Integrating Storage and Renewable Energy Sources Into a DC Microgrid Using High Gain DC DC Boost Converters

Gene Krzywinski, Member IEEE
Engineering Department
eIQ Energy, Inc.
San Jose, CA USA genek@eiqenergy.com

***Abstract*—Adding photovoltaic (PV) energy sources to a DC Microgrid can be complicated and costly. The PV-module's output does not match the high voltage DC (HVDC) bus to which it is attached so PV-modules must be connected in a series string fashion in order to reach the required level. This means all PV-modules must be identical in electrical characteristics, must be connected in identical string lengths, be oriented in the same direction and are subject to complete string failure if PV-modules within the series strings fails.**

A high gain DC DC Boost Converter that can output a voltage that matches the HVDC bus allows each PV-module to be an independent contributor, regardless of its technology or electrical characteristics, and to be connected in parallel so that now each PV-module is an independent power generator. This paper describes the DC DC converter, the advantages of the parallel connectivity and some of the other benefits attainable with PV-module level electronics as PV is integrated into microgrids.

Keywords— DC DC Converter; Renewable Energy; Microgrid; PV; Boost Converter; Battery; Parallel PV; DC Bus; Storage

I. Introduction

Energy generation, transmission and distribution are undergoing profound changes with the emergence of localized grids in favor of a centralized grid. Whatever the reason: disaster mitigation, energy independence or financial gain, they all subscribe to and advance the separation from a central grid. And, it is happening across all sectors, from residential to commercial, communities to nations and urban to rural. These localized grids – minigrids, microgrids, nanogrids and picogrids – however are not just miniaturizations of the grid as we know it. They are more in tune with today's energy and how it is used. And, not just the use, but also the generation, as diverse energy sources become more technologically available and affordable. According to the eMerge Alliance, 80% of all AC electricity is now being used by DC based power electronics [1] heralding the change to energy sources that don't incur significant conversion losses at the point of use.

The general term of these localized grids, microgrids [2], can be divided into AC and DC. However, the problems associated with AC microgrids – synchronization of generators, reactive power and line unbalances, as well as their energy losses when converting to DC, favors the move to the DC microgrid. Such DC microgrids may include AC and DC loads, dispatchable and non-dispatchable generators, energy storage, common distribution, management and demand response, and, a tether to the grid, where available, for increased reliability of service.

Although there is consistency in dispatchable generators such as diesel generators, fuel cells, natural gas and biomass, there is an irresistible attraction to non-dispatchable generators such as wind and solar, because once they are built, the energy source is free and virtually unlimited. Unlike other generating sources, wind and solar do not necessarily compete for the same demand and therefore can happily co-exist within the same microgrid, with solar during the day and wind at night (or even 24-hours).

However, in this paper, we deal primarily with solar, or PV [3] which is potentially available to all. With continuous hardware and soft costs reduction, and no increase in the cost of the source of energy, the sun, its growth is phenomenal and all but assured. While developed nations adopt PV as either a lifestyle change or for financial benefits, it is imperative for emerging nations, where the cost of a central grid is prohibitive. This is the beauty of the DC microgrid – it can be adapted for all, and it is scalable and expandable as the need or capital increases.

While PV generation is localized, its distribution, even within a local microgrid, can suffer losses if it is improperly managed and provisioned. Distribution is optimized by reducing current and increasing voltage which is leading us to a 380Vdc standard bus. However, PV generation is low voltage, high current and so this generated power must be converted to the bus operating voltage. Typically, this is accomplished by stacking PV generators in a series string so that their voltages add. A parallel connected array offers significant benefits which are discussed in detail in the following sections.

As noted earlier, PV is a non-dispatchable energy source and by itself it is unstable and unpredictable. This can be mitigated through energy storage elements, typically batteries, on the same bus, where PV energy is stored until it is needed when sunlight is unavailable. These batteries are the mirror of PV generation. They are low voltage devices that must be series stacked so that they can be connected to the 380Vdc bus.

Serial connection of these devices creates an interdependence among its neighbors, that when all are performing optimally provides maximum power and energy. However, this series string, whether PV-module or battery cell, is limited by the weakest member of the string and one under-performer causes the whole string to underperform, or in some cases cease operating.

The goal of creating a high gain DC DC boost converter was to enable each finite element, PV-module or battery cell, to perform at its optimum capability as an independent power generator, regardless of the operation of its neighbors.

II. PARALLEL PV

First, Initially, PV was deployed with the PV-modules connected in a parallel mode, operating at 12-20Vdc, and under the control of an MPPT charge controller which transferred the power to the battery pack, typically lead acid. This in turn either directly fed a low voltage load or an off-grid inverter. This system worked well unless the PV was some distance from the battery pack/inverter where I^2R losses had a large, negative effect on production. Then, as PV gained popularity and feed-in tariffs or net metering took effect, it became important to connect to the electrical grid for bidirectional power flow, using the grid for power when needed or selling the PV power when it was not utilized by the system owner. This drove the need for higher capacity systems, but which increased the current for a parallel connected installation. However, PV-modules, like batteries, can be series string connected to increase their output voltage and keep the line current to a minimum. The inverter now took over the role of charge controller, but at a higher voltage, since it was connected to the grid. The magnitude of the series string voltage is limited to the National Electrical Code limit of 600Vdc for residential and commercial applications (1,000Vdc for "behind the fence", or utility type installations) which bookends the amount of power that can be transported over #10AWG wiring.

The advantages of the series string connected PV are offset by the inherent weaknesses of such an arrangement. Series strings are subject to the "Christmas tree lights" effect, whereby if one light, or PV-module, faults then the whole string faults. But, it isn't just catastrophic faults that are of concern. Any effect that reduces current in one PV-module affects the current for that series string and subsequently that string's total power. Economic returns are calculated over long time frames, typically 20-25 years and PV-module power degradation must be accounted for in the financial analysis. With a series string, the weakest power producing PV-module sets the operation of the entire string. This degradation and mismatch of PV-modules has a number of different sources. PV-modules, even those with very tight manufacturing tolerances, will have different rates and modes of degradation when deployed in the field, and this effect increases as the installation ages. Mismatch can also occur because of soiling, temperature gradations, shading due to obstructions, manufacturing defects, damage and weather. So, a mismatch or defect in a single PV-module can affect the string's other 12-15 PV-modules' power production.

In series string configurations, the strings are aggregated in a combiner box whose output is to the inverter. The inverter must interpret the power of the array and perform a global MPPT operation. While this is acceptable where there is no mismatch, in reality power is lost by operating at a mean value, rather than each operating at an optimal value.

Parallel PV is an alternative to the series string, but in order to provide the required input voltage for the inverter, the PV-module itself must output that voltage. Since the PV-module is comprised of individual photovoltaic cells of approximately 0.6V each, it would require over 600 such cells to achieve a 380Vdc output. Boosting the PV-module's output voltage became the subject of investigation and, in 2007 the company developed a boost DC DC converter that accepted a range of PV-module outputs and converted their low voltage/high current power to a high voltage/low current output. This converter can transfer the power to a high voltage DC (HVDC) bus and aggregate the current, not stack the voltages.

A. *High Gain Boost DC DC Converter*

The Converter is a high gain, DC DC boost converter that converts the low voltage/high current output of a PV-module and outputs the power as high voltage/low current. The immediate benefit is that the Converter equipped PV-module can be connected in parallel with other such equipped PV-modules and can directly feed a high voltage DC (HVDC) bus on which other sources and loads can be attached. The PV-module now becomes an independent power generator, unaffected by other PV-modules attached to the same bus.

Boosting a PV-module's output to >350Vdc has a number of challenges. The output voltage of the PV-module is dependent on the technology and number of cells, and can vary between 15Vdc and 120Vdc for commercially used PV-modules, so, an efficient, high gain boost circuit is required. The PV-module's power output is dependent on its operation at its maximum power point, which varies with voltage, which in turn varies with irradiance and cell temperature, so the converter front end must perform impedance matching with the source in order to achieve Maximum Power Point Tracking (MPPT). The boost converter must operate at greater than 95% efficiency or it is not economically feasible.

The Converter employs a tapped inductor topology to achieve a high gain boost, unattainable with a traditional boost circuit. The gain for a traditional flyback boost converter is given by:

$$Vo/Vin = 1/(1-D) \qquad (1)$$

However, this gain is limited by the duty cycle, which as it approaches unity, degrades the efficiency, rendering it unusable for maximum energy harvesting. The tapped inductor topology was chosen because the gain is high at a reduced duty cycle, as can be seen in the gain equation below:

$$Vo/Vin = 1 + D/n(1-D) \qquad (2)$$

Where n=turns ratio of the primary and secondary windings.

