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PhotoVoltaic DC-DC Module Integrated Converter for Novel Cascaded and Bypass Grid Connection Topologies – Design and Optimisation

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Abstract—Grid connected PhotoVoltaic (PV) inverters fall into three broad categories – Central, String and Module Integrated Converters (MICs). MICs offer many advantages in performance and flexibility, but are at a cost disadvantage. Two alternative novel approaches proposed by the author – cascaded dc-dc MICs and bypass dc-dc MICs – integrate a simple non-isolated intelligent dc-dc converter with each PV module to provide the advantages of dc-ac MICs at a lower cost. A suitable universal 150W 5A dc-dc converter design is presented based on two interleaved MOSFET half bridges. Testing shows Zero Voltage Switching (ZVS) keeps losses under 1W for bi-directional power flows up to 15W between two adjacent 12V PV modules for the bypass application, and efficiencies over 94% for most of the operational power range for the cascaded converter application. Based on the experimental results, potential optimizations to further reduce losses are discussed.

I. THE GROWTH OF GRID CONNECTED PV

The installation of grid connected photovoltaic (PV) systems is growing at a staggering rate, driven by a number of factors including growing concern about global warming and energy security, and improvements in technology and subsequent decreasing costs. Growth rates of approximately 40% each year are reported in the member countries of the International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS) (Fig.1). The total reported installed PV capacity in 2004 is over 2500MW, with over 80% of that grid connected [1]. Note that these numbers do not include the rapid recent growth in non-member countries China and India, among others. Grid-connected systems typically cost about 5 to 7 US$ per watt, with PV modules accounting for 50-60% of system costs [2].

Grid connect inverters are becoming more important. The number of inverter manufacturers is significant – more than ten in Japan, several in the United States, and some 25 to 30 in Europe (in 2003) [2]. In Japan, "products mainly target residential systems with an output in the range 3 kVA to 5 kVA", while "A large number of 10 kVA units have also been supplied to public and industrial facilities, … generally, … connected in parallel for installations up to 200 kW" [2]. The boom in the PV market translates to grid connect inverters: "Manufacturers of PV inverters for grid connection faced a boom in 2004 and many companies more than doubled their output compared to 2003." [1]

A number of different approaches for grid connecting PV installations have been implemented commercially and yet more proposed by the academic community. Two good reviews have been written by Kjaer [3] and Ishikawa [4]. The traditional commercial approaches fall in to three broad groups as shown in top half of Figure 2. Centralised inverters consist of a single large three phase inverter fed by many parallelled series strings of PV modules. Smaller distributed installations most often use either a single string converter, or multiple Module Integrated Converters (MICs). Each of these approaches has both advantages and disadvantages; and trade off various attributes such as complexity, efficiency, flexibility, reliability, safety, additional functionality, and of course cost. These characteristics will be compared in the next section.

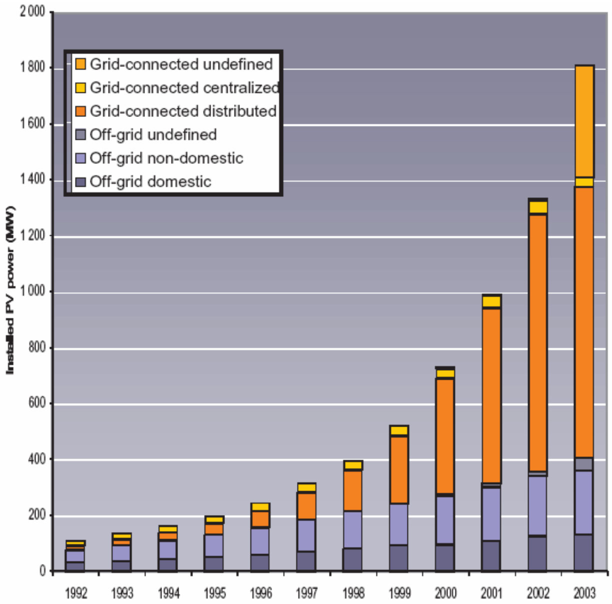

Fig. 1: The recent exponential growth of PV installation shows no sign of slowing down. Installed PV power in 2004 (not shown) was over 2500MW, another rise of 40% on the previous year. Most installations are distributed grid-connected PV. [1,2]

Two novel topologies proposed by the author are a hybrid of the string inverter and module integrated inverter (lower half of Figure 2). Low cost non-isolated dc-dc converters placed at each PV module can offer many of the advantages of Module Integrated Converters while minimising the trade offs. These two topologies are explained in Section III. The design of a dc-dc converter suitable for evaluating these new topologies is the subject of this paper, and is outlined in Section IV. Results of the experimental testing of this dc-dc converter are given in Section V, along with a discussion of

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the implications for the operation of these dc-dc converters in their intended application.

