribution of the energy content of the conductors, based on a lifetime of 20 years.

Assumptions: The PV-laminates are 75 Wp@5 A, the PV-string system uses 2.5 mm^2 copper-wire, 2 meter per module for interconnections between the PV-modules. The distance between the modules and the string-inverter is 10 meters. The PV-wirefree mounting bus has a cross section of 120 mm^2, width of PV-modules is 0.7 m. The PV-wirefree inverter is mounted on the bus.

Thus, the efficiency of a PV-wirefree system will be higher than the efficiency of a comparable PV-string system. However, testing and measurements foreseen in the follow-up study should provide the "proof of the pudding".

5 CONCLUSIONS, APPLICATIONS, FUTURE

5.1 Conclusions

PV-wirefree systems are inherently safe and offer additional advantages: increased reliability and efficiency. PV-wirefree uses considerably less components and material, and offers ease of installation. As a result, an estimated BOS costs reduction of 50% can be realized.

5.2 Application possibilities

The application possibilities of PV-wirefree are unlimited and the concept offers many advantages:

- PV-wirefree is not only extremely suitable for building integrated PV, roofs and façades, but also economically interesting for large-scale PV-plants, sound barriers, etc.;
- PV-wirefree laminates can be mounted horizontally, vertically or in tilted position;
- PV-wirefree is both suited for new buildings and for add-on at existing building envelopes;
- Adaptable to functionally integrated façade cladding;
- PV-wirefree offers design flexibility to architects;
- The frameless PV-wirefree laminates are not only aesthetically pleasing, they also prevent soiling;
- Since installation of PV-wirefree is easy and inherently safe no qualified personnel is required.

5.3 Future developments

The results of the PV-wirefree feasibility study, presented in this paper, are very promising. Therefore the PV-wirefree partners have decided to initiate a follow-up, a proof of principle project, in which the following issues will be addressed:

- Out- and indoor testing of the new PV-wirefree components: focus on the electrical connections, mounting and building integration aspects and system performance;
- Redesign and optimization of the PV-wirefree concept to meet building and installation requirements even better;
- Inverter aspects, especially integration of conversion of high current / low voltage to low current / high voltage into inverter;
- Inclusion of paralleling PV-modules in PV-standards, including safety issues.

6 REFERENCES, PARTNERS AND ACKNOWLEDGEMENTS

6.1 References

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[2] Flyer PV-wirefree – redesigning PV-systems, October 2002.

6.2 Partners

PV-wirefree is an invention of Henk Oldenkamp, OKE-Services. Other PV-wirefree partners are:

- Energy research Centre of the Netherlands ECN;
- NKF Electronics;
- Oskomera Solar Power Solutions BV.

For more information visit http://www.pv-wirefree.com.

6.3 Acknowledgements

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