The MPPT function is performed with a two-stage algorithm. A basic Perturb and Observe (P&O) is performed to initiate the MPPT operating point. Then, a windowing algorithm performs minute adjustments as slow moving temperature or irradiance changes are experienced. If a fast transient forces the MPPT outside of this window, the system performs a P&O to determine the new window range. An MPPT efficiency of 99.9% across the Converter's operating range has been achieved with this method. The output capacitance of the converter behaves as a distributed capacitance to the inverter and helps isolate the MPPT function from the both inverter generated noise and 120Hz ripple current effects.

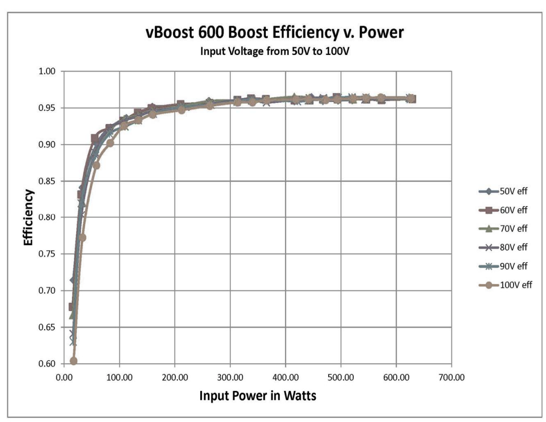

Figure 1: DC DC Converter Efficiency Curves

Efficiency of conversion is critical to the economics of the solution, and in order to achieve a flat efficiency curve across the full power range of the PV-module, a dual phase switching network is employed, with the phases 180^{o} apart. Each phase switches at 50kHz, giving an effective 100kHz switching frequency for the filter elements. The flyback is operated in Discontinuous Conduction Mode (DCM) and its operation is similar to the traditional boost with minor modifications to the filter elements.

The Converter achieves a CEC rated efficiency of 97.9% with a peak efficiency of 98.3% The graph below shows the efficiency curves for a range of PV-module output voltages and across the full power spectrum.

Both input and output voltage and current are measured and digitized for the MPPT function as well as Over Current Protection (OVP), Over Voltage Protection (OVP), and PV-module level data collection. The converter's free-wheeling diode also performs an OR'ing function to the bus to prevent backfeed of the bus voltage into the PV-module.

The resulting topology enables the Converter to self-level to the required bus voltage without the need for an external controller or command center. The load is operated at a fixed, constant voltage and each Converter provides sufficient gain to present that voltage to the load, self-compensating for any IR drops experienced in the transmission wires or connectors between the Converters and the load.

In this configuration, the Converter acts as a current source and hence, multiple converters can be present on the same bus without interaction with each other. This also means that the power source, the PV-module, for each converter is independent of the bus and its neighboring converters, so PV-modules of differing technologies, power and other characteristics can be placed on the bus.

A block diagram of the Converter is presented below.

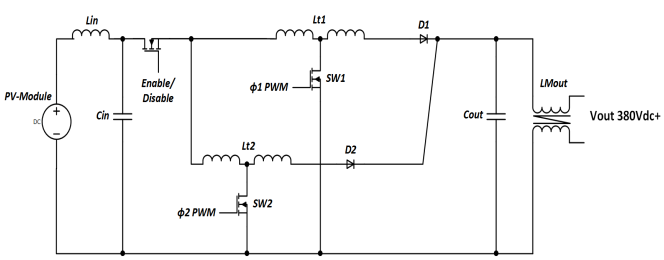

Figure 2: DC DC Converter

The Converter employs an optional Power Line Communications circuit with CANBUS protocol that can transmit and receive data. This is used to receive control functions such as enable and disable, as well as to transmit power and energy harvesting data to a central collection point.

The Converter has been designed and built with reliability and longevity a critical element. It has a 25 year operating guarantee and has been designed such that all components have an operating duty cycle of 50% or less. The 600W device is enclosed in a NEMA 6 (IP67) cast aluminum case and the new 300W device is enclosed in a NEMA4 (IP65) polymer case that is integrated onto the back of the PV-module.