II. GRID CONNECTED PV INVERTER OPTIONS

A. *Central Inverters*

Large PV installations of several tens of kiloWatts or more have been traditionally grid connected using a central three phase inverter system, often a thyristor line commutated inverter. The 39.5kWp photovoltaic facade project at the UK University of Northumbria installed in 1994 is a good example [5]. The significant amount of PV wiring to the inverter is all high voltage DC, which demands careful safety and protection considerations, and is unfamiliar to most electrical contractors. The DC strings of PV modules must be connected in parallel with diodes, with diodes around each module, to protect the PV modules in the event of partial shading of the array. Without these, cells and modules can be destroyed [6].

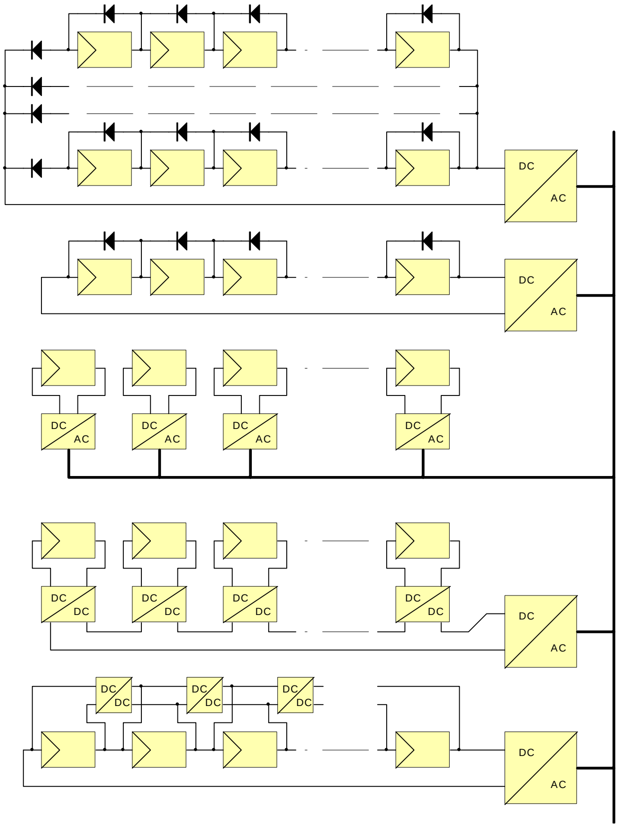

Fig. 2: From top to bottom, different converter topologies used for grid connection of PV – three traditional approaches: Centralized inverters, String inverters and Module Integrated Converters (MICs); and two new topologies proposed by the author: Cascaded dc-dc MICs and Bypass dc-dc MICs.

The Northumbria installation has 31 parallel strings of 15 series connected PV modules distributed across the face of a building as a façade. The parallel connection of strings forces their voltage to be equal, so should some of the modules in a string become shaded, the entire string may no longer deliver power to the inverter. This is indeed a problem in the Northumbria installation and Module Integrated Converters were considered as a possible solution [7].

In their favour, centralised systems can simplify monitoring, maintenance and repair, and have lower system costs and higher system reliability [8].

B. *String Inverters*

A more recent approach is to give each high voltage DC PV string its own dc-ac inverter, which usually has a rating of between 1-5kW. The string inverter is an ideal solution to residential PV installations, which are usually about this size. Maximum Power Point Tracking (MPPT) is performed on the string, but not yet on each module. Efficiency is high and costs reasonable. An example of one possible string inverter topology is shown in Figure 3.

