PV STRING PER-MODULE MAXIMUM POWER POINT ENABLING CONVERTERS

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Abstract

Many grid connected PV installations consist of a single series string of PV modules and a single DC-AC inverter. This efficiency of this topology can be enhanced with additional low power, low cost per panel converter modules. Most current flows directly in the series string which ensures high efficiency. However parallel Cúk or buck-boost DC-DC converters connected across each adjacent pair of modules now support any desired current difference between series connected PV modules. Each converter "shuffles" the desired difference in PV module currents between two modules and so on up the string. Spice simulations show that even with poor efficiency, these modules can make a significant improvement to the overall power which can be recovered from partially shaded PV strings.

1 SERIES PHOTOVOLTAIC MODULE CONNECTION

Three specific examples of such DC energy sources that will have a role in distributed generation and sustainable energy systems are the photovoltaic (PV) panel, the fuel cell stack, and batteries of various chemistries. These DC energy sources are all series and parallel connections of a basic "cell". These cells all operate at a low DC voltage ranging from less than a volt (PV cell) to three or four volts (Li-Ion cell). These low voltages do not interface well to existing higher power systems, so the cells are series connected to create a module with a higher terminal voltage.

Focusing on PV systems, a typical "12 Volt" PV module or panel has 36 series connected solar cells with a maximum power point (MPP) of approximately 15V at normal operating temperatures (approx 50°C). These system voltages are appropriate for lower power systems, but beyond powers of a few hundred Watts, these panels themselves are placed in series strings – PV arrays – to maintain lower currents and higher efficiencies. The terms PV cell, PV panel and PV array will be used in this paper, to avoid confusion with the term "module" which may be used to refer to the power electronic converter associated with a panel.

These long strings of cells bring with them many complications. A problem occurs when even a single cell in the array is shaded or obscured. The photocurrent generated in a shaded cell may drop to perhaps 20% of the other cells. The shaded cell will be reverse biased by the remaining cells in the string, but current will continue to flow through it causing large localised power dissipation. Bypass diodes, generally placed in parallel around each 18 cells (half a panel), limit the reverse bias voltage and hence the power dissipation in the shaded cell to that generated by the surrounding half panel. However, all the power from that sub string is lost while current flows in the bypass diode [1,5,6].

Module MPP currents may be permanently unbalanced for other reasons. PV modules in a string are never exactly identical. Because PV modules in a series string are constrained to all conduct the same current, the least efficient module sets this string current. The overall efficiency of the array is reduced to the efficiency of this module.

For similar reasons PV panels in a string should be given the same orientation, and be of identical size. This is not always possible or desirable for ascetic or other architectural reasons. An example of a PV array with a curved surface [2] is shown in Fig.1.

2 PV MODULE CONVERTER CONNECTION

2.1 Current approaches for Grid Connection

In grid-connected inverters for PV applications, a number of different approaches have been developed and used over the last 20 years. An excellent review of such systems available in Europe is given in [3]. Only the two most common approaches used in smaller residential scale installations (1-3kW) are compared here.

The original approach was to create a single high voltage DC series string connected to a single DC-AC inverter: In a residential system of say 1.5kW (a typical size) all the PV panels on the rooftop can be connected electrically in series, to create a high voltage (360V) low current (4.5A) DC source. This source is connected to a single DC-AC inverter within the roof or house. The AC then runs to the residential switchboard.

Note that this approach uses a single series string of modules, and so can only search for and operate at a global Maximum Power Point (MPP).

Fig.1 This curved roof of a commercial building conservatory space in the Netherlands is formed by PV modules [2]. Such curved PV surfaces limit string connection options.

The more recent Module Integrated Converter (MIC) approach is to mount individual DC-AC inverters per PV module, mounted at the module on the rooftop. A 240Vac connection from the switchboard runs to the rooftop, and loops from inverter to inverter, panel to panel. Each panel is now effectively placed in parallel, via its own dedicated inverter. Each panel can now operate at its own MPP independent of other panels.

To be small, light and low cost, module-integrated converters generally use high frequency switch mode techniques. They require several conversion stages to efficiently convert the module's low DC voltage to the 240Vac grid voltage – a boost stage probably including an isolation transformer, rectification to a high voltage DC bus, and an AC inversion stage. An example of a European 100W 24Vdc – 240Vac MIC before potting [4] is shown in figure 2.