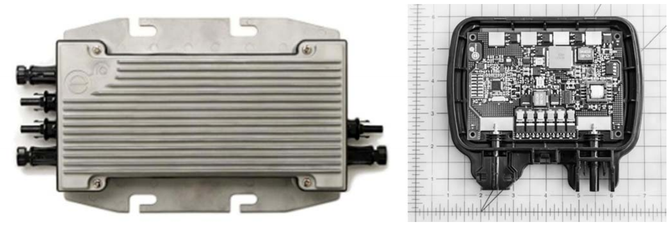

Figure 3: DC DC Converter: 600W standalone (left) and PV-Module integrated (right)

B. Benefits of the DC DC Converter and Parallel Operation

The Converter transforms the PV-module into an independent power generator that is connected in a parallel fashion to other such equipped modules. This offers several advantages in design, installation, cost and operation.

Independent Power Generation

Series-string connected PV-modules produce power that is only as good as the weakest PV-module in the string. Since the string current is common through each PV-module, any shading, soiling, damage or other current limiting phenomenon will adversely affect the performance of that string. It is critical that all PV-modules in a string be of the same electrical characteristics, be oriented in the same direction and that any additional strings be identical. Mismatch of any kind will manifest as poorer performance. Despite the rapid adoption of PV, there is very little age related degradation or mismatch data, although several studies are finding that PV modules have different degradation mechanisms and rates than originally thought and these adversely affect the economics of the installations.

A summary of Selected Field Studies as reported by NREL [4], is shown below. The most common failure was in the interconnection, while problems with glass and delamination were second, followed by junction box and cabling.

Table 1: PV-Module Failure Mechanisms

Observation	***Sample Size***
~2% of modules failed after 8 years. 36% of failures were due to laminate internal electrical circuit; glass 33%; j-box and cables 12%; cells 10%; encapsulant and backsheet 8%.	21 manufacturers; ~0.9 GW
16% of systems required replacement of some or all modules because of a variety of failures, with many showing breaks in the electrical circuitry.	483 systems
3% developed hot spot after <7 years; 47% had non-working diodes	1232-module system
35 modules degraded outside of warranty. Large power loss (>20%) came from decrease in FF because of increased series resistance; smaller power loss was from reduced transmission of glass and encapsulant and light-induced degradation. Glass/encapsulant designs showed less degradation than glass/glass designs.	204 modules from 20 manufacturers
For problems reported: encapsulant discoloration 66%; delamination 60%; corrosion 26%; glass breakage 23%; j-box 20%; broken cells 15%.	~2000 reports
200 thermal cycles design qualification testing correlated to ~10 years in the field	>10 years of manufacturing
* BOS included switches, fuses, blocking diodes, surge protectors, and dc contactors.	

The key point here being that single PV-module failures affect the whole series-string and moving to a parallel connectivity where the PV-modules are now independent power generators has a significant positive effect on the installation.

Since Converters operate independently of each other, regardless of electrical parameters, orientation, irradiance, mismatch or PV-module technology. Each PV-module performs at its maximum operating capacity and this power is transferred to the bus.

Maximum Power Transmission

With a series-string connected PV array, the maximum power capacity is determined by the PV-module's current and the maximum allowable line (or bus) voltage. For a US residential or commercial installation, this maximum voltage is 600Vdc, however, the series-string maximum voltage is in reality far less than 600Vdc because derating factors and operating temperature conditions present a much lower figure. The voltage limit is calculated using the PV-module's open circuit (non-power producing) voltage, Voc, which is typically 40-45% higher than the power producing voltage Vmp. Additionally, the PV-module has a negative voltage temperature coefficient, typically -0.30%/^{o}C from 25^{o}C which further reduces the practical line voltage limit.

By way of example, a PV-module with a Vmp of 25Vdc and temperature coefficient of -0.30%/^{o}C will have a Voc of approximately 35Vdc at 25^{o}C and a Voc of 37.6Vdc at 0^{o}C. This means that the series string can only have 15 PV-modules in a string, instead of a 22 PV-modules if the working voltage, Vmp, was used to calculate maximum string length. For a 250W module, the maximum current is approximately 10A and so the maximum power that can be produced in that string is 3,750W

With the Converter, instead of stacking voltages, the current is aggregated, up to the allowable ampacity of the wire. Using the same PV-module specifications as above and a 380Vdc bus, the output of each Converter is 250W/380Vdc or 0.66A. With temperature derating, the maximum allowable ampacity of a 30A fused, #10AWG wire is 24A which translates to approximately 36 Converter equipped PV-modules, or 9,000W – a power transmission increase of over 240% for the same wire size. This offers significant saving for the PV installation, both in copper wiring and labor costs.

