PV-WIREFREE:
BRINGING PV-SYSTEMS BACK TO THEIR ESSENTIALS

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ABSTRACT

Over the years, grid-connected PV-systems have developed into complex installations containing a variety of components and features supposed to be necessary for proper operation under all circumstances. In this paper it is shown (in theory and practice) that it is possible to simplify system design and installation dramatically, without any compromise. In fact, such systems are inherently safe and respond extremely well to non-optimal operating conditions and faults. PV-wirefree is based on the concept of combining the functions of support or integration with those of electrical connection and current conduction. Within one (sub)system all modules are connected in parallel, at a DC-voltage of less than 21 V. A PV-wirefree system consists *only* of PV laminates, click-on-click-off dual-purpose clamps, aluminium extrusions and an inverter. No diodes, no cables, no connectors, no junction boxes, etc.

The main objective of PV-wirefree is to minimize costs of PV-systems and costs of electricity generated by PV-systems. With PV-wirefree we estimate the BOS-costs can be reduced with more than 50%.

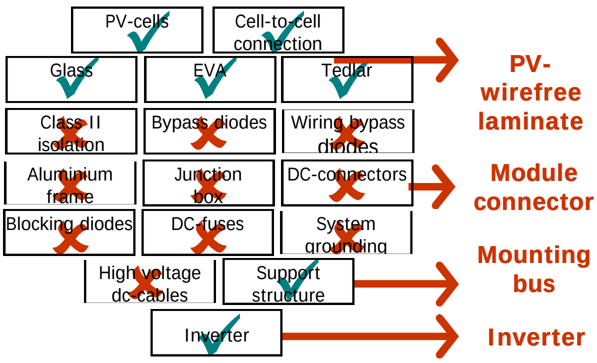

Fig. 1. PV-wirefree consists of only four components

1. ELIMINATING COMPONENTS

1.1. Ultimate integration of functions

In order to minimize the number of components we used a back-to-basics approach. The essential components of a PV-system are (Fig. 1): PV-laminates consisting of PV-cells to generate electricity, connectors to electrically connect the PV-laminate to a current carrier , conductor to carry the DC-current from the PV-laminate / connector to an inverter and an inverter to convert DC to AC-power

These components form the main parts of PV-wirefree systems, whereas we aim not to add any unnecessary components by integrating functions. In current PV-string systems electrical functions and mechanical functions are fulfilled by different components. In a PV-wirefree system these functions are integrated into the main components of PV-wirefree (Fig. 3).

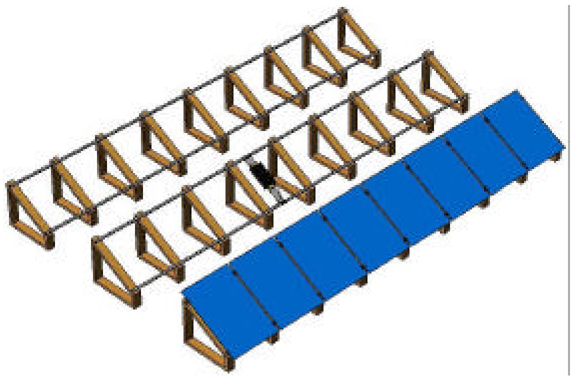

Fig 2. Impression of a PV-wirefree system. First the mounting buses are mounted on a support structure, then the inverter is mounted between the mounting buses, and finally the PV-laminates are clicked onto the mounting buses.

So, PV-wirefree consists of PV-laminates connected in parallel using a current carrying mounting frame (the mounting bus). Each group of PV-laminates connected to one set of mounting buses has its own inverter and is called a subsystem.

