Differential Power Processing Architecture for Increased Energy Production and Reliability of Photovoltaic Systems

Pradeep S. Shenoy, Brian Johnson, Philip T. Krein
Grainger Center for Electric Machinery and Electromechanics
ECE Dept., University of Illinois at Urbana-Champaign
pshenoy@ieee.org, krein@illinois.edu

***Abstract*—Conventional energy conversion architectures in photovoltaic (PV) systems are often forced to trade off conversion efficiency and power production. This paper introduces a power processing architecture that enables each PV element to operate at its maximum power point (MPP) while only processing a small fraction of the total power produced. This is accomplished by providing only the mismatch in the MPP current of a set of series-connected PV elements. The differential power processing architecture increases overall conversion efficiency and overcomes the challenges of unmatched MPPs (due to partial shading, damage, manufacturing tolerances, etc.). Local control of the differential converters enables distributed protection and monitoring. The reliability analysis included in this paper shows significantly increased overall system reliability. Simulation and experimental results are included to demonstrate the benefits of this approach.**

I. Introduction

If photovoltaic (PV) systems are to reach grid parity [1], they need to reliably produce as much energy as possible over the life of the system. This simple conclusion is reached when comparing the levelized cost of energy (LCOE) of PV systems and other sources of energy [2]. The viability of PV is strengthened by relatively long lifetimes, with warranties typically 25 years or more [3]. In past practice, the power electronics used to convert and control energy from a PV installation tended to have a much lower mean time to failure (MTTF) than PV panels, which increases the balance of system (BOS) costs [4]. Hence, it is important that the power processing architecture and components result in high efficiency, reliability, safety, and performance of the overall PV system. The differential power processing architecture introduced in this paper can effectively meet those objectives.

Existing architectures for PV power processing are shown in Fig. 1. The conventional bulk conversion approach, shown in Fig. 1 (a), is a series string of PV panels connected to a central inverter. This approach is efficient when operating points are well matched but can have substantially reduced power output when even one segment is degraded (due to shading, damage, manufacturing tolerances, degradation, etc.) [5]. Modular panel-by-panel architectures, shown in Fig. 1 (b) and (c), have been introduced to overcome reduced output [6], [7]. These approaches allow each panel to operate at its local MPP through distributed controls and enable relatively simple installation and maintenance [8]. However, overall conversion efficiency may decrease and significant cost, reliability, and complexity challenges arise when attempting to scale down these approaches. Even so, reliable system-level designs based on Fig. 1 (c) have been presented [9], [10]. As is well known, inverter designs often seek to avoid electrolytic capacitors to enhance reliability [11].

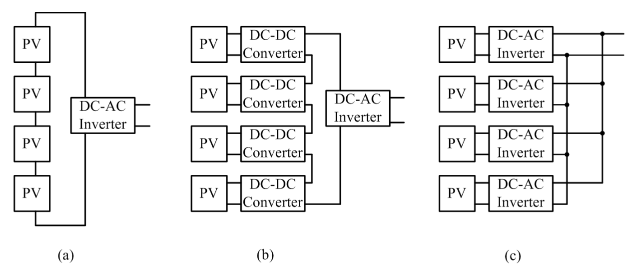

Figure 1. Existing PV power processing architectures include (a) series PV with central inverter, (b) modular cascaded dc-dc converters with a central inverter, and (c) module integrated inverters (microinverters)

A fundamental operating challenge with series strings of PV elements is mismatch in MPP current. In a series string, the voltage of each element is independent, but the current of each element must be equal. Several techniques have been explored to maximize each PV element's energy production, including a generation control circuit [12], parallel power conversion [13]-[14], returned energy current converters [15], bypass converters [16], multiple input converters [17], and current diverters [18]. This paper introduces a simple differential architecture that can track the MPP of each series PV element while processing only a small fraction of the total energy produced. The series connection of the PV elements is maintained and bulk power is processed only once. The

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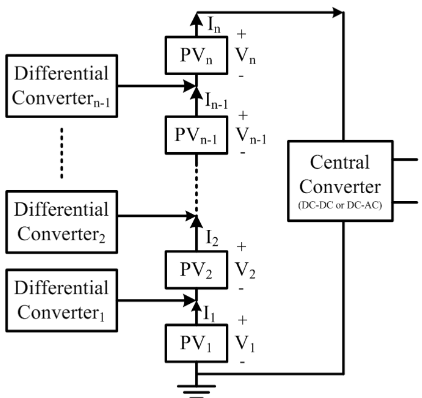


Figure 2. Differential power processing architecture.

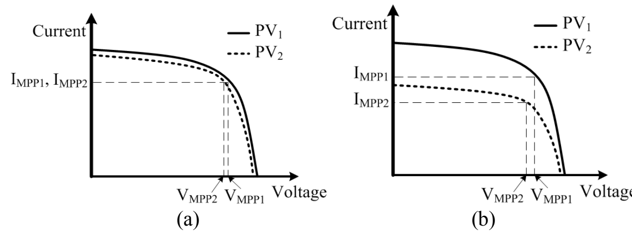


Figure 4. The I-V characteristics of two PV elements when the maximum power point currents are (a) matched and (b) unmatched.

proposed method enables local, distributed control and improves overall system reliability. An important practical advantage is substantial reduction in PV system cost as the approach facilitates utility-scale PV systems. This approach can be applied at various scales including multiple panel strings, single panels, and also at the sub-panel level.

II. Differential Power Processing Architecture

One key to improving PV power conversion efficiency is to operate converters only when necessary and only with as much power as necessary. The differential power processing architecture, shown conceptually in Fig. 2, enables each PV element in a series string to operate at its MPP by providing the *difference* in the MPP current of two adjacent PV elements. This means that when MPP current mismatch does occur, the MPP can be reached while only processing a small fraction of the total power being produced. The series string is not broken. A differential converter acts as a controllable current source with limited ratings as shown in Fig. 3.

When the MPPs of series PV elements match, the energy produced can be sent directly to an inverter without additional processing (assuming ac output is the goal). Power is processed just once thereby avoiding conversion loss. The differential power processing architecture takes advantage of this by only processing power if there is mismatch in the MPP current of the series PV elements. If the MPP currents are matched, the differential converters need not operate. This is in contrast to cascaded dc-dc converters that must process the entire load power over all operating conditions [7], [8]. The I-V curves of two PV elements are depicted in Fig. 4 under matched and unmatched conditions.

A. Comparison to Relevant Prior Work

There are two pieces of previous research that are closely related to the differential power processing architecture. In [12] Shimizu presents a few "generation control circuits", and in [16] Walker describes a "bypass converter". Both approaches can maximize the power out of each PV element using a non-isolated converter without breaking the series connection. However, there are noteworthy differences between these works and differential power processing. In [12], the switching scheme used for the "multistage chopper circuit" requires each switch to be rated for the entire main bus voltage and be able to conduct the sum of the inductor currents. The control is also implemented in a central unit. The differential power converters presented here are designed with lower component ratings and with local control in mind.

In [16] several bypass converter topologies are suggested, and a two phase interleaved converter is chosen for experimental verification. A key drawback with Walker's approach is that it requires an isolated converter to "complete the shuffling loop". This means that if there are n PV elements, there needs to be n bypass converters. In contrast, the differential power processing architecture presented in this paper only needs $n-1$ converters. The n^{th} control actuator is the central converter which tracks the global MPP and, in effect, is also tracking the MPP of the n^{th} PV element.

B. Converter Topology

The differential power processing architecture can be implemented using a variety of dc-dc converter topologies. Isolated or non-isolated converters can be used to process power. A bidirectional, buck-boost converter (shown in Fig. 5) is shown in this work due to its simplicity. This [19] and other

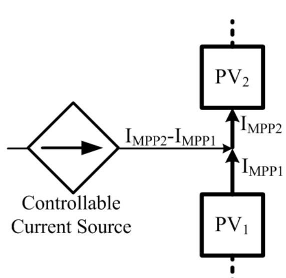


Figure 3. A differential power converter acts as a controllable current source to enable local maximum power point tracking while only processing a fraction of the generated power.

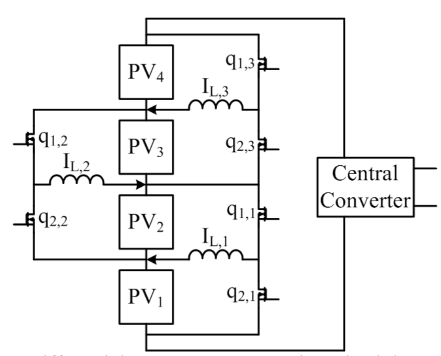


Figure 5. Differential power converters using a buck-boost topology connected to neighboring nodes.

architectures [20] follow from battery equalization strategies and have similar objectives. Work on series connected digital circuits has also informed the differential power processing architecture [21]. Notice that the architecture of Fig. 5 applies at any level: panel by panel, string by string, or even cell by cell.

The differential converters can be designed to interact with other PV elements, the main bus, or an independent energy storage element (i.e. a virtual bus). In Fig. 5, the drain of switch q_1 and the source of switch q_2 are shown connected to the neighboring PV voltage nodes. The illustrated configuration enables a low voltage rating for the switches and local control. The switches can be connected to other nodes or with other topologies to form various differential power processing structures. Each PV element may have a parallel capacitor for filtering. If the configuration in Fig. 5 is used for the entire series PV stack, the average inductor current of the i^{th} differential converter is

$$I_{L,i} = I_{MPP,i+1} - I_{MPP,i} + D_{i-1} I_{L,i-1} + (1 - D_{i+1}) I_{L,i+1} \qquad (1)$$

where I_L is the inductor current, I_{MPP} is the PV maximum power point current, and D is the steady state duty ratio of switch q_1. Equation (1) will be slightly altered for first and last differential converter. The first converter will not have the $I_{L,i-1}$ term, and the last converter will not have the $I_{L,i+1}$ term.

III. Local Control

The differential power processing architecture is well suited for local control. Differential converters can maximize the power output of their respective PV element with only local information. Protection and monitoring activities can add value to the converters.

A. Maximum Power Point Tracking

A variety of maximum power point tracking (MPPT) algorithms can be implemented using local information [22]. Some MPPT algorithms may be difficult to effectively implement. For example, a fractional open-circuit voltage approach may not be desirable since it would open the main circuit path. Simple, low power overhead techniques may be appropriate when power conversion is managed at the sub-module level [23].

The aim of the local controller is to maximize the power out of its respective PV element as shown in Fig. 6. In this work, a basic perturb and observe algorithm is implemented. Periodic voltage and current measurements are made locally at each PV element. These measurements inform the local controller whether power has increased or decreased from the previous step. The algorithm can generate a reference for a compensator or simply update a constant duty ratio value. The duty ratio of the switches controls the average voltage of the PV element to operate at the local MPP. If the PV element is operating at its MPP voltage, it must be generating its MPP current since the I-V curve is a one-to-one function. The current of the differential converter follows from the need of the system to balance the flow of charge. A differential converter can be disabled to save energy if its average current is close to zero.

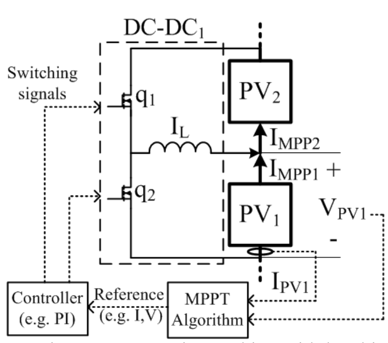


Figure 6. Maximum power point tracking with local information.

In a system with n PV elements and n-1 differential converters, the central converter acts as the n^{th} control actuator. In general, the differential converters would be able to track their local MPPs quicker than the global MPP tracking capability of the central converter. This time scale separation aids effective MPP tracking and should limit unwanted interaction. With differential power processing, the true MPP of each PV element can be reached with little conversion losses.

B. Protection and Monitoring

The need for local protection and monitoring is a major issue in PV systems, especially at large scale. This architecture enables integrated protection and diagnostics. For instance, if an arc fault occurs, the local converters can safely act to prevent fire or other hazards. The differential converters could use local information to determine if shunting around the PV element or opening the circuit is necessary. Operation and maintenance costs are likely to go down as a result.

Differential converters can also interact with the central inverter or other central unit to provide distributed monitoring. This information could be relayed back to a central hub or communicated to other converters using a variety of techniques like power line communication or wireless transmission. The differential converter provides a natural framework for local diagnostics, since the circuit can sense local voltage and current and has information about local mismatch based on the amount of power it must handle. This added value circuit that provides both energy production advantages and diagnostics represents a fundamental innovation.

C. Simulated Example

To further explain differential power processing, a system with three series-connected PV panels and two differential converters is modeled and simulated. The structure of the system is similar to that in Fig. 5. BP7185N panels are modeled using standard techniques. The first PV panel has 90% insolation (i.e. short circuit current of 4.58 A), and the other two panels have 100% insolation (i.e. short circuit current of 5.09 A). The MPP of each PV panel is reached with

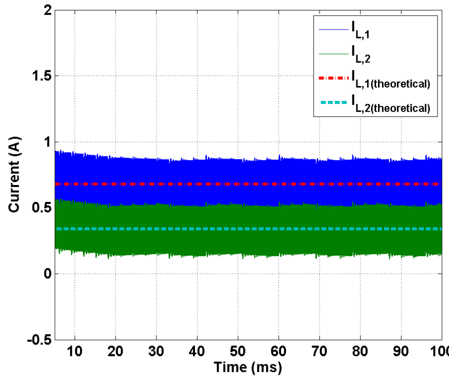


Figure 7. Current delivered by differential converters

perturb and observe (P&O) using local information. Every three milliseconds the P&O algorithm updates the duty cycle of its converter. The differential converters switch at 250 kHz and have filter component values of L = 50 μH and C = 50 μF.

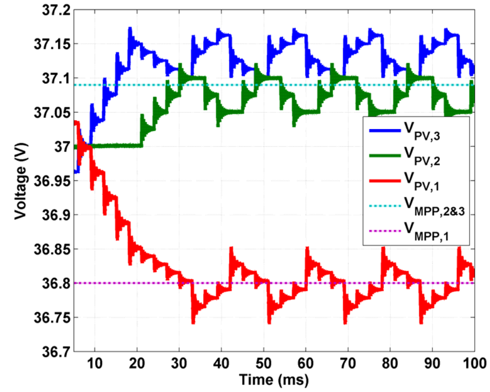
Maximum power point tracking is successfully reached while only a fraction of the total power is processed. Differential converters provide a low average current (less than 1 A, shown in Fig. 7) in keeping with theoretical analysis. This means that the differential converters process 25 W or less. Each PV panel reaches its local MPP as shown in Fig. 8. The power output from this system increases by about 16 W (a 3% increase) under the given conditions.

IV. Reliability Analysis

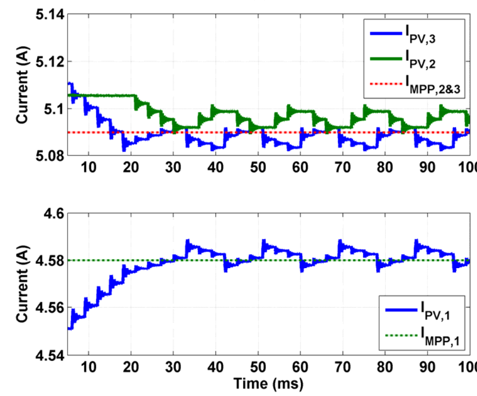
The proposed differential architecture actually improves system reliability relative to conventional PV systems. A local failure in the basic differential architecture will not compromise conventional bulk power delivery. For example, the power devices in the differential converter can be used even under extreme circumstances. If heavy shading or local damage occurs within a panel, the associated substring can be shunted out of the energy production process. This augments or even replaces the function of protection bypass diodes now employed in PV panels to prevent local thermal runaway. As the approach is implemented, we anticipate that bypass diodes can be replaced, and hotspots can be avoided [24].