Installation Design and Layout

Designing a series-string PV installation requires that each string be identical in PV-module electrical characteristics, length (number of PV-modules), orientation, and obstruction free. All PV-modules must be from the same manufacturer. A change in manufacturer may necessitate a re-design or re-layout if the differences are significant enough, especially if there is a physical size difference and layout space is restricted.

Since all PV-modules in a series-string must be identically oriented, any obstruction (rooftop HVAC, access hatches, ventilation, parapets etc.) may severely limit the amount of PV that can be placed. Available space is limited to the string length design, which may orphan areas where PV-modules could physically fit, but which are unusable because the string length does not conform to the rest of the system.

Since the Converter normalizes the PV-module to the bus, PV-modules of differing technologies, electrical characteristics, physical sizes can be placed for optimum energy harvesting. Designs can be easily completed and do not need modifications should the PV-module manufacturer or type change. Islands of power, normally unusable in a series-string configuration, can now contribute to the energy harvest thereby maximizing available space.

Safety

When illuminated, the PV-module has a voltage potential equal to its Voc rating. As the series-string is connected, that voltage increases in steps of that Voc and is present at the exposed terminals. A qualified electrician is required to make the final terminations.

With the Converter, the output of the PV-module is disabled until the installation is complete and commissioned. Installations can be performed by semi-skilled labor since all connections are with keyed, MC-style connectors and there is no voltage potential at the terminals. Low level testing can be performed on the installation prior to power up to ensure all connections are properly made. This can be particularly cost effective when the installation crew is finished, but the system is not yet approved for power production.

Improved Inverter Reliability and Efficiency

Modern day inverters are designed to perform the MPPT function on a global basis. Some have multiple MPPT inputs to allow for multiple dissimilar strings. As a result, inverters must be capable of operation over a very wide input voltage range, and have the required circuitry to match those voltages to the necessary grid voltage. All of this adds cost to the inverter and is also a point of potential failure. With a constant voltage from the Converters, the inverter no longer needs to perform the MPPT function or accept a wide input range, thereby lowering costs and improving reliability. Additionally, the distributed output capacitance of multiple Converters, and the PV-module's insulation from inverter noise or ripple current means less electrolytic capacitors are required by the inverter, again lowering costs and improving reliability.

Since the inverter is operating at a single, fixed voltage its efficiency is maximized and future inverter designs can be optimized at a fixed voltage operation. This is especially true for transformerless inverters that cannot modify their input voltages without additional buck-boost circuitry.

Communications and Data

With data collection possible at the PV-module level, an installation's health can be remotely monitored and analyzed at minimal cost. Compare this to additional circuitry needed at either the string termination or combiner boxes for series-string connected installations, which in many cases is not added due to costs. With detailed operational data, the health of the power plant and alerts to possible faults or underperformance determines the Operational and Maintenance tasks schedule now being performed on a scheduled basis, not on a needed basis.

III. Examples

The following are some examples of operating installations using the Converter:

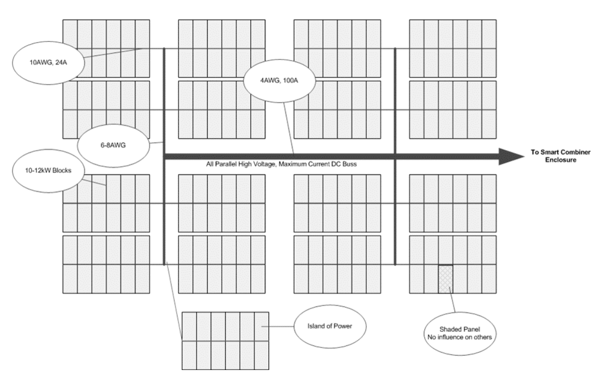

Figure 4: Independent Power Generation provides Flexibility for maximizing space for PV-module placement

With parallel connectivity, islands of power are possible to interconnect on the same bus regardless of their power output. Also, for buildings that integrate rooftop, parking structure, BIPV and other areas of PV or wind, the HVDC bus and parallel connectivity make it plug and play simple.

