

Predictive Reliability for AC Photovoltaic Modules Based on Electro-Thermal Phenomena

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Abstract—AC photovoltaic modules promise many performance enhancements but expose their embedded power electronics to rigorous environmental stressors. The ability to identify reliability consequences in the early design phase is critical to rapid market adoption. This paper develops the capability to generate long-term reliability predictions based on electric and thermal performance over multiple time scales. The model is validated with measurements from centralized inverters as well as power electronics that are integrated into the module. The resulting model will enable manufacturers to optimize the design and physical layout of next-generation AC modules for microgrid systems prior to mass production. Preliminary results indicate direct electrical performance impact due to heat transfer between the module and embedded power electronics. Non-unity power factor experiments show that an operation factor of 0.85 can cause a 60% increase in DC voltage ripple, while raising voltage to approximately 90% of the open circuit value.

Index Terms—microgrid, microinverter, AC PV module, photovoltaics.

I. INTRODUCTION

Residential PV systems with integrated Power Electronics will become as ubiquitous as modern smart phones. Module-Level Power Electronics (MLPE) are projected to see significant adