Fault Impacts on Solar Power Unit Reliability

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***Abstract*—This paper introduces a generalized reliability model of a solar power unit (SPU) based on physical characteristics including material, operating conditions, and electrical ratings. An SPU includes a photovoltaic panel, power converter, control and sensing. Possible faults in each component of the unit are surveyed and their failure rates based on physics-of-failure models are formulated. PV panel faults include possible installation faults, environmental effects, and material degradation. Power electronics faults are developed in depth for different components of a dc-dc boost converter. A system-level simulation model is developed and verified experimentally, and then used to define the survivor function of the SPU. Results show that it is important to include panel faults for accurate reliability values. The developed model is flexible and can be tailored for various SPU operating conditions, panel designs, and electrical ratings. The proposed reliability model can be extended to parallel and series interconnected topologies of multiple SPUs.**

***Keywords*—photovoltaic reliability, solar power unit, reliability modeling procedure.**

I. INTRODUCTION

Photovoltaic (PV) power generation has seen significant penetration into different applications ranging from space systems to residential and commercial installations. With this increase, high reliability and availability of PV systems are essential. Two of the earliest topics studied in PV systems are panel efficiency and reliability as shown in the complete issue [1]. With the development of more efficient and reliable material, installation technologies, and standards, modern PV reliability studies focus on power conversion. Panels are assumed to be significantly more reliable than the power converter, and are often ignored [2]. However, statistics and field experience have shown that PV panel reliability and efficiency can drop over time due to installation faults and environmental effects [3]. To the authors' knowledge, there has been no attempt to include panel reliability in a system-level reliability analysis.

In this paper, a solar power unit (SPU), shown in Fig. 1, is developed and analyzed to find its equivalent mean time to failure (MTTF). The SPU includes the PV panel, power converter, control and sensing. This SPU can then be used in larger systems, i.e., series-parallel combinations, as a basic block in system reliability evaluation. Since failure rates in components, specifically the PV panel, are rarely available or accurate, this analysis addresses the SPU as a generic unit where operating conditions (e.g., temperature), electrical ratings, and other physical effects are considered.

The approach is to integrate well-established physics-of-failure-based component life models into dynamic models of a complete system. This supports the determination of component lifetime reliability for expected operational and environmental conditions. One advantage of this approach is that it combines lifetime models of different components. This is of interest, as the degradation of one component can affect system operation and impact the life of other components. For example, in a dc-dc converter, as the ESR of the output filter capacitor increases, the ripple current in the capacitor, and therefore the ripple in switching devices, also increases. This ripple increases heat dissipation and degrades capacitor and switch performance.

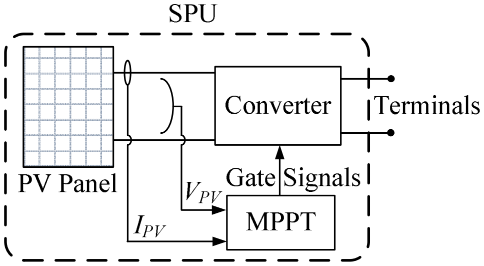

Fig. 1. Proposed SPU

The paper proceeds as follows: Section II describes the SPU; Section III presents essential faults in the PV panel and addresses their effect on panel performance; Section IV summarizes different faults in the power converter and sensing components, in addition to the physical effects on

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the failure rates; Section V shows experimental validation of the simulation model utilized in the reliability modeling and analysis; Section VI presents the reliability modeling results where the importance of panel faults is highlighted; Section VII elaborates on the physical effects on the SPU lifetime, and Section VIII concludes the paper.

II. SPU DESCRIPTION

The SPU under study, as shown in Fig. 1, consists of three main subsystems: (1) PV panel, (2) power converter, and (3) sensing components. The PV panel is a series-parallel interconnection of PV cells, and is the main power source. The power converter sets the maximum power point of the panel as desired by the controller that uses maximum power point tracking (MPPT). PV panel current and voltage sensing is achieved with simple sensing resistors or other devices, such as hall-effect current sensors. The SPU under study uses a dc-dc converter per panel, also called a micro-converter, with a dc output. Recent technologies show a push towards micro-inverters that are mounted on the PV panel and provide an ac output rather than dc.

A. Micro-converter vs. Micro-inverter

Micro-converters have been widely used in PV applications due to several advantages including ease of MPPT, battery charging capabilities, low cost, ability to supply dc loads, etc. These applications are still valid even with the penetration of micro-inverters. Among the disadvantages of micro-converters are the dc wiring cost and strict standards, and the central inverter, which poses a reliability bottleneck.