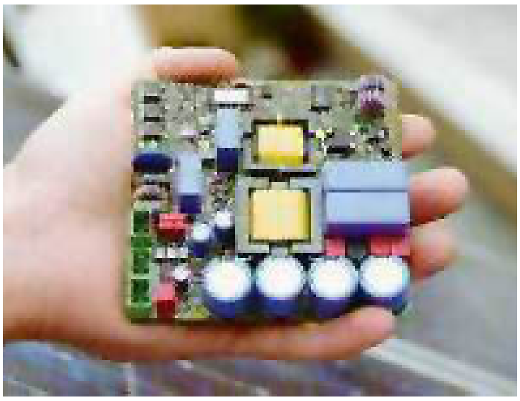

Fig.2 A 100W module integrated converter [4].

Compared to a single central converter, a per module collection of these converters will certainly be more expensive to purchase. This may be justified by simpler installation and protection and by the advantages of per module conversion – individual MPP tracking and module independence and thus higher reliability.

2.2 Alternatives for MPP tracking of PV arrays

Several alternative configurations have been proposed which will allow per module MPP tracking, without resorting to the MIC approach of attaching a complete DC-AC grid connection converter to each PV module.

Shimizu [5,6] gives two versions of a "Generation Control Circuit" (GCC) which may be placed in parallel with each PV module of a series string of modules to allow independent MPP tracking. The first is an auxiliary HF transformer isolated converter with a single MOSFET full bridge primary powered from the entire PV string's DC output. The converter has multiple identical diode full bridge rectified secondaries, one connected across each PV module in the series string. These force the modules to have identical secondary voltages and can supply the shortfall of current any shaded module may require. With identical module voltages, each PV module is close to its MPP, since the MPP voltage does not depend strongly on irradiation [7].

A similar solution using a multiple secondary converter was proposed for battery equalisation by Kutkut [8]. This converter used a multi-winding coaxial transformer to ensure accurate matching of the multiple secondary voltages.

Shimizu's second version is a non-isolated "multi-stage chopper" which is further developed in [6]. This converter effectively places a boost converter with an input on each PV module, boosting to the total string voltage.

Both of these converters are shown to be effective in recovering more power from a partially shaded PV array. Both of these converters are single centralised modules which then require "tap" connections to each PV module in the series string.

A low power "balancing" converter has been suggested for the purposes of battery equalisation [9]. This flying capacitor converter, otherwise similar in architecture to Shimizu's second version, achieves its goal by equalising the voltage across each battery. A flying capacitor converter is well suited to the requirements of that application with equal voltages and initially low and continually falling currents. These conditions may not be true in the PV string application.

An alternative distributed architecture of converters, one per PV module, is proposed by Walker and Sernia [10]. These converters are not complex, isolated DC-AC converter – inverter grid connection modules but rather simple non-isolated DC-DC converters. They give each PV module in the series string independence from the string current and thus independent operating point operation. A singe central DC-AC inverter is still used for grid connection.

A disadvantage of this proposal is that the complete power of the PV module must flow through its associated DC-DC converter module. A better solution would be converters associated with each PV module which only process the power difference between adjacent modules. Normally this power difference would be small, approaching zero ideally, so smaller rated converters with less stringent efficiency performance could be used without lowering the efficiency of the PV string.

3 OPERATION OF BYPASS CONVERTERS

3.1 Explanation of Operation

This paper proposes non-isolated inverting dc-dc converters as suitable for passing power between neighbouring series connected PV modules. A diagram of this power "shuffling" topology is shown in fig.3. Each adjacent pair of series connected PV modules has a non-isolated inverting bidirectional dc-dc converter such as the buck-boost or the Cúk connecting them. A single isolated module such as a bidirectional flyback converter is required to complete the shuffling loop.