Electrical functions	PV-wirefree	Mechanical functions
PV-module	PV-wirefree laminate	Module frame
DC-connectors	Module connector	Mechanical fixing
DC-wiring	Mounting bus	Support structure

Fig. 3. Integration of mechanical and electrical function in the main components of PV-wirefree

1.2. Eliminate bypass diodes

In PV-systems in which PV-modules are connected in series, bypass diodes are required for hot spot protection. When a string of PV-modules is illuminated while a few cells are shaded, the illuminated cells force the shaded cells to operate in reverse direction. Excessive power will be dissipated in the shaded cells, causing hot spots, which may eventually lead to cell defects. To avoid hot spots bypass diodes are added (usually one bypass diode for each 18 cells). However, bypass diodes are not fail-safe. When one fails, the diode itself may become a short circuit, which might lead to excessive back-feeding current in one string in case many strings are connected in parallel. This may result in overheating of the PV-modules and over-current in the DC-wiring of the string. In other words, by adding bypass diodes a new problem was introduced, which can only be avoided by adding fuses to avoid over-current.

The question is whether an alternative approach without using bypass diodes is possible resulting in at least the same level of protection against hot spots.

Suppose a bypass diode is used across every 18 cells, which is common in current PV-systems. The worst case occurs when 17 cells are illuminated and one cell is dark and the bypass diode is conducting. In that case the dark cell will feel the voltage of 17 cells plus the forward voltage of the bypass diode. Since the forward voltage of the bypass diode is approximately the same as the voltage of one cell the dark cells feels a voltage equivalent to the voltage of 18 cells. So, equal protection against hot spots is obtained when the PV-system consists of modules of 19 cells in series, which are connected in parallel. The worst case situation occurs when these modules are short circuited, resulting in the same worst case scenario as the worst case scenario in a string system with a bypass diode across every 18 cells. Superior protection can be obtained when this system is designed in such a way that a long term short-circuit is avoided under all circumstances, even under single fault conditions (1 cell short-circuited).

This approach opens a solution for systems in which PV-modules with more than 19 cells per module are connected in parallel.

Table I. Typical values of PV-modules

V_{oc}@stc	0.6	V/cell
Temperature coefficient	- 2	mV/ºC
$V_{oc,hot}$ = V_{oc}@1000W/m², 75ºC	0.5	V/cell
$V_{oc,cold}$ = V_{oc}@1000W.m², -25ºC	0.7	V/cell
$V_{inv,min}$	0.333	V/cell
N_b = number of cells per bypass diode	18	cells

Suppose a module consist of N cells in series (without bypass diodes) and the PV-system consists of only single modules in parallel and is designed in a way that, for longer periods, even under single fault conditions, the module will not be loaded at lower voltage than $N.V_{inv,min}$. If one cell of a module is shaded this cell will feel the voltage of N-1 cells minus $N.V_{inv,min}$. This gives $V_{darkcell,reverse} = (N-1)\ Voc - N.V_{inv,min}$. In the string system the worst case is $V_{darkcell,reverse} = N_b.V_{oc,cold}$. So under the condition $(N-1).V_{oc,cold} - N.V_{min,inv} < N_b.V_{oc,cold}$ this system will have at least equal protection against hot spots. Solving N from the previous equation results in $N < (N_{b+1})/(1-V_{min,inv}/V_{oc,cold})$, with N_b the number of cells per bypass diode in a string system. Using the figures from table I gives: N < (18+1)/(1-0.333/0.7) = 36 cells.

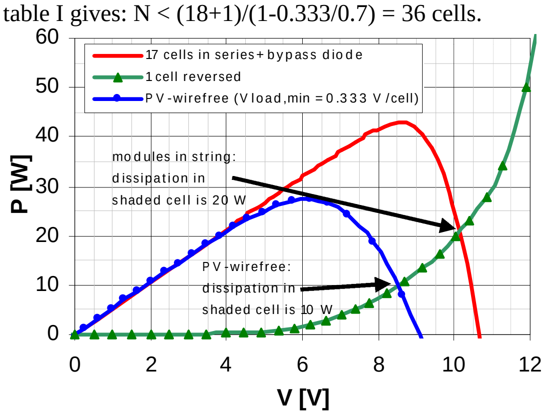

Fig. 4. Effect of partial shading

So under the condition the PV-modules will not be loaded below 0.333 V/cell equal protection against hot spots is obtained provided that the number of cells is limited to 36. However, this is a worst case. Under practical conditions the cell temperatures will be higher, and therefore, the cell voltage will be lower. Therefore the protection will be far better (Fig. 4). In other words even in the worst conditions no bypass diodes are necessary as long as the PV-modules are connected in parallel and the inverter will not load the PV-modules below 0.333 V/cell.