A large number of PV micro-inverter topologies have been developed as shown in [4, 5]. Micro-inverters provide the main advantages of direct grid interconnection, elimination of the central inverter, and ac output regulation in the event of a failure at one point in a PV array in the presence of appropriate fault detection and isolation. Although there are several types of inverters, a large number of them consist of an input dc-dc converter or micro-converter, and an output dc-ac stage. An example is shown in Fig. 2 where the dc-dc stage is used for MPPT and stepping up the panel voltage. The dc link maintains a dc bus voltage and stores the double-frequency power ripple for energy balance. Lastly, the dc-ac stage interfaces the dc bus to the ac grid and typically consists of an H-bridge.

From a reliability perspective, the following SPU reliability model can be used to analyze the dc-dc converter stage and the dc-link. If the dc-dc stage is isolated, the reliability model must include a transformer. The reliability of the dc-link depends highly on the type of capacitor technology used. Generally, electrolytic capacitor reliability is regarded as unfavorable and techniques exist which allow for the use of film capacitors [6]. In general, augmenting the SPU model with an output H-bridge can complete the reliability analysis of several micro-inverter topologies.

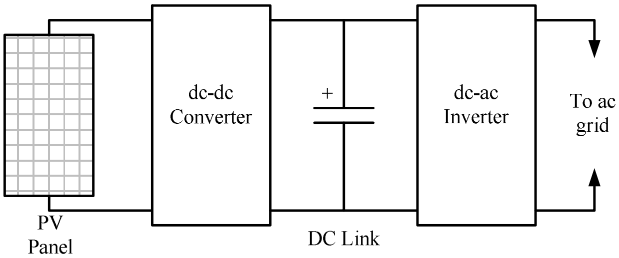

Fig. 2. Typical micro-inverter topology

Given that most common micro-inverter topologies utilize the dc-dc stage, the SPU used hereafter incorporates a dc-dc boost converter that operates under MPPT control and boosts the voltage to support the load. It is well understood that the micro-inverter vs. central inverter will affect the overall system reliability with multiple panels, but the SPU remains as the fundamental building block.

B. MPPT

In most PV applications, an MPPT algorithm is employed to extract the maximum possible power from the panel for any operating condition. Several MPPT algorithms exist and have been surveyed in [7]. The *perturb-and-observe* (P&O) algorithm is simple to implement and well established in literature. However, the algorithm suffers from a relatively slow response time and oscillations around the maximum power point (MPP). P&O is a local maximum finding algorithm and works well for functions with a single maximum power point.

Partial shading over a set of panels is a common occurrence in residential PV systems and panel mismatch can occur due to manufacturing variations or uneven degradation. In a series string of PV panels used in the central converter topology these effects can cause multiple local maxima in the power curve. Using P&O, the algorithm may stabilize at a local maximum different to the global maximum power point [8]. The SPU approach eliminates long strings of PV panels, and controls each panel individually. This reduces the effects of partial shading, reduces the change for local maximum, and makes local maxima searching algorithms, like P&O, more effective [9]. P&O is considered as the control in this SPU, but any other MPPT algorithm can be used in its place.

C. SPU Circuit Model

The SPU described thus far, which utilizes a PV panel, boost converter, and a P&O MPPT algorithm, is shown in Fig. 3. This SPU is among the simplest available topologies, and can demonstrate the reliability evaluation methodology with simple simulation models and experimental validation.

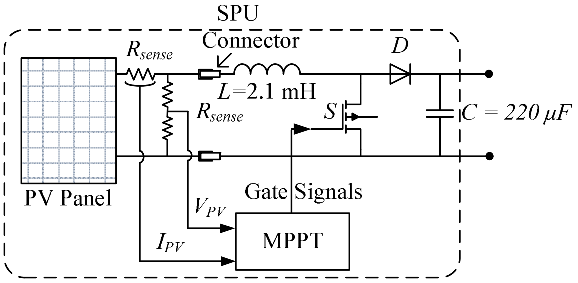

Fig. 3. SPU topology used

A synchronous boost converter is not used as the diode (D) provides inherent protection to the PV panel. The pair of connectors shown in Fig. 3 is an important component for reliability in PV systems as these connectors can degrade due to environmental exposure or fault as a result of improper installation. A current sensing resistor is used at the PV terminals along with a voltage divider that supplies a logic-level scaled PV voltage to the digital signal processor (DSP) running the MPPT and control algorithms. The power rating of the proposed SPU is around 200W and utilizes a BP7185 185W solar PV panel.

III. PV PANEL FAULTS

PV panels are usually assumed significantly more reliable than the rest of the system. However, literature reports that there are several faults in the panel that can cause significant malfunction in the system. This is shown in several surveys performed around the year 1982 [1]. These surveys and statistics address large systems consisting of hundreds of PV panels as large arrays. Early works in [10, 11] date back to the 1970s and address several installations in the US. There are also a handful of long-term reliability studies on systems in the US and around the world ranging from the 1990s to present day summarized in [12]. From these studies it is found that PV reliability depends heavily on the PV material and the temperature, humidity, and radiation of the environment. Monocrystalline and polycrystalline silicon PV panels, which make up over 90% of the market, degrade at a reasonably small rate. Amorphous silicon and copper indium de-selenide (CIS) PV panels preliminarily show significantly higher degradation rates, but additional studies are needed to provide accurate values. In general, the degradation process occurs in two stages: after the first year, the PV panel power production degrades by approximately 1-3% per year, and following the first year, it decreases to 0.5-1% per year; both degradation rates are approximately linear [12].

A component-based approach can also be used to estimate PV panel reliability. The closest component to a PV cell in [13] is the photodiode. The solar panel can be modeled as a series-parallel combination of photodiodes, where the equivalent failure rate is that of a 6 by 12 matrix of photodiodes.

In [10], component failure statistics over a time interval are used to calculate fault probabilities and associated failure rates. The calculated failure rates from both approaches are reasonable sources for determining reliability. These values provide general guidance for current installations, but finding accurate reliability data for new PV systems is difficult due to the latency of results from long-term studies on newer PV panels. More recent advances in manufacturing, installation, and interconnection technologies may not be incorporated in these failure rates. For simplicity, a PV degradation at a constant failure rate is assumed in this study.

Failure rates extracted from the studies or photodiode model can be used to identify the associated failure rates of possible faults in different panels. Common faults surveyed in literature are shown in Table I [11, 14-16]. Also, shading degrades panel performance and can be considered a fault [17], especially in jurisdictions where rebates require unshaded mounting.

Localized heating within a PV panel, called a hot spot, is another occurrence that reduces panel power output and reliability. Hot spot heating occurs when a cell in a series string of cells, as in a standard panel configuration, becomes negatively biased and dissipates power as heat rather than producing electrical power. This occurs when the current produced by the cell is lower than the string current, which is often a result of partial shading, cell damage, connection failure or uneven degradation. Hot spots cause nearby cells to increase in temperature, which advances degradation and reduces reliability. Bypass diodes are often used to limit the reverse bias voltage across the PV panel and limit hot spot heating [18]. However, a study in [19] identified the bypass diode as a weak link in many PV modules due to use of diodes underrated for the extreme temperatures that occur during a fault. Hot spot heating is of particular concern as it increases degradation and can develop into additional faults.

TABLE I
MAJOR FAULTS IN A PV PANEL AND ITS INTERCONNECTION [11, 15, 16, 20]

Fault	Electrical effect
Interconnect, contact, or insulation failure	Arcing or open circuit
Corrosion of Wire, terminals, and cell metal (including hail impact, moisture, and delamination)	Open circuit if severe, or reduced P_{PV}
Severely cracked, fractured, mismatched cell (including hail impact)	Cell back-biasing (reduced I_{SC}) and/or overheating (reduced V_{OC})
UV weathering	Material degradation (reduced P_{PV})
Optical surface soiling	Temporary reduction of P_{PV} and I_{SC}

Recent work in [21, 22] addresses PV panel availability from a probabilistic perspective, based on solar irradiance and ability to supply the load. Installation faults and incorrect panel connections should also be considered, especially when panels are exposed to severe variations in environmental conditions. As shown in Table I, most panel faults can be modeled by degrading efficiency, open-circuit voltage (V_{OC}) (e.g. under material aging), or short circuit current (I_{SC}) (e.g. under shading, dust, or loss of a string of cells). Thus, panel faults are modeled as drops in V_{OC} or I_{SC}.

IV. OTHER FAULTS AND PHYSICAL EFFECTS ON FAILURE RATES

A. Power Converter and Sensor Faults

With one converter, control, and sensing per PV panel, SPUs can be aggregated in series-parallel combinations to form larger arrays. As the SPU under study includes a boost converter, common faults in a boost converter are addressed. These faults occur in semiconductors, electrolytic capacitors, and other components as summarized in Table II for the SPU model in Fig. 3. Most of these faults are outlined in [2] for an interleaved boost converter and in [23] for a micro-inverter.