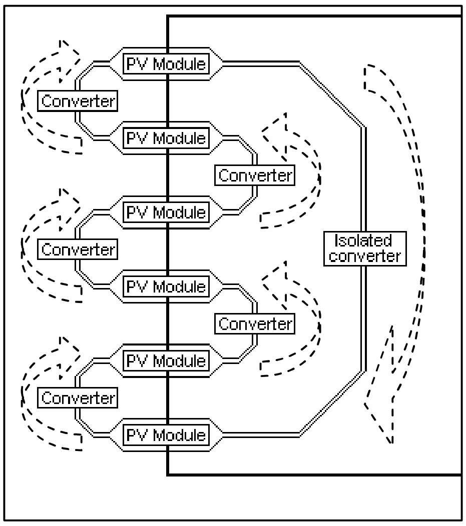

Fig.3 Each pair of adjacent PV panels in the series string has a bi-directional dc-dc converter associated with them, which can "shuffle" power up or down the string.

With the shuffling converters disabled, all PV modules connected in series are forced to pass the same current. If they cannot carry this current, then their associated bypass diodes conduct. A Spice simulation DC sweep plot of string current and power is shown in figure 4a for six series connected 60W PV modules (BPsolarex msx60) with six bypass diodes. A step in the current curve and double maxima in the power curve is shown because one PV module is shaded, modelled with 2A of photo-generated current versus 3.88A for the other five. The two power maxima are 267W at 74V (five panels at 3.88A) and 200W at 100V (six panels at 2A).

With the shuffling converters enabled, adjacent modules may operate at different currents if these converters support the difference in current between adjacent modules. Figure 4b shows this situation for the example discussed. The two dc-dc converters in parallel with the shaded panel each supply 0.78A, half of the difference in current between the string current of 3.57A and the shaded PV module current of 2A. That current in turn is "robbed" from the PV modules above and below the shaded PV module. This current is greater than the photo-current of these unshaded panels (3.57A+0.78A > 3.88A) so they in-turn require 0.47A to be passed along the string to them. This cascade of balancing currents continues up and down the string so that equilibrium exists as Kirchoff's current law is satisfied at each node.

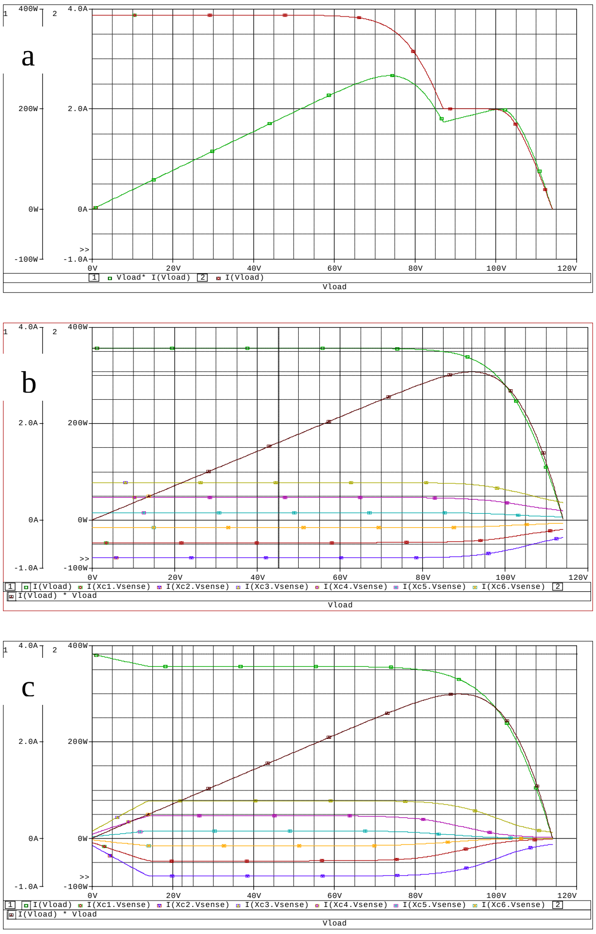

Fig.4 The simulated current and power vs voltage curves for six series connected msx60 60W PV panels. a) Five panels receive full sun (Isc = 3.88A) while the sixth is partially shaded (Isc = 2A). MPP = 267W b) The six “shuffling” dc-dc converters are enabled and move current as shown between PV panels. A new string IV curve is generated, MPP = 307W. c) MPP = 300W even when shuffling converters have poor efficiency (3 Ohm equivalent series resistance).