The following subsections analyze the reliability of several PV system architectures. A simple model for each system is formulated, and a corresponding, closed-form reliability function is derived. The reliability functions are then compared to obtain a mean time to failure (MTTF) for the system. This analysis will take an axiomatic interpretation of reliability and make a few assumptions. One assumption is that components in the system fail randomly. While there may in fact be a deterministic cause for each failure, a probabilistic framework allows us to model and analyze the system in a tractable manner. With this approach in mind, let T be a random variable representing the time to failure of a component. The reliability R of that component at time t is the probability that T is greater than t and can be expressed as

$$R(t) = \Pr\{T > t\}\,. \tag{2}$$



(a)



(b)

Figure 8. Tracking the MPP of a 3 PV panel system with differential converters. Each panel's voltage and current are shown in (a) and (b), respectively.

Another assumption is that the failures are independent and exponentially distributed. This means that the failure rate λ is constant (i.e. in the bottom part of the "bathtub curve") during the lifetime of a component. With this assumption the reliability of a given component is

$$R(t) = e^{-\int \lambda dt} = e^{-\lambda t}\,. \tag{3}$$

The result is that the mean time to failure (MTTF) of a component is simply found to be

$$\text{MTTF} = \int_0^\infty R(t)dt = \frac{1}{\lambda}\,. \tag{4}$$

A final assumption made to simplify the analysis will be that the failure rates of the same component type are the same. In our case, the failure rate of each of the PV elements is the same (i.e. $\lambda_{p,1}=\lambda_{p,2}=\ldots=\lambda_{p,n}=\lambda_p$), and the failure rate of each of the dc-dc converters (either cascaded or differential) is the same (i.e. $\lambda_{d,1}=\lambda_{d,2}=\ldots=\lambda_{d,n}=\lambda_d$). This is a reasonable assumption since most installations use the same components that are rated for the same life.

A. Series PV String

Developing a reliability model for a series PV system is fairly straightforward. Since this analysis just examines the dc system, only the series PV elements are included. Whenever

Figure 9. Reliability model for series connected PV elements.

there is a fault in one of the PV panels, the series string is considered to be open-circuited and the system fails. This system can be modeled from a reliability perspective as n PV elements in series. The corresponding component-based reliability diagram is shown in Fig. 9. The failure rate λ_p of each PV element is assumed to be constant during the useful life of the system. The reliability of the overall system is

$$\begin{aligned} R(t) &= \Pr\{T > t\} \\ &= \Pr\{T_1 > t, T_2 > t, \ldots, T_n > t\} \\ &= \Pr\{T_1 > t\} \cdot \Pr\{T_2 > t\} \cdots \Pr\{T_n > t\} \\ &= e^{-\lambda_{p,1} t} \cdot e^{-\lambda_{p,2} t} \cdots e^{-\lambda_{p,n} t} \\ &= \prod_{i=1}^{n} e^{-\lambda_{p,i} t} \end{aligned} \tag{5}$$

This product can be further simplified since we assume that the failure rate of each PV panel is the same. Hence, the reliability of the system becomes

$$R(t) = e^{-n\lambda_p t}. \tag{6}$$

B. Cascaded DC-DC Power Optimizers

The reliability models for a PV system that employs cascaded dc-dc converters can also be expressed in somewhat simple terms. If one of the dc-dc converters in the series string fails, then the system fails as it can no longer deliver any power. The dc-dc converter failure can be thought of as an open circuit in the string. On the other hand, when a PV panel fails, the system can still operate, presumably at a lower power level. The system is no longer operational when all of the PV panels fail since there would be no output power from the system. An easy way to represent this in the component-based reliability model, as shown in Fig. 10, is to have the dc-dc converters in series and the PV panels in parallel. The model shows n PV elements and n cascaded dc-dc converters with failure rates λ_p and λ_d, respectively.