TABLE II
FAULTS CONSIDERED IN THE SPU

Component	Faults
MOSFET (S)	Open circuit (OC) Short circuit (SC)
Diode (D)	OC SC
Capacitor (C)	Degradation: C drops by 25% OC SC
Inductor (L)	Multiple-winding short: L drops by 90%
Current R_{sense}	Gain: ×1.5 Omission
Voltage R_{sense} R_{sense}	Gain: ×1.5 Omission
PV panel	V_{OC} drop by 50% I_{SC} drop by 50% V_{OC} and I_{SC} drop by 25%
Connector	OC
Physical faults	Connector OC, V_{OC} and I_{SC} drop

Semiconductors usually fail as short or open circuits. Even though it is more common for a diode to fail as SC, the OC case is still considered. The inductor can suffer from inter-winding SC due to insulation failure, and the capacitor, especially electrolytic, suffers from capacitance degradation over time. A capacitor can also fail as a SC between terminals or plates, or can blow up to fail as an OC. Current sensing resistors and voltage divider resistors are affected by temperature, and their DSP interface circuitry (not modeled explicitly) can have incorrect gains or total omission. Table II also includes PV fault models where V_{OC} and I_{SC} decrease. Note that the connector is at the panel terminals and the PV fault is modeled as shown in the second row of Table I. Physical faults that can affect the SPU as a whole are also shown in Table II. These faults could be due to problems in the SPU installation, wind damage to the setup as shown in Fig. 4, or any other physical reasons. These faults usually degrade panel operation or cause the panel to disconnect from the system, thus they are modeled as PV panel and connector faults.

Fig. 4. Damage to a photovoltaic solar system caused by wind

B. Failure Rates

Failure rates associated with different faults should accommodate variable operating conditions and ratings for a more complete study. Numerical failure rates are avoided initially to establish generalized reliability models. Numbers can later be used from the literature, e.g. [12, 13, 24], to have an estimate of SPU performance. Reference [13] is used to understand factors that affect performance and faults of different components, accepting that the absolute failure rates reported in [13] are substantially higher than encountered in most commercial field installations. Table III summarizes the failure rates, denoted by λ with appropriate subscript for each component, and the subscript b denoting the component base failure rate having b. The values of affecting factors, denoted by π with the appropriate subscripts as defined in Table IV, vary from one component to another. The use of physics-based failure rates enables a general study of various fault impacts. The resulting reliability functions can be formulated symbolically and analyzed for dominant faults, while numbers from any trusted references or statistics can be used. The effects of different environments, temperatures, electrical ratings or stresses, construction, and other factors in Table IV on the SPU reliability will be studied in Section VII. These effects are essential to estimate the SPU reliability in different applications, e.g., remote desert units, space applications, and military environments.

TABLE III

FAILURE RATES AND AFFECTING FACTORS

Component	Failure rate model
Capacitor (*C*)	$\lambda_C = \lambda_{C,b}\,\pi_T\,\pi_C\,\pi_S\,\pi_{SR}\,\pi_Q\,\pi_E$
Inductor (*L*)	$\lambda_L = \lambda_{L,b}\,\pi_T\,\pi_Q\,\pi_E$
MOSFET (S)	$\lambda_S = \lambda_{S,b}\,\pi_T\,\pi_A\,\pi_Q\,\pi_E$
Diode (*D*)	$\lambda_D = \lambda_{D,b}\,\pi_T\,\pi_{CC}\,\pi_S\,\pi_Q\,\pi_E$
R_{sense}	$\lambda_R = \lambda_{R,b}\,\pi_T\,\pi_P\,\pi_S\pi_Q\,\pi_E$
Connector	$\lambda_{CN} = \lambda_{CN,b}\,\pi_T\,\pi_K\,\pi_Q\,\pi_E$
One PV cell	$\lambda_P = \lambda_{P,b}\,\pi_T\,\pi_Q\,\pi_E$

TABLE IV

DEFINITION OF AFFECTING FACTORS

Term	Definition	Term	Definition
T	Temperature	*S*	Stress
Q	Quality	*A*	Application
E	Environment	*CC*	Contact Construction
C	Capacitance	*K*	Mating factor
SR	Series resistance	*P*	Power rating

V. SIMULATIONS AND EXPERIMENTAL VALIDATION

In order to establish a safe testing platform under different faults, a simulation model of the SPU is built in MATLAB/Simulink. Using this model avoids generating catastrophic or irreversible faults, such as SC of the switch, in a hardware setup, which would require maintenance and is likely to be expensive. The SPU simulation model is similar to the one shown in Fig. 3 where the MPPT is P&O and the panel model is of the BP7185. The simulation model was verified with an experimental setup shown in Fig. 5. The actual PV panel was unavailable for this purpose, so a dc power supply was used to mimic panel operation at a single operating point.

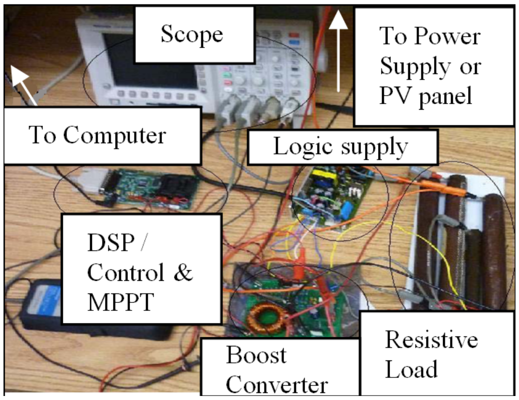

Fig. 5. Experimental setup

In addition to nominal system operation at one operating point, several faults were tested to verify the model, and examples are shown here. Nominal operation was simulated and is shown in Fig. 6. Experimental results are shown in Fig. 7 and show that the model captures all basic dynamics and steady-state characteristics including the boost converter output voltage (V_o), the panel voltage or input voltage (V_{in}), and the panel current (i_{in}).