1.3 Eliminate the fuses

Under the condition that the bypass diode is eliminated the back-feeding current is limited by the physics of the cells. In Fig. 5 the normalized back-feeding current in a complete dark PV-wirefree module in parallel with a number of fully illuminated PV-modules is shown. It is clear that under all circumstances the back-feeding current remains well below I_{sc}. Even under single fault conditions the current is well limited below I_{sc}. Therefore the fuses can be omitted as well.

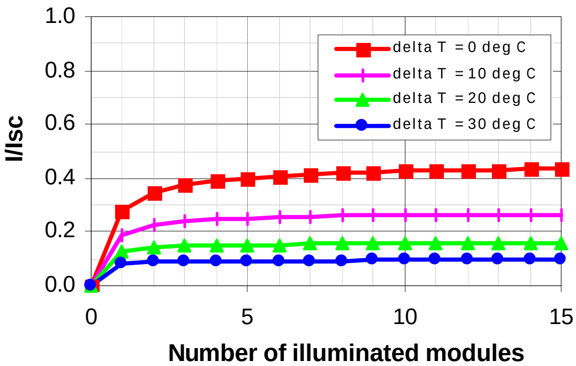

Fig. 5: Normalized back-feeding current in one shaded PV-module versus the number of parallel connected PV-modules under standard illumination conditions, at various temperature differences between illuminated and unilluminated modules.

1.5 Eliminate the PV-module frame

Most PV manufacturers use an aluminium frame for the laminates. This increases both the weight and the energy payback time of the module. Moreover, practice shows that algea growth starts at the boundary between the glass and the frame. PV-wirefree uses frameless laminates and therefore has eliminated these disadvantages.

2. DESIGNING THE COMPONENTS

As explained in paragraph 2, a PV-wirefree system consists of only four components: the PV-laminate, the module connector, the mounting bus and the inverter. To minimize the integral costs of these components the design of the most expensive component, the PV-laminate, has been leading, affecting and limiting the design freedom of the other components.

Furthermore, the design was restricted by general safety standards. International standards concerning touch safety require for bare conductors – which are used in PV-wirefree systems to minimize costs, a system voltage of less than 60 volts in dry conditions and less than 30 volts in wet conditions. Since the open circuit voltage of PV-wirefree is 21 volts these requirements are easily met. A second safety aspect is related to the energy hazard. When the power of the system is above 240 Watt and bare conductors are used sufficient separation between the conductors is required. The IEC requires that a test finger of 80 mm shall not be able to make a short circuit. The US regulations indicate that a tool shall not be able to make a short circuit. Since the distance between the mounting buses in a PV-wirefree system is more than 0.5 m, these requirements are easily met.

The third design principle concerns the application area: PV-wirefree should be suitable for “nearly all” PV-market sectors. Thus the system should be designed for use on flat and sloped roofs, facades and desert plants (VLS-PV). It should also be suitable for both multi- and monocrystalline cells, more specific, PV-wirefree should be usable for laminates based on cells of 125 x 125 mm, 150 x 150 mm and 200 x 200 mm.

Finally, to minimize costs, the cell-to-cell wiring needs to be minimized while the junction box, bypass diodes, fuses and frame shall be omitted. The laminate dimensions need to be optimized while using standard (heat strengthened) 4 mm PV-glass. Easy installation will be obtained by using a click and fit system.

With these requirements and limitations in mind, first the PV-wirefree laminate was designed.

2.1. PV-wirefree laminate

From the general requirements regarding wind loads and maximum stress in glass the following design requirements were defined. First the PV-wirefree laminate should be able to withstand a wind load of 2400 Pa (IEC 61215), while the stress of the glass should not exceed 80 N/mm², implying 50 N/mm² at a wind load of 1500 Pa. Preferably the weight of the laminate should not exceed 10 kg, which corresponds with an area of about 1 m² when using 4 mm glass.