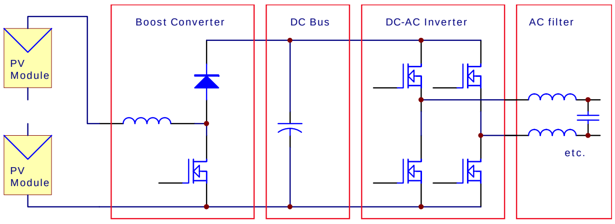

Fig. 3: An example non isolated string inverter topology. The inverter accepts the high voltage (100's of Volts) low current (5 A) from a series string of PV modules, and interfaces this to the AC grid (120/240 Vac). One converter serves the entire installation for small powers (<3 kW).

C. *Module Integrated Converters (MICs)*

Module Integrated Converters (MICs) are the most recent approach to grid connection. Each PV module has its own DC-AC inverter, eliminating all DC high voltage wiring. An ac grid connection loops from inverter to inverter, module to module, which leads to simplified wiring familiar to electrical contractors, greater safety and easier protection. Each PV module is now effectively placed in parallel, via its own dedicated inverter, which allows individual Maximum Power Point Tracking. An example MIC topology is shown in Figure 4.

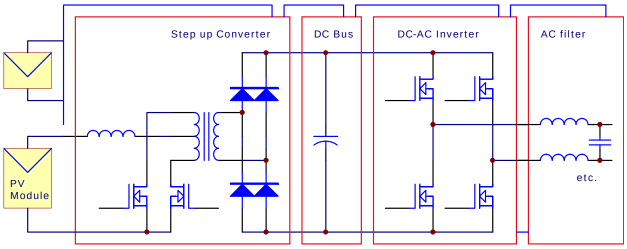

Fig. 4: An example isolated Module Integrated Converter (MIC) topology. The inverter directly connects to each PV module (5A, 15 or 30 V) and interfaces this to the low voltage AC grid (120/240Vac).

Module Integrated Converters are generally at a cost disadvantage compared to other approaches.

Myrzik [9] and Kjaer [3] are excellent review papers of both MICs and string inverters, while Ishikawa [4] provides a good review of products in the market.

III. TWO ALTERNATIVE APPROACHES

Placing a converter at each PV module as MIC installations do has several advantages. The list presented here is a summary of an expanded discussion from a previous paper by the author [10]:

- Per PV module MPPT allows better utilization of each PV module
    - Tolerance to partial shading
    - Tolerance to mismatched modules
    - Allowance for differing orientations
- Easy expandability, one PV module at a time.
- Greater fault tolerance, on a per PV module basis
- Better data gathering, on a per PV module basis
- Greater safety during installation and maintenance.

The disadvantages of MICs as already noted are their cost and potentially their efficiency when compared to string inverters.

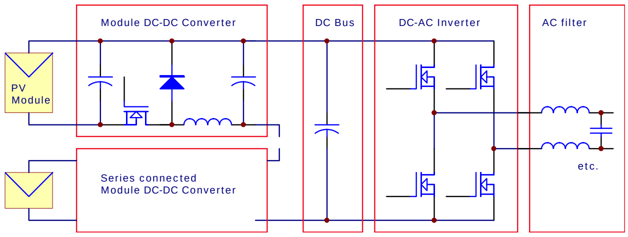

Fig. 5: Alternative approach #1: Cascaded dc-dc Module Integrated Converters, one per PV module, connect to a single central DC-AC inverter (with isolation if necessary). Any dc-dc converter topology can be used for the cascaded converters. Buck converters are shown here.

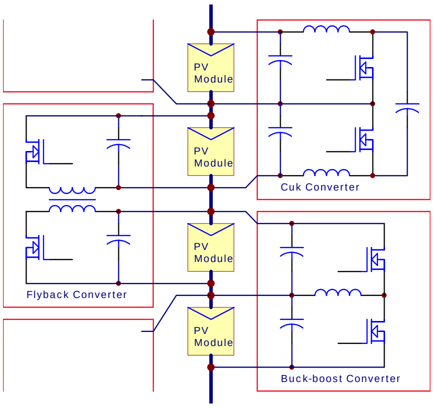

Fig. 6: Alternative approach #2: Bypass dc-dc Module Integrated Converters, one per PV module, connect across each PV module pair. The converters “shuffle” or “bypass” power to allow mismatches in PV module output. Three possible dc-dc converter topologies are shown.