The worst situation of unbalance occurs when two adjacent PV panels in a large array are completely shaded or fail. The string current will be very nearly equal to the current of the remaining panels, and the two converters connected to the non-performing panels must each supply this full array current. Hence the converters must have current, voltage and power ratings equivalent to the panels they support.

Note that one final isolated converter is required to link the bottom and top panels in the PV array to make a symmetrical configuration. If a non-symmetric arrangement is acceptable, the balancing can still occur without this module, but with larger loads on the converters near the ends if an end module is shaded. It is also notable that with a full complement of converters, any one converter can fail and perfect MPP tracking operation can still occur, since each PV panel has two converter modules connected to it.

3.2 Simulated Performance

The spice model for the dc-dc converters was a simple cross coupled connection of a voltage controlled voltage source (E1) and a current controlled current source (F2). In an arrangement which can mimic a transformer or dc-dc converter, these blocks transfer the voltage seen at one port to the other, and the current seen at that port back to the first, through an appropriate turns / duty ratio. Here that ratio was set at unity, which models an inverting converter with D=0.5. A series resistance initially set at 0.1 Ohm models copper or conduction losses.

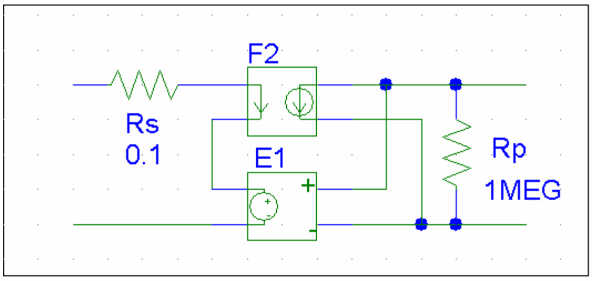

Fig.5 The spice model used for the dc-dc converters consists of cross coupled voltage controlled voltage source and current controlled current source. Resistances model losses.

With these converter models between all adjacent PV panels, the new maximum power point was 307W at 92V, as shown in figure 4b. Since the converters are operating at currents less than 1A (15W), their losses are low. At 1A, the 0.1Ohm series resistance modelled will produce a loss of only 0.1W, or an efficiency of greater than 99% at 15W which is perhaps somewhat unachievable.

To see the impact of converter efficiency on the proposed power shuffling, this series resistance is increased to 3 Ohm, which corresponds to a loss of 3W at 1A, and 12W at 2A, or an efficiency of 80% and 60% respectively at 15V. Even with this poor performance, the maximum power point was 300W at 91V (figure 4c), which was still a marked improvement on 267W (figure 4a).

Because the PV array will often be evenly lit, the converters will usually operate with no power flow. It will be perhaps more important to ensure the converters consume very low quiescent than optimising their efficiency at high currents.

3.3 Converter topology

As stated, Each adjacent pair of series connected PV modules has a non-isolated inverting bidirectional dc-dc converter such as the buck-boost or the Cúk connecting them. A single isolated module such as a bidirectional flyback converter is required to complete the shuffling loop. Bi-directional versions of these converters are created by replacing the diode with a second MOSFET which is driven in a complementary fashion to the first MOSFET. One of the two MOSFETs acts as a synchronous rectifier, depending on the direction of power (current) flow. If both MOSFETs are always driven, this also ensures the converters operate in continuous conduction mode (CCM) from a positive current, through zero current, to a negative current. This gives a stable and predictable transfer function for the converter.

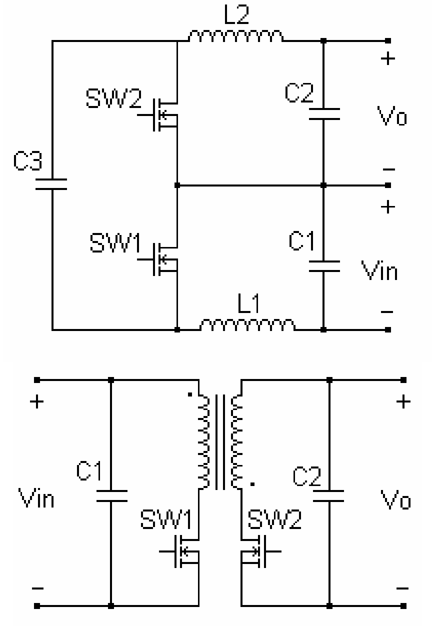

Fig.6 The Cúk and flyback converters with two MOSFETs to achieve bi-directional operation.