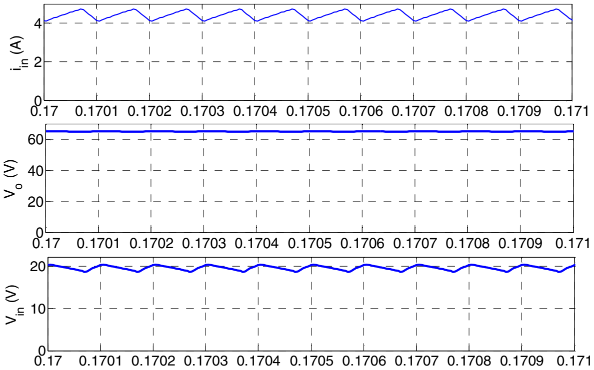

Fig. 6. Simulation results of nominal operation

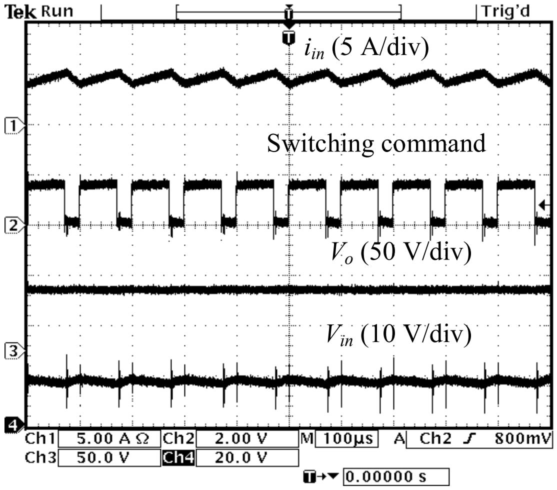

Fig. 7. Experimental results of nominal operation

One of the tested faults is the connector OC, i.e., the main power source in the SPU is lost. Simulation and experimental results are shown in Figures 8 and 9, respectively. The results match as expected, where the PV panel voltage rises to V_{OC} as it does not see any load, and the input current drops to zero while the capacitor discharges in the load. Note that the model is accurate enough to match the capacitor-load time constant.

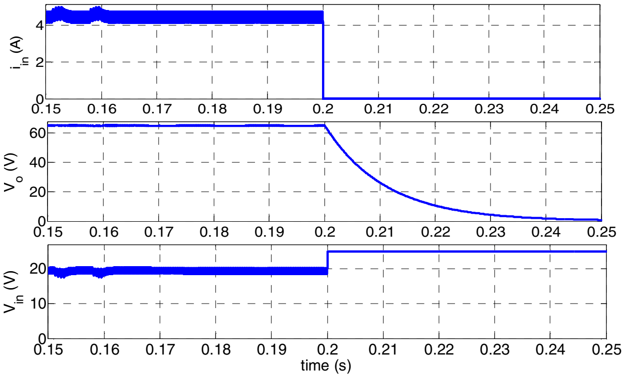

Fig. 8. Simulation results for connector OC

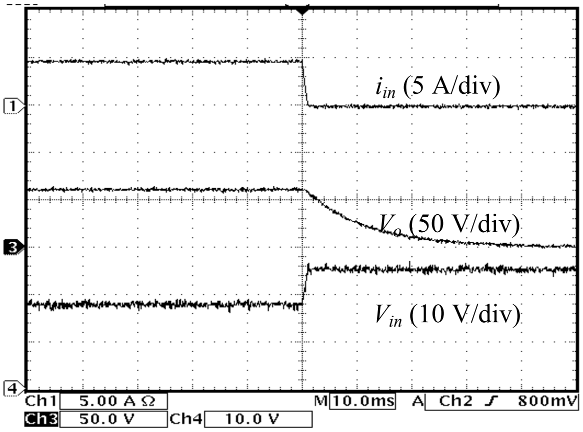

Fig. 9. Experimental results for connector OC

Another tested fault is the diode SC. Again, simulation and experimental results match as shown in Figures 10 and 11, respectively. The transient response simulation result after the diode SC is less accurate, but the steady-state performance of both simulation and experimental setup matches. This transient modeling inaccuracy can be attributed to the finite switching time in experiments compared to the step command with zero switching time in simulations, in addition to the power supply transient in experiments compared to the simulated PV panel.