The author has previously proposed two alternative hybrid topologies which seek to capture the benefits of per PV module converters while minimizing the cost and efficiency penalties. In the first approach, multiple non-isolated dc-dc converters (one per PV module) are connected in series and a single central or string dc-ac converter performs isolation (if necessary) and grid connection (Figure 5) [10]. The multi-string concept proposed by Meinhardt [11] has similarities, with *parallel* dc-dc PV *string* converters feeding a central dc-ac inverter. Any of the basic dc-dc converter topologies are suitable, although some are better suited than others. The buck converter (as shown in Figure 5) is the most suitable for this application, and generally the most efficient, but will require the most PV modules to ensure a minimum output voltage at the dc bus. The boost converter minimizes the number of PV and converter modules per string and can be as efficient. However, under unusual circumstances, it may be forced away from the PV modules MPP. An example boost converter is examined in this paper.

In the second proposed approach, PV modules are once again directly connected as a series string for connection to a single string inverter. However, each pair of PV modules has a buck-boost, Cúk or flyback “shuffle” or “bypass” converter able to shuffle power between any mismatched PV modules, allowing per PV module MPPT and monitoring, but with lower losses (Figure 6) [12]. The buck-boost topology is the simplest but will lead to high current and thus voltage ripple at both input and output ports. An example converter design which solves this problem by using two interleaved half bridges is presented in this paper.

Each of these two approaches again has advantages and drawbacks. The series cascaded dc-dc converter approach must process the entire PV module power, so must be rated accordingly and have high efficiency so as not to erode the performance benefits offered. As partial compensation, the string output voltage is independent of the PV module voltages, which may allow an additional conversion stage to be removed from the dc-ac inverter (compare Figure 3 with Figure 5). Strings of cascaded dc-dc converters may also be paralleled, feeding a central converter. For example, they would provide a good solution to the partial shading problem faced at Northumbria [7].

In its favour, the dc-dc shuffle or bypass converters process no power under normal conditions. So long as their quiescent power consumption approaches zero, they do not impact system efficiency at all, while still providing the benefits stated. Even with poor efficiency at rated load, system performance has been shown to be greatly improved [12]. However, the PV modules (mostly) set the string voltage, requiring global maximum power point tracking in the string inverter. They are unlikely to improve the system performance when paralleled to a central converter.

IV. UNIVERSAL PV DC-DC CONVERTER DESIGN

To enable the evaluation of these two new topologies, a universal dc-dc converter capable of fulfilling the requirements of either application has been designed, built, and evaluated. The application influenced the specific design choices made. An initial design was tested, and a revision of the converter was then been produced. Both are shown in Figure 7. The board dimensions are 120mm by 75mm, and could be reduced if required.

The power converter circuitry is quite conventional. It consists of two parallel MOSFET half bridges (essentially a full bridge, with each phase having its own inductor). Based on the definition of input and output ports, the converter can be viewed and operated as a buck, boost, or buck-boost converter.

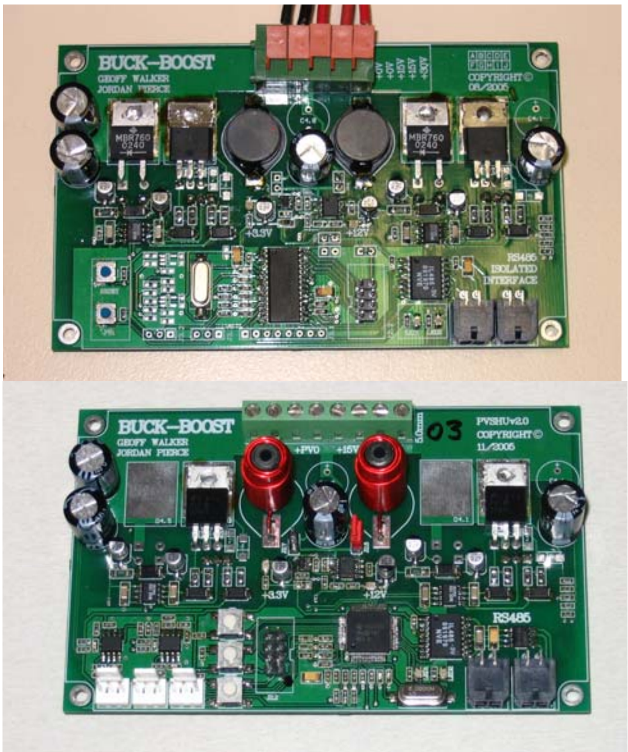

Fig. 7: The first and second versions of the dual half bridge converter. The upper MOSFETs and (if fitted) Schottky diodes are visible on the top side of the PCBs. The lower MOSFETs and diodes are not visible, being directly underneath them on the underside of the PCB.