The Cúk converter is considered possibly more advantageous in this application because of its lower input and output ripple current. With high frequency operation, it might be possible to avoid the need for electrolytic capacitors, which would be advantageous for a converter which would be mounted behind the PV panel most likely in its junction box. The Cúk converter is shown in figure 6 redrawn to highlight its inverting nature and connection to two adjacent PV panels.

The flyback converter is also shown in figure 6, drawn to highlight its symmetrical nature when designed for bi-directional operation.

3.4 Control Strategy

The control strategy adopted for this study was the trivial case of assuming the bi-directional converters would operate with equal input and output voltages. This is easily achieved for the converters described by operating them in CCM at a duty cycle D=0.5. Under these conditions, the voltages of the PV panels will all be forced equal (assuming efficient converters). This does not guarantee MPP tracking for each panel, as the MPP voltage drops slightly as illumination and power falls, however the fall is slight. Furthermore there may be partial compensation by cooler operating temperatures of the shaded panels, which lifts the output voltages.

A more complex control algorithm could be developed which for example performs “hill-climbing” in the now several dimensions available. This would most likely require microcontrollers and possibly communication between the modules, and robs this proposal of its simplicity. This would be an interesting area for further research.

Global MPP tracking would be performed on the PV string by the dc-ac grid inverter, or similar string connected converter. Because the voltage of shaded panels should no longer collapse until the bypass diodes conduct, this task will be eased as the string MPP voltage should be remain more constant. Further without the non-linearities of the bypass diodes switching in, there should only be one MPP (no multiple local maxima).

4 CONCLUSIONS AND FUTURE RESEARCH

PV strings of modules can forfeit significant power when partly shaded. This problem can be eliminated by placing small low power dc-dc converters, one per PV panel, which can “shuffle” power between adjacent PV modules. These converters generally process very little power unless shading is occurring, and even inefficient implementations are shown to still make a significant improvement to the overall power delivery of the array.

Future work will include building and characterising low cost bi-directional inverting dc-dc modules using both fixed 50% duty cycle control and intelligent microcontroller control. The focus on this work will be in a number of areas:

- Reducing cost, and showing that the inclusion of these modules is sensible economically.
- Reducing size and ensuring reliable operation, to allow the converters to be place in the junction box of rear of the PV panels.
- Assessing effectiveness of both simple and complex control algorithms in simulation as well as on an actual working PV array.

APPENDIX – Spice listing

```
* PV_shuffle.cir
Vload 7 0 90
Rload 6 7 0.2

Xpv1 0 1  msx60
Xpv2 1 2  msx60
Xpv3 2 3  msx60  PARAMS: I_gen = 2.0
Xpv4 3 4  msx60
Xpv5 4 5  msx60
Xpv6 5 6  msx60
Xc1  1  0   2  1  txfmr
Xc2  2  1   3  2  txfmr
Xc3  3  2   4  3  txfmr
Xc4  4  3   5  4  txfmr
Xc5  5  4   6  5  txfmr
Xc6  6  5   1  0  txfmr

* msx60 PV panel by BPsolar at 50degC -- not exact but close
.subckt msx60 1 3 PARAMS: I_gen = 3.88
G_PV 2 1 VALUE = {3.88*(exp(V(2,1)/(36*0.026))-1)
+                              /(exp(19.1/(36*0.026))-1)}
I_PV 1 2 {I_gen}
R_s  2 3 0.288
R_p  1 3 1Meg
D_bypass  1 3  POWER_DIODE
.MODEL  POWER_DIODE  D(CJO=0.001fF, IS=1E-6, RS=0.01)
.ends msx60

* subcircuit for DC capable transformer
* Simulates bi-directional DC DC converter too.
* turns ratio / duty ratio  fixed at 1.0
*                  in+ in-  out+ out-
.subckt txfmr  1   2    3    4
* combined pri+sec series resistance
Rs  1 5  0.1
Vsense 6 5  0V
E1  6 2  3 4  1.0
F2  3 4  Vsense  1.0
* combined pri+sec parallel resistance
Rp  3 4  1MEG
.ends txfmr

.dc Vload 0  114  0.1
.probe
.end
```

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