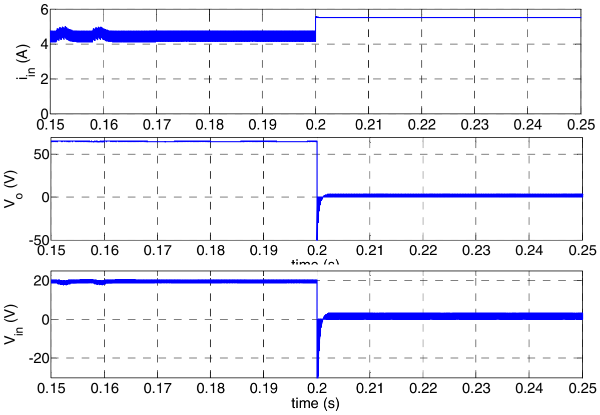

Fig. 10. Simulation results for diode SC

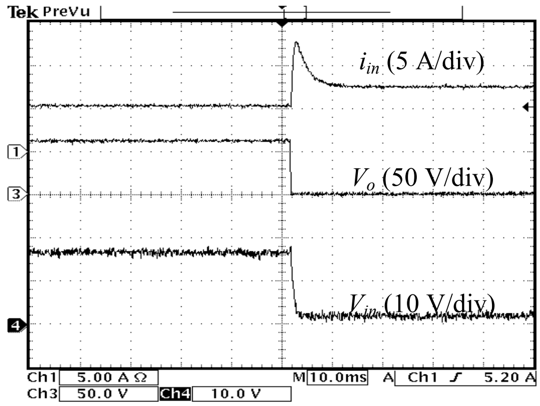

Fig. 11. Experimental results of diode SC

After running several simulations and experiments, the SPU model used was verified to accurately match the experimental setup. Although some transient responses are not as accurate, steady-state operation matches well. For the reliability analysis of the SPU under study, the time required to check if the SPU is supplying the load as desired following a transient is 100ms, which is long enough to reach steady-state operation in most cases where the switching frequency is 10kHz.

VI. SPU RELIABILITY MODEL UNDER NOMINAL OPERATING CONDITIONS

Faults were injected into the simulation model and the system status was assessed. In order to assess the failure or survival of the system, a performance requirement was set—the load of 100 Ω should be maintained with at least 47.5 W within 100 ms of the fault occurrence. This performance requirement gives the SPU around 1000 switching cycles to maintain the load power, which is long enough to determine whether the SPU is still functional or not. Different performance requirements affect the final reliability outcome, but the procedure presented here can be modified as needed. Note that the analysis presented here is based on failure modes and effects analysis (FMEA) and mathematical formulations in [25]. A similar methodology was used in [26]. Two consecutive faults were injected in different components described in Table II. The first fault is injected after the system reaches steady state under nominal operating conditions. The second fault is injected after the system reaches steady state if it survived the first fault. Two faults in the same component are ignored as this situation has a very low occurrence probability. Base failure rates are shown in Table V, and the physical-effect factors are shown in Table VI for nominal operating conditions found in [13]. Given the values in Tables V and VI, nominal failure rates are shown in Table VII.

TABLE V

BASE FAILURE RATES AND RELATED FACTORS

Component	Value (failures/hour $\times 10^{-6}$)
Capacitor	$\lambda_{C,b}$=0.00012
Inductor	$\lambda_{L,b}$=0.00003
MOSFET	$\lambda_{S,b}$=0.012
Diode	$\lambda_{D,b}$=0.025
R_{sense} (current)	$\lambda_{R,b}$=0.0037
R_{sense} (voltage)	$\lambda_{R,b}$=0.0017
Connector	$\lambda_{CN,b}$=0.007
One PV cell	$\lambda_{P,b}$=0.04

In order to study the importance of considering PV panel faults in any solar system reliability analysis, SPU reliability was evaluated with and without PV panel faults. Fault coverage—the probability that a system survives given that a fault occurs—is studied by varying the solar irradiance between 400 and 1000 W/m^2. The resulting reliability functions, $R(t)$, are shown in Fig. 12 along with the expected MTTF. It is clear that ignoring PV panel faults drastically overestimates the MTTF of the SPU to around 74 years, but the actual MTTF is around 50 years, 33% less. This leads to the conclusion that PV panel faults should be carefully considered in any reliability analysis of a photovoltaic solar system.