The bypass or shuffle converter application will generally have equal input and output voltages. For the buck-boost topology this leads to maximum current ripple and thus voltage ripple and loss in the capacitors. Operating two parallel half bridges out of phase at 50% duty cycle cancels the current ripple in the input and output capacitors, minimizing both loss and voltage ripple at the likely operating point. This is true also for the boost converter configuration. Minimized capacitor ripple currents may allow the converter to avoid electrolytic capacitors, which is highly desirable in a PV module mounted piece of electronics.

The converters can run in continuous or discontinuous conduction mode with bi-directional or unidirectional current (power) flow depending on whether one or both MOSFETs in the half bridges are driven. Provision is made to place Schottky diodes in parallel with each MOSFET. Different operational strategies can be employed to simplify control or reduce losses. Past research does suggest that synchronous rectification certainly reduces losses at higher powers [10]. For easy availability to a broad range of MOSFETs, TO220 devices are used. Given losses are expected to total less than ten Watts, their bodies are soldered to the PCB to provide heatsinking. This has proved acceptable to date – under testing in the laboratory, the PCB has never become too hot to hold, indicating quite a low temperature.

All N-channel MOSFETs are used. Initially IR2108 half bridge gate drivers with built in logic and dead time were used. With the change to a microcontroller with a more capable timer, an IR2101 with independent gate driver logic was used.

Provision is made for various surface mount and through-hole inductors to be mounted, depending on the application.

Two 10 milliOhm current shunts are used to sense PV module current and dc-dc converter current. If used, these add 0.25W of loss each at 5A, which was considered acceptable. Temperature sensing of the MOSFETs, converter ambient, and PV module (via an external sensor) is allowed for, and various converter voltages are sampled by the controller's 12 bit analog to digital converter.

The controller (from the TI MSP430 family) and other ancillary electronics are designed to operate with minimum power while still giving useful control, data acquisition and communications. Quiescent current is approximately twelve milliamp with gate drivers switching (but no current flowing in the MOSFETs), and can be minimized further if needed. An isolated RS485 communications port is included on each module. Power for the insolated side of the converter is provided on the communications cable.

The best combination of components (particularly MOSFETs, diodes and inductors) to most efficiently fulfill these two applications could be found by exhaustively searching the parameter space created by varying the mode of operation (Continuous or Discontinuous Conduction Mode – CCM/DCM), operating frequency, and selection of devices chosen. Given time is never unlimited, a faster approach was to be directed by past research and a degree of intuition in the selection of the first search space. Testing will then direct further parameters and device choices.

V. RESULTS AND DISCUSSION

A. *Initial Converter Design and Testing*

The key components used in the first configuration tested are IRFZ24N (55V 0.07Ω) MOSFETs, IR2108 half bridge MOSFET drivers, MBR760 (7A 60V) Schottky diodes, 68μH 3A 0.13Ω surface mount inductors and low ESR capacitors. The controller is a TI MSP430F1232. The MOSFETs chosen have relatively high resistances, and it was hoped they would return lower losses at low currents than larger devices with larger gate drive requirements.

The initial set of results was taken with the converter operating as a synchronous buck converter in Continuous Conduction Mode (CCM). Input and output voltages and currents were measured by digital multi-meters and recorded by hand. Input voltage was set at 30V, and with a fixed duty cycle (at the microcontroller) of 50%, the output voltage ranged from 15V to 11V (Figure 8).

It can be seen that while the inductor current swings both positive and negative each cycle (at low currents where $I_{OUT} < \Delta I_L/2$), the switching commutations are natural and the duty cycle remains close to 50% regardless of the 500ns deadtime defined by the IR2108. Once the inductor current remains always positive, the deadtime significantly reduces the duty cycle, especially at higher frequencies. These results brought to our attention the desirable side effect that operating in CCM at low currents led to zero voltage switching (ZVS).

The losses of this converter were higher than hoped, especially at low currents (Figure 9), but never-the-less, the efficiency was pleasingly high for a first attempt, remaining around 95% for much of its operating region (Figure 10).