Based on the reliability model, the reliability of the system is found by aggregating the parallel PV components into one component that is in series with the dc-dc converters. The reliability R_{PV} of the parallel PV components is found by utilizing the unreliability Q_{PV} and is

$$\begin{aligned} R_{PV}(t) &= 1 - Q_{PV}(t) \\ &= 1 - (1 - \Pr\{T_1 > t\}) \cdots (1 - \Pr\{T_n > t\}) \\ &= 1 - \prod_{i=1}^{n} (1 - R_{p,i}(t)) \\ &= 1 - \prod_{i=1}^{n} (1 - e^{-\lambda_{p,i} t}) \end{aligned} . \tag{7}$$

This result can be used to find the system reliability which is given by

$$\begin{aligned} R(t) &= R_{PV}(t) R_{dc,1}(t) \cdots R_{dc,n}(t) \\ &= \left(1 - \prod_{i=1}^{n} (1 - e^{-\lambda_{p,i} t})\right) \prod_{i=1}^{n} e^{-\lambda_{d,i} t} \end{aligned} . \tag{8}$$

Using the assumption from before that the failure rates of each like component is the same, the reliability equation can be simplified to

$$R(t) = (1 - (1 - e^{-\lambda_p t})^n) e^{-n\lambda_d t}. \tag{9}$$

C. Differential Power Processing Architecture

From a reliability modeling perspective, the differential converter is in parallel with its adjacent PV element and improves overall system reliability. Just like the series PV system case, the PV elements are modeled in series. One or two differential converters are modeled in parallel with each PV element, depending on its location in the system. The first and last PV element can only be bypassed by one circuit in the event of a failure. The rest of the PV elements can be bypassed by either of two differential converters. Hence, from a reliability modeling perspective, the PV elements and differential converters are modeled in parallel as shown in Fig. 11. The model shows n PV elements and $n\text{–}1$ differential power converters with failure rates λ_p and λ_d, respectively.

The system reliability function is found by analyzing the component model of the system. The component model is formed by a series string of parallel components. Each parallel segment can be aggregated into one component that is analyzed in series with the rest. If $R_1(t),\ldots,R_n(t)$ represent the reliability function for each parallel aggregate, then the system reliability function is

$$R(t) = R_1(t) R_2(t) \cdots R_n(t). \tag{10}$$

As in the two previous systems, the assumption that the failure rates for like components are equal is made. The reliability for the first and last segment is therefore

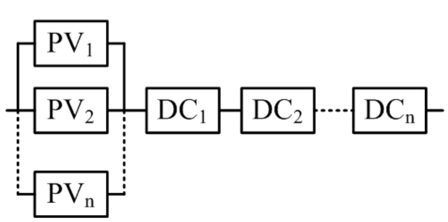


Figure 10. Reliability model for a PV system with cascaded dc-dc converters

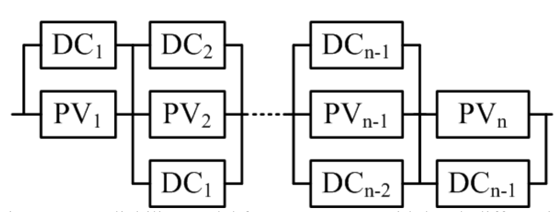


Figure 11. Reliability model for a PV system with local, differential power converters.

$$R_1(t) = R_n(t) = 1-(1-e^{-\lambda_p t})(1-e^{-\lambda_d t}) = e^{-\lambda_p t} + e^{-\lambda_d t} - e^{-(\lambda_p+\lambda_d)t} \quad (11)$$

The reliability of all of the intermediate segments are

$$R_2(t) = \cdots = R_{n-1}(t) = 1-(1-e^{-\lambda_p t})(1-e^{-\lambda_d t})^2 \quad (12)$$

Equations (11) and (12) can be substituted back into (10) to obtain the system reliability function which is

$$R(t) = \left[R_1(t)\right]^2 \left[1-(1-e^{-\lambda_p t})(1-e^{-\lambda_d t})^2\right]^{n-2}. \quad (13)$$