Stress analysis of a common 4 x 9 cells (150 mm) laminate, but optmized for a four points connection resulted in a maximum stress in the laminate of about 130 N/mm² at a wind load of 2400 Pa. So, a 4-points connection is not feasible for these modules. Therefore, stress analysis was carried out for PV-laminates with other dimensions. It appeared that a 4-points connection for a 5 x 7 cells (150 mm cells with a distance between fixings of 0.648 m is actually feasible, since the maximum stress is reduced to 80 N/mm² at a wind load of 2400 Pa, provided a properly engineered connector is used. Also for the other cell sizes PV-laminates with a 4-points connection appeared to be feasible: 4 x 5 cells (200 mm cells) and 5 x 7 cells (125 mm cells). The features of the identified top 3 PV-wirefree laminates are given in table II.

2.2. PV-wirefree mounting bus

The mounting bus replaces the DC-wiring and the support structure. So, the mounting bus should be strong enought to carry the weight of the PV-laminates and the wind load on the PV-mdoules and at the same time have a cross area sufficient to carry the current of the PV-wirefree subsystem. The material should be suitable to provide a reliable electrical contact.

To select a proper material three options – copper, steel and aluminium - were compared regarding costs, energy content, etc. Though at first glance steel seemed to be a good choice, aluminium showed to be far better since its costs per amount of conduction is lower than that of steel and copper. Also, its energy content per amount of conduction is lower than of steel. Moreover, aluminium is used as common building material and can easily be extruded in virtually any shape. Therefore aluminium is the first choice material for the PV-wirefree mounting bus.

The profile should be rugged and thick enough to withstand mechanical loads from the PV-modules.. Calculations showed a strength optimized profile of about 150 mm² is required. Using this profile the maximum PV-wirefree subsystem size is approximately 3-4 kW for the 5 x 7 cells laminates and 1 kW for the 4 x 5 cells laminates. The aluminium used is 0.67 kg per module, resulting in a energy payback time of 2 months (5 x 7 cells, 150 mm) at 1000 W/m².

Table II: Features top 3 PV-wirefree laminates

	5x7 cells 125 mm	5x7 cells 150 mm	4x5 cells 200 mm
Dimensions (mxm)	0.677 x 0.933	0.802 x 1.108	0.849 x 1.052
Area [m²]	0.632	0.889	0.893
Bus distance [m]	0.533	0.648	0.612
Weight [kg]	6.9	9.8	9.8
Power [Wp] @cell efficiency	88 @ 16%	118 @ 15%	88 @ 11%
Voc [V]	21	21	12
Vmpp [V]	17	17	9

2.3. PV-wirefree module connector

The PV-wirefree module connector replaces the junction box and the PV-module frame. So it should provide mechanical support for the 4-points connection, be strong enough to withstand the wind loads at the PV-laminates, electrically connect the PV-laminates to the mounting bus.

As for the mounting bus aluminium is selected, and corrosion due to difference in electrochemical potential of different metals should be avoided, the only right solution is an aluminium-aluminium contact and thus all electrically connected outdoor materials should be made of aluminium. However, this requires additional measures to ensure a reliable contact for more than 20 years. A stabilized normal contact force of about 100 N is needed to crush the thin aluminium oxide layer, whereas afer mating the contact should be fixed.

2.4. PV-wirefree inverter

Based on the design choices for the three other PV-wirefree components, the inverter should have a working input voltage matching the PV-wirefree laminates of approx 15 V (35 cells laminate) or 8 V (20 cells laminate), not load the PV-modules below 0.33 V/cell for longer periods and should never short the PV-laminates even in single fault conditions, both inside and outside the inverter for longer periods. Furthermore it should have an efficiency and price per watt comparable with existing inverters. To increase reliability it should have redundant and rugged connections to the mounting bus.