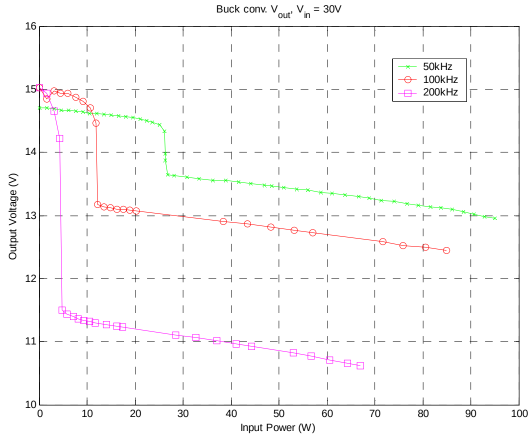

Fig. 8: The output voltage of the first version of the converter operating as a buck in CCM at a fixed duty cycle (neglecting deadtime) of 50%, for Vin = 30V. The step drop is due to the fixed deadtime of the gate drive ICs effectively lowering the duty cycle.

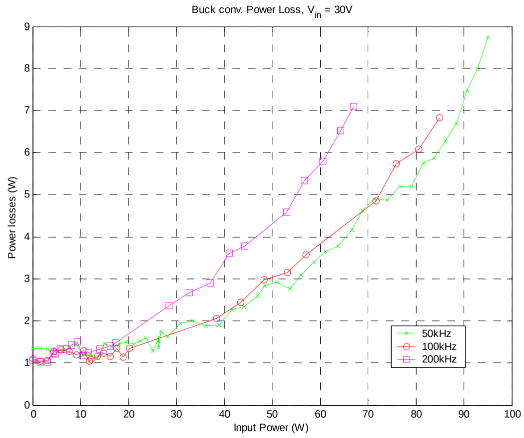

Fig. 9: The power loss of the first converter circuit operating under the conditions outlined in Figure 8.

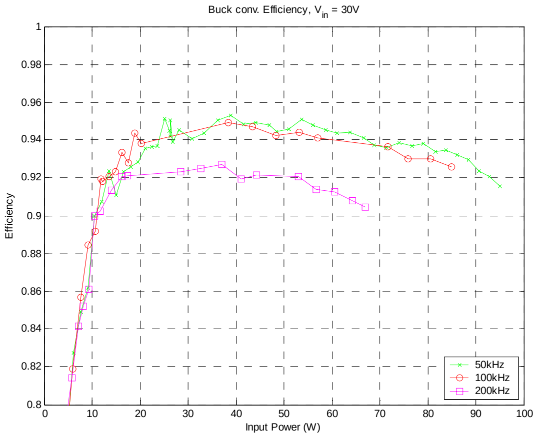

Fig. 10: The efficiency of the first converter circuit operating under the conditions outlined in Figure 8.

B. Converter Design Revision and Testing

Using these first results for direction, a revision of the converter design was undertaken. The microcontroller was upgraded to an MSP430F147 as this afforded us a more sophisticated timer capable of interleaved switching and software settable dead time (although a conservative value was chosen). The gate drivers were changed from IR2108 to IR2101 parts accordingly. Attention was paid to reducing the quiescent current consumption of the board, and additional sensing was added. Photographs of the two versions of the board for comparison are shown in Figure 7.

Given CCM leads to ZVS at low currents, it was decided to use larger die MOSFETs in the second round of testing. The FTP33N10 100V 0.05Ω devices have more than twice the gate charge of the IRFZ24N MOSFETs. The higher voltage ratings allowed testing at both 15V – the nominal maximum power point of a 12V 36 cell PV module – and 30V, which is typical of larger 72 cell PV modules used for grid connection. The open circuit voltage of a cold 72 cell module can approach 50V, so a shuffle converter requires a 100V rating for that application. Given the higher voltages, larger value inductors were chosen to lower the inductor ripple current, which appeared to be effectively setting the low power losses. After initially trying 100µH rod cored inductors (pictured in Figure 7) with poor results, two 220µH 3.5A 0.1Ω drum cored inductors were used with good success.

Results were this time recorded automatically using 6 digit bench Volt and Amp meters with GPIB connections. Accuracy was checked by parallel connecting the voltmeters and series connecting the ammeters. In both cases the meters tracked with at least five digits of precision. For currents over 3A, the mV drop across the on board 0.01Ω sense resistors was measured, and corrected with a separate calibration. These results were manually recorded and appended to the computer gathered results, hence the discontinuities seen in the input – output voltage plots. Four-wire sensing at the PCB connector was used throughout testing.

Testing this time configured the converter as a boost converter, with either 15V or 30V input voltage. The converter was operated at a fixed 50% duty cycle, but various switching frequencies. Results are presented in the final six figures in this paper, Figures 11-16.

For powers below 15W at 15V, total converter losses remain below 1W. At PV voltages of 30V, losses can be maintained between 1.5W and 3W for converter powers of 0W to over 60W. Higher switching frequencies lead to lower losses but only so long as ZVS is occurring. At higher currents, once ZVS is lost, switching losses are dominant and lower frequencies are best. This converter achieves an efficiency of 94-95% over most of its operating range. Better might be achieved with further optimization.

C. Discussion of Results

The purpose of this testing was to firstly assess the viability of dc-dc converters for series cascaded dc-dc PV

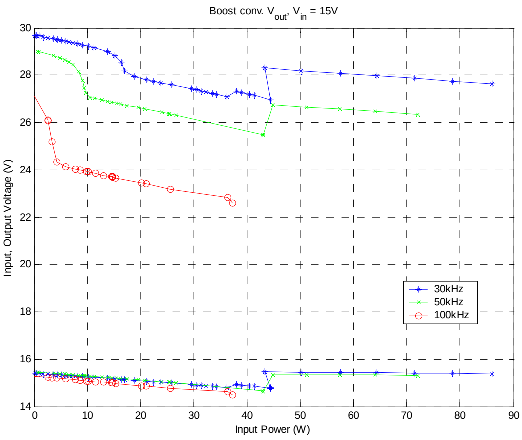

Fig. 11: The The input and output voltages of the boost converter running in CCM at a fixed duty cycle of 50%, for Vin = 15V. The discontinuities at higher powers are due to manual collection of data above 3A (a limit imposed by the Ammeter range)

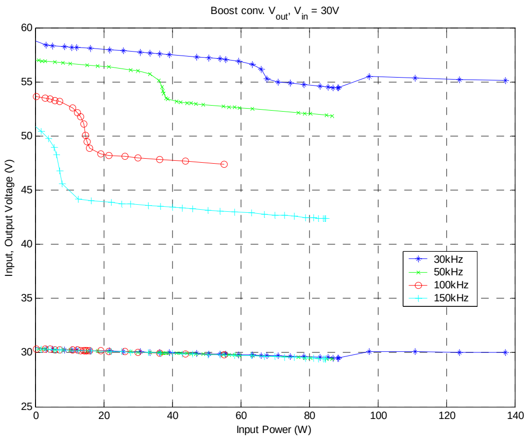

Fig. 14: The input and output voltages of the boost converter running in CCM at a fixed duty cycle of 50%, for Vin = 30V.

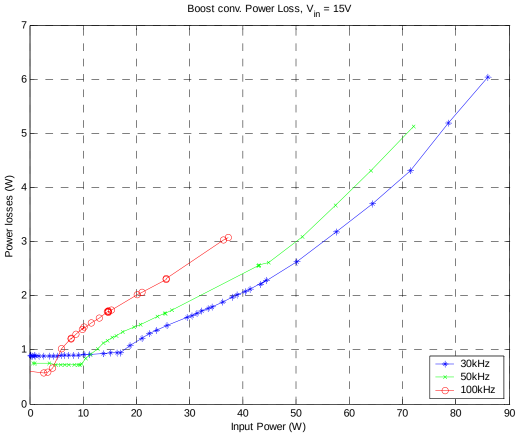

Fig. 12: The power losses of the boost converter running in CCM at a fixed duty cycle (neglecting deadtime) of 50%, for Vin = 15V. At higher power levels, lower switching frequencies lower switching losses and overall losses. At power levels approaching zero, ZVS occurs due to CCM in inductor current. Higher frequencies lead to lower inductor current ripple and so lower losses.

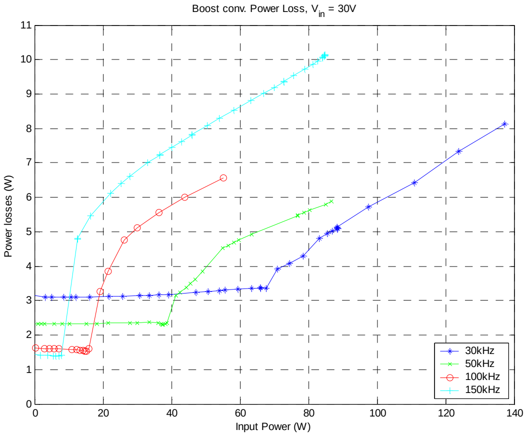

Fig. 15: The power losses of the boost converter running in CCM at a fixed duty cycle (neglecting deadtime) of 50%, for Vin = 30V.

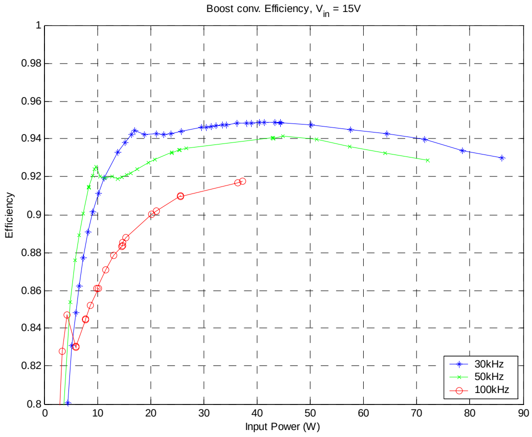

Fig. 13: The efficiency of the boost converter running in CCM at a fixed duty cycle (neglecting deadtime) of 50%, for Vin = 15V. The best efficiency at low currents will be obtained by continually raising frequency to remain on the border of zero voltage switching.

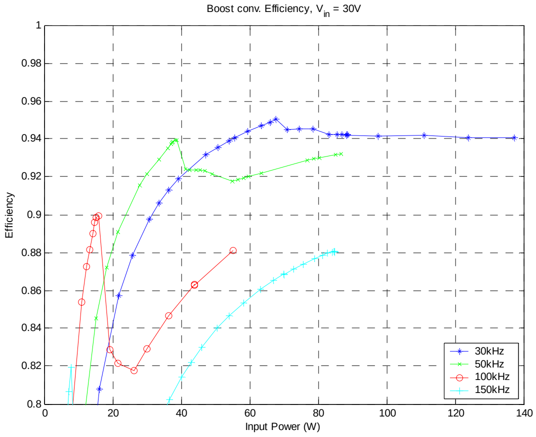

Fig. 16: The efficiency of the boost converter running in CCM at a fixed duty cycle (neglecting deadtime) of 50%, for Vin = 30V.

module converters and dc-dc bypass converters. This has been achieved – a boost converter with approximately 95% efficiency for most of its operational range is certainly achievable, and the same converter, when operated as a buck-boost converter can achieve losses of 1.5W at 30V and half that at 15V while “shuffling” several Watts of power.

These results have secondly given insight into the likely operational modes of these converters. These dc-dc converters should use variable frequency operation to minimize losses. For example, referring to Figure 15, the 30V input boost converter tested should operate at 30kHz (or less) from rated power down to approximately 70W. At this point, ZVS begins, and the switching frequency should be steadily raised as current continues to fall to remain in Critical conduction mode, up to some upper limit (say 150kHz). There is still much scope for optimizing inductor size and MOSFET size given ZVS can remove switching losses, while the interleaved arrangement of two bridges avoids significant losses in the input and output capacitors.

One other area to examine is the use of burst operation to reduce the burden of quiescent power losses. When not switching, the converter will consume very low power. It would be better to operate at a 10W level for 1ms in every 10ms to transfer 1W of power. This will also be an area of further study.

The final test will be to install these converters on a PV array. The University of Queensland has a suitable array of 12 60W 12V modules with a single string inverter. Testing on the array itself should begin this year.

VI. CONCLUSION

A suitable universal 150W 5A dc-dc converter design is presented based on two interleaved MOSFET half bridges. Testing shows Zero Voltage Switching (ZVS) keeps losses under 1W for bi-directional power flows up to 15W between two adjacent 12V PV modules for the bypass application, and efficiencies over 94% for most of the operational power range for the cascaded converter application.

ACKNOWLEDGMENT

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