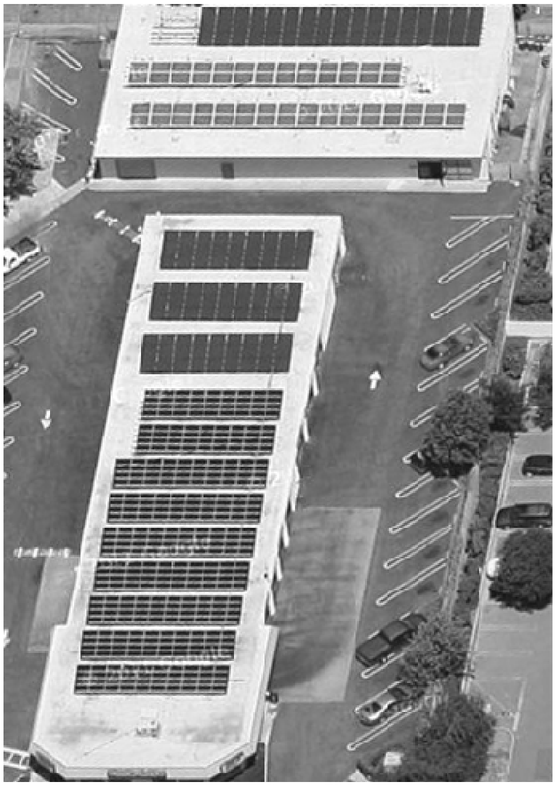

Figure 5: Installation with three PV technologies onto a single HVDC bus, with a single inverter

In the installation in Dublin, California, there are three different technologies: CdTe (front rows), amorphous silicon (second and fourth rows) and crystalline silicon silicon (first row, back building) all on the same HVDC bus, providing DC power to a single 50kW inverter operating at a fixed voltage.

Figure 6: Installation where all roof orientations are used

In this installation at Schofield Barracks, all roofs, regardless of orientation (N, S, E & W) have PV-modules equipped with the converter and feeding a HVDC bus (340Vdc). In addition, the PV-modules area combination of crystalline silicon and crystalline silicon with a water heating membrane on their underside that provides hot water in addition to PV electricity.

IV. Integrating Battery Storage

A microgrid can have multiple energy sources and multiple loads operating on the same bus and this can create challenges, especially when some of these sources are variable, renewable energy sources such as solar and wind. Instability of source power causes system wide disruption unless mechanisms are in place to provide backup power and stabilize the delivery. Additionally, variable loads that are coming on and off line create fluctuations in the bus that have to be smoothed. Battery storage helps provide such stability and back-up power, and helps smooth bus voltage variations.

However, in many respects, battery banks are analogous to the PV-module, except now the power flow is bidirectional. A typical LiIon-based chemistry battery pack of 1.5kWh to 2.5kWh, operates at 48-50Vdc and at currents that can approach 100A, depending on the charge/discharge operations. In order to reach the 380Vdc bus voltage, the batteries are typically series connected until that voltage is attained. This quantizes the battery pack into large sized capacities of 15-20kWh. In addition to the larger energy resolution, there are challenges with charging and discharging such series connected batteries, including cell balancing, cell monitoring, battery replacement and power control.

Ideally, individual battery packs could be bus connected if their operating voltage is sufficiently high. Boosting the voltage of each battery pack now offers some of the same benefits as a vBoost equipped PV-module. Each battery pack is now independent of any other battery pack and can be added or removed with minimal effect on the overall power distribution. The individual battery pack can be more easily controlled, monitored and operated.

However, as stated above, the battery has bidirectional power flow and needs to receive its recharge power from the same bus that it provides power to. Since the bus voltage is 380Vdc, a buck DC DC converter is needed to downconvert to the battery pack's 48Vdc and at currents up to 100A.

The buck and boost operation can be performed with either a bidirectional DC DC converter, or with discrete buck and boost converters. Bidirectional DC DC converters offer smaller size and operational ease, however at a potentially lower round trip efficiency. Also, the buck converter should have an isolated topology to prevent battery direct connection to the high bus voltage. Discrete buck and boost converters offer control flexibility, but with added complexity

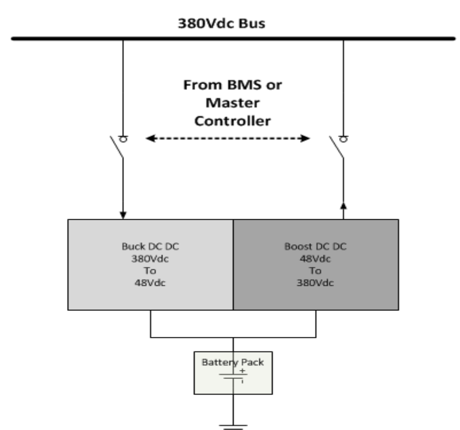

Figure 7: Bidirectional DC DC 380Vdc/48Vdc for Battery Pack Charging/Discharging

and cost. Communications between converters, the battery's Battery Management System (BMS) and overall system controller is essential to coordinate the charge/discharge functionality and synchronize the overall power distribution and delivery.