TABLE VI

PHYSICAL-EFFECT FACTORS

Factor	Value
π_T Ambient temperature=20°C, junction temperature=40°C	*C*, 0.79 *L*, 0.93 *S*, 1.4 *D*, *1.6* R_{sense} (current), 0.95 R_{sense} (voltage), 0.88 Connector, 1.3 PV cell, 1.6
π_E, Benign environment	1
π_Q, Quality	*C*, *L*, R_{sense}(current), R_{sense}(voltage), 3 *S*, *D*, PV cell, 5.5 Connector, 2
π_S, Stresses (voltage or power)	*C*, 1.4 *D*, 0.19 R_{sense}(current), 0.79 R_{sense}(voltage), 0.66
π_C, Capacitance	3.4
π_{SR}, Series resistance	3.3
π_A, Application, 250W max	8
π_{CC}, Contact construction	1
π_K, Mating factor	1
π_P, Power rating	0.4

TABLE VII

ACRONYMS OF THE OPERATING ENVIRONMENT

Component	Value (failures/hour $\times 10^{-6}$)
Capacitor	λ_C=0.0045
Inductor	$\lambda_{L,}$=0.000084
MOSFET	λ_S=0.74
Diode	λ_D=0.042
R_{sense} (current)	λ_R=0.0033
R_{sense} (voltage)	λ_R=0.0012
Connector	λ_{CN}=0.018
PV Panel (12×6 cells)	λ_P=2.96

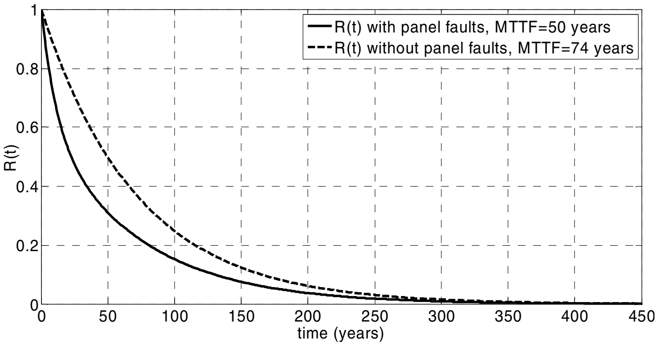

Fig. 12. Reliability function and MTTF of the SPU with and without PV panel faults

VII. PHYSICAL EFFECTS ON SPU RELIABILITY

The factors shown in Table VI are for nominal operating conditions, but the SPU application, environmental conditions, and additional operating circumstances can alter these values. The parameters shown in Table VI were extracted from tables in [13] where other values for different conditions can be found. In order to establish a better quantitative understanding of the effect of each parameter on the SPU reliability, the MTTF was found for a sweep over different values of every factor. For example, over a range of operating temperatures, the corresponding π_T was changed for each component while the other π factors remained unchanged. The base failure rates were held constant as the components are assumed to be the same except for the varying operating condition. Calculating a new MTTF does not require re-running the fault-injection simulations—the state transition matrix generated from the nominal case is symbolic, and only new failure rates need to be plugged in it to evaluate the MTTF. The MTTF is evaluation is discussed in detail in [25].

The temperature effect is studied for an operating temperature range between 20 and 150 °C. Fig. 13 shows that the MTTF drops exponentially with higher temperatures. Thus, in warm or hot areas, careful cooling considerations or material quality that handles heat should be considered.

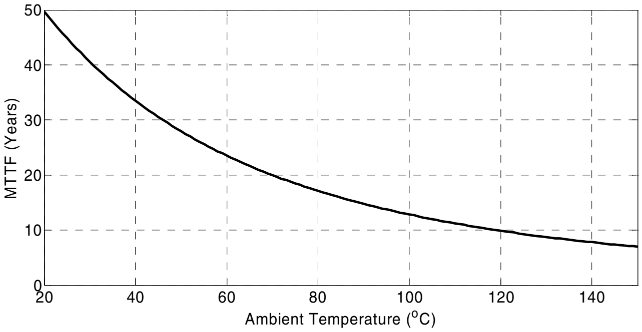

Fig. 13. Temperature effect on SPU MTTF

The effect of the operating environment was also studied and varies from benign ground applications to space and military applications. The acronyms of different environmental conditions are defined in Table VIII. Fig. 14 shows that the MTTF significantly drops for applications other than benign ground, e.g., residential, and airborne inhabited, e.g. sealed on a passenger airplane. Note that some of these environments might not be applied to current SPU applications, but could be used in advanced future applications.

TABLE VIIII
ACRONYMS OF THE OPERATING ENVIRONMENT [13]

Environment	Symbol	Environment	Symbol
Ground benign	GB	Ground fixed	GF
Airborne uninhabited (cargo)	AUC	Airborne uninhabited (fighter)	AUF
Ground mobile	GM	Missile launch	ML
Naval sheltered	NS	Space flight	SF
Naval unsheltered	NU	Missile flight	MF
Airborne inhabited (cargo)	AIC	Airborne rotary winged	ARW
Airborne inhabited (fighter)	AIF	Cannon launch	CL