D. Reliability Comparison

The reliability of each system can be compared using the reliability functions obtained. The reliability metric of mean time to failure (MTTF) will be used for comparison. To start, it is assumed that the MTTF of each PV panel is 30 years (i.e. failure rate λ_p=1/30), the MTTF of each DC-DC converter is 15 years (i.e. failure rate λ_d=1/15). If more accurate failure rate data is available to the reader, the system reliabilities obtained could be easily updated. The MTTF of a system is found by integrating the reliability function

$$\text{MTTF} = \int_0^\infty R(t)dt\,. \quad (14)$$

The final step is to examine a couple of sample systems. A system with 4 PV panels is examined and a system with 20 PV panels is examined. This gives a sense of how reliability is affected as n, the number of PV elements, changes. Using equations (6), (9), and (13) the reliability functions are plotted in Fig. 12. (a) and (b). It can be seen from the graphs that the reliability for the system with differential converters is the highest, followed by the basic series PV system, and trailed by the system with cascaded dc-dc converters in both cases. When the number of PV panels increases, the benefit of the differential power processing architecture is more apparent; the system reliability is considerably higher than the other two system architectures (shown in Fig. 12 (c)). The MTTF of each of the systems is found using (14). In PV systems that have 4 PV elements, the MTTF of the system with differential converters is nearly double that of the series PV system and almost four times greater than the system with cascaded dc-dc converters. Similarly, for PV systems that have 20 PV elements, the MTTF of the system with differential converters is about five times longer than of the series PV system and almost ten times longer than the system with cascaded dc-dc converters.

V. Experimental Results

A simple PV system was built and tested to demonstrate the operation of differential power processing. Differential converters with a buck-boost topology connected to neighboring nodes were built with component values of L = 33 µH, C = 50 µF, and f_{sw} = 250 kHz. The converters were not optimized for efficiency, were hard switched, and did not enter into a light load mode (e.g. pulse frequency modulation or similar techniques). Two differential converters were tested on

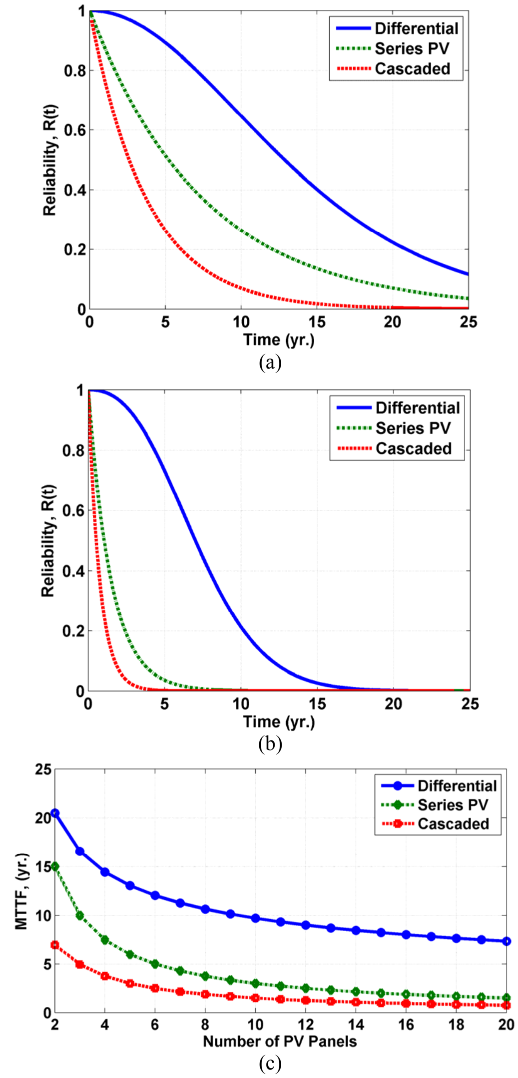


Figure 12. Reliability of a PV system using series panels, cascaded dc-dc converters, and differential converters with (a) 4 PV panels and (b) 20 PV panels. In (c) the mean time to failure is shown.

three series PV panels, and a boost converter with a resistive load tracked the global MPP. The efficiency of a differential converter was tested over various inductor currents levels as shown in Fig. 13. A prototype is shown in Fig. 14.

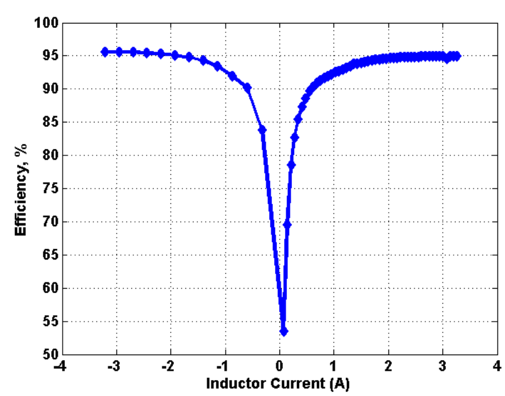


Figure 13. Measured efficiency of differential converter

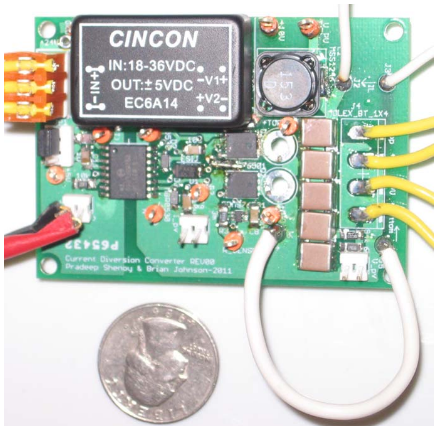
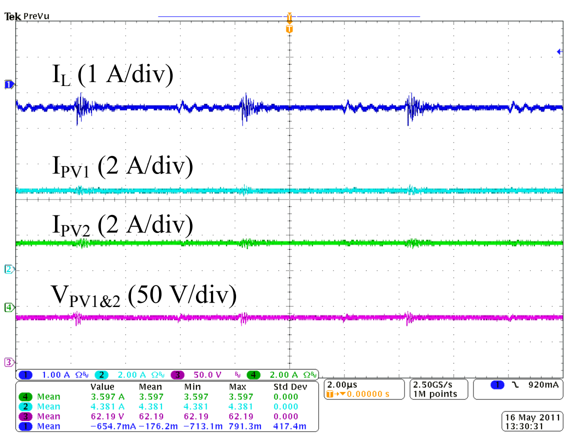
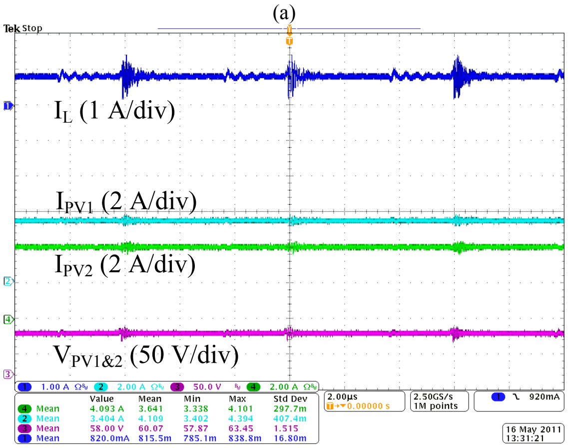


Figure 14. Differential converter prototype.

The differential power processing function of the experimental system is shown in Fig. 15. In Fig. 15 (a), the inductor removes 0.7 A from the midpoint to reach the MPP and in Fig. 15 (b) provides 0.8 A. The power processed by the differential converter is about 23 W in both cases, over 4 times less than the power produced by the panel. This demonstrates the basic promise that the MPP of the PV panels can be reached while only processing a small fraction of the total power.



(a)



(b)

Figure 14. The differential converter diverts current in (a) and adds current in (b) to reach the MPP.

VI. Conclusion

Differential power processing enables a series PV system to track the true global MPP by reaching the MPP of each PV element. Only a small fraction of the total output power is to be processed when a mismatch in MPP current exists. Differential power converters offer several advantages that tend to keep costs low: (1) the differential converter requirements are simple and routine in a power conversion sense, with many possible local conversion solutions, (2) voltage and current ratings are modest (and a small fraction of system current), and (3) there are no special dynamic performance requirements, as MPPT performance on time scales of a few milliseconds is the state of the art.

Differential power processing has the potential to substantially improve the levelized cost of energy of PV systems. A comparative analysis of system reliability concludes that the differential power processing architecture results in a longer mean time to failure (MTTF) than other dc architectures. Protection and monitoring capabilities add value to locally controlled differential converters. Even if differential converters have more power loss than their counterparts, overall energy conversion loss decreases since differential converters process much less power. It may be possible to integrate these systems in small packages or on chip for high volume, low cost production.

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