A topology is developed meeting these requirements. Even under multiple fault conditions – like mosfet, diode or driver failure – the inputs will not be short-circuited. The topology has an acceptable efficiency and appears to be well-scalable to the power required for PV-wirefree systems. Testing of a 350 W model has started.

3. COMPARISON OF PV-WIREFREE AND STRING SYSTEMS

In this section we compare a PV-wirefree system with a common string system in case of optimal, suboptimal, single fault and multiple fault conditions. "Optimal conditions" means that all PV-modules are equally illuminated and have the same temperature. "Suboptimal conditions" means that the modules are not equally illumined (partially shaded, polluted).

3.1. Optimal conditions

Under optimal conditions the performance of a PV-wirefree system is comparable with the performance of a string system with a transformerless inverter: the efficiency of the transformerless inverter will be slightly higher than the efficiency of the PV-wirefree inverter (which uses a transformer). Due to a small mismatch between the currents of the laminates some mismatch losses will occur in the strings. This effect does not occur in PV-wirefree systems and roughly cancels the previous effect. Also reliability, touch safety and energy hazard are comparable under optimal conditions.

3.2. Suboptimal conditions

Under suboptimal conditions the PV-wirefree system will outperform any string system since the PV-laminates in the PV-wirefree system operate almost independently from each other and thus mismatch losses at system level will not occur (Fig 7). Moreover, hot spot effects are reduced, and thus the reliability of the PV wirefree system will be better. Suboptimal conditions will not affect the touch safety and the energy hazard significantly.

3.3. Single fault conditions

In a string single fault conditions cause at least the loss of power in a complete string. In a PV-wirefree system only the power of one module will be lost. Therefore the PV wirefree system will perform much better under single fault conditions. For the same reason also the reliability of a PV-wirefree system is better. In case the wiring or the laminates are damaged the transformerless string system is no longer touch safe. Touch safety remains guaranteed for the PV-wirefree system. In most cases when the laminates of a PV-wirefree system are heavily damaged the remaining situation will still meet the requirements for the energy hazard. A damaged module in a high voltage string is an energy hazard. When one of the bypass diodes in a string system fails (open circuit) the protection against hot spots caused by partial shading is lost. Note that this failure can not be detected at system level.

3.4. Multiple fault conditions

Even under most multiple fault conditions the PV-wirefree system remains operating safely. Only when the buses are short circuited (this requires two faults) the system will stop functioning. Under this condition the protection against hot spots caused by partial shading is lost. Note that this failure can be detected easily at system level. Recovering from this failure is easy: as the voltage is touch safe and too low to maintain an arc the short circuit can be opened with bare hands. This is tested in practice for systems with short circuit currents up to 200 A. In string systems opening a short circuit is extremely dangerous.

Table III: Comparison PV-wirefree system with string system

Conditions Subject	Optimal	Suboptimal	Single fault	Multiple fault
Performance	=	++	++	++
Reliability	=	+	++	++
Touch safety	=	=	++	++
Energy hazard	=	=	+	+
Costs	+	++	++	++

4. CONCLUSIONS AND FUTURE DEVELOPMENTS

PV-wirefree systems outperform PV-strings in suboptimal conditions. Since the chance of failures in PV-wirefree systems is reduced an order of magnitude because of the redundancy in connections, the reliability of a PV-wirefree system is far better. Moreover PV-wirefree remains touch safe under all circumstances, even in multiple fault conditions. Regarding energy hazard there are no significant differences between the systems.

But the most important conclusion is that PV-wirefree will reduce costs considerably, since many components can be omitted and the system only consists of four components. The BOS-costs are expected to be reduced with more than 50%, whereas a decrease of costs of electricity generated by PV can be obtained.

In January 2003 a proof-of-principle project has started, in which partners from different background participate: Bear Architects, Energy research Center of the Netherlands, NKF Electronics, OKE-Services, Oskomera Solar Power Solutions BV and TNO Bouw. Market introduction is aimed at for 2005. But more work needs to be done especially adapting the PV-standards is necessary, since these do not include paralleling large numbers of PV-modules.

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

5. ACKNOWLEDGEMENTS

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