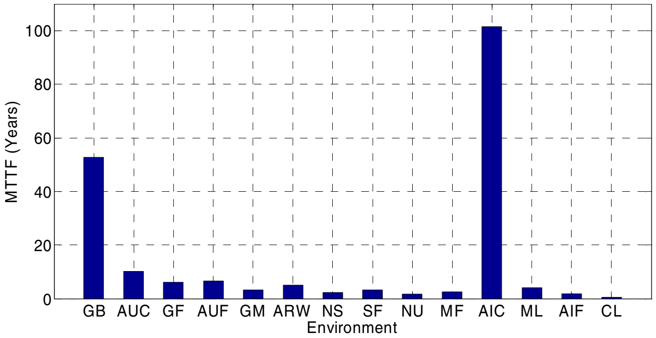

Fig. 14. Effect of operating environment on SPU reliability

Other effects that showed influence on the SPU MTTF are the diode voltage stress, shown in Fig. 15, and MOSFET power rating, shown in Fig. 16.

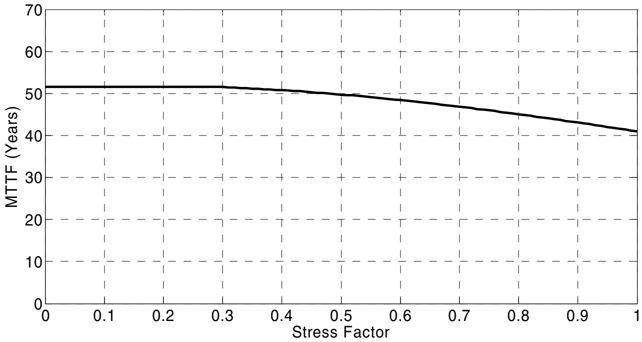

Fig. 15. Effect of diode voltage stress on the SPU MTTF

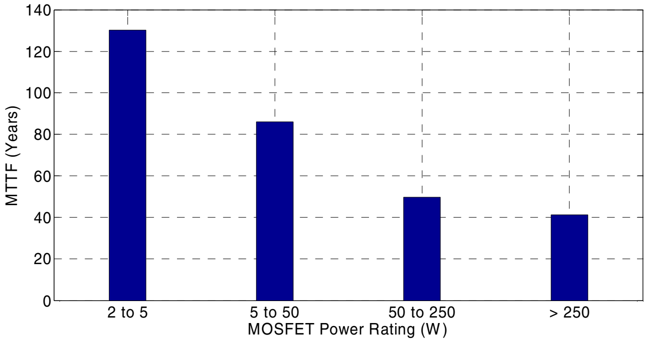

Fig. 16. Effect of MOSFET power rating or application on SPU MTTF

Quality was not varied as it is not straightforward to quantize qualities of different components, and it is intuitive that components with low quality will have a high failure rate that would dominate other components. Varying all other factors showed minor influence on the SPU MTTF. Results shown in Figures 13–16 show that for residential or ground benign applications with moderate temperatures and power ratings, the SPU MTTF is expected to be around 50 years. They also show that higher voltage and power ratings reduce the SPU MTTF. These results encourage the use of modular converters per panel or even at the cell level compared to central converters with higher ratings.

VIII. CONCLUSION

This paper examines system-level reliability of PV systems that incorporates the PV panel reliability as an important contributing factor to the system MTTF. Accurate PV reliability values are difficult to identify due to dependence on location and the small number of long-term studies conducted. However, the available values can be used to provide a general estimate of PV panel reliability. Utilizing an SPU approach reduces the affects of partial shading or other panel mismatch conditions and allows for implementation of simple MPPT algorithms, such as P&O. Based on the outlined SPU, the reliability of each component is analyzed and an equivalent reliability function is developed to determine the MTTF. Depending on the overall configuration of the PV system, for example a micro-converter versus micro-inverter approach, additional device reliability, e.g. inverter and dc link, must be taken into account as additional analysis to the SPU unit reliability formulated in this paper.

Typical faults in PV panels and power converter components and the effects of each failure are considered for its effects on the system as a whole. A reliability function for each component is developed based on physical effect factors, for which nominal values are provided. The SPU is modeled and validated against an experimental setup. Faults were simulated in the model and the system status was assessed based on a performance requirement to determine failure or survival, and FMEA is used to determine the resulting reliability function. With the parameters outlined in the study, the MTTF of the SPU is around 74 years when the PV reliably is ignored, while including this information decreases MTTF to around 50 years. PV panel faults affect system reliability and should be taken into careful consideration. The physical effects of temperature, operating environment, diode voltage stress, and MOSFET power rating on system reliability are also examined. MTTF decreases exponentially with higher temperatures. Benign ground and airborne inhabited environments maintain a reasonable MTTF, while harsher operating environments greatly reduce the reliability. Higher voltage and power ratings also reduce the MTTF. Quality is not explicitly examined, but it is clear that low quality parts limit overall reliability.

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