Challenges exist in the development of such a system. In many cases, the battery is the source of bus voltage stability and this bus voltage control is lost during the charging process. Complex charge/discharge algorithms or controllers will be necessary to maintain bus stability and direct the power flow between disparate sources and variable loads. This higher control level is also necessary where multiple microgrids, or DC buses, are tied together and current flow is controlled by imposing voltage drops between the buses.

Continued development is needed to provide optimum solutions for a diverse range of scenarios. This method offers the advantage of small unit sized battery packs, typically 1.5-2.5 kWh that can be nuilt up as necessary. This is also advantageous when maintaining or replacing batteries, removing just the necessary pack, not bringing down the whole bank for maintenance.

V. Integration Into Microgrids

Integrating renewable energy and storage into a DC microgrid should be made as easy as possible. Today, it is made difficult due to the complexities of connecting PV-modules and battery cells in series in order to reach the bus operating voltage. Using a high gain DC DC boost converter like the one described herein, alleviates a considerable amount of those complexities and also provides additional operations and maintenance tools to ensure that the components are performing optimally.

There are however, continued challenges. The PV is a non-dispatchable energy source and therefore only as good as the atmospheric conditions prevalent at the moment. Complex algorithms are needed for high reliance on renewable energy to ensure that sufficient storage backup is maintained to avoid blackouts. The ability to predict availability and match it to usage will become increasingly important as renewables become more integrated into the microgrid.

DC Microgrids are significantly easier than their AC counterparts but still not without their integration challenges. The control of the bus voltage, its regulation and its tie-in with other microgrids needs to be fully addressed.

DC Microgrids that are not tied to a grid will increase in adoption, especially in developing nations where extension of an existing grid will be prohibitively expensive. In many case, the microgrid will be the only viable option for rural electrification, so it is equally important that design and construction of such microgrids be done by the labor force at hand, which in most cases, will be unfamiliar with current electricity supply design and construction.

As DC Microgrids make inroads into urban areas, real estate that can be dedicated to renewable energy will be harder to find. Technologies such as Building Integrated PV (BIPV) with includes windows, facades, parking structures and rooftops will be increasingly important and so a cost effective method of design and construction is imperative.

VI. Conclusion

The present method of connecting PV-modules into an array consists of connecting them in series until the required voltage is reached. This has several drawbacks including matching PV-modules, maintaining the same number of PV-modules in each string, orienting each string in identical fashion and the interdepencence of PV-modules within a string for power production. Integrating into a microgrid generally requires a level converter since the PV string is built up of discrete voltage steps which may not match the DC bus voltage. Additionally, Maximum power point tracking on each string is necessary for maximum energy harvesting. These complications affect the installation price and operations and maintenance costs, as well as the return on investment for underperforming arrays.

Performing a DC DC conversion at each module was not possible due to converter size, efficiency and cost. With the described DC DC converter, each PV-module now becomes an independent power generator permitting flexibility in design, layout and installation. In addition, the output of the converter integrated PV-module will automatically match the HVDC bus voltage and track it. Such a system is also scalable, not just at the original installation site, but also anywhere within the microgrid, so additional PV resources can be added later if desired.

VII. References

[1] eMerge Alliance Presentation "The DC Microgrid Revolution"

[2] Arindam Maitra, Ben York, Haresh Kamath, Tom Key, Vikas Singhvi, "Microgrids: A Primer" EPRI September 6, 2013

[3] Anis Ammous, Hervé Morel, "LVDC: An Efficient Energy Solution for On-Grid Photovoltaic Applications" Scientific Research, Smart Grid and Renewable Energy, 2014

[4] Sarah Kurtz, John Wohlgemuth, Michael Kempe, Nick Bosco, Peter Hacke, Dirk Jordan, David C. Miller, and Timothy J. Silverman "Qualification Plus Testing", National Renewable Energy Laboratory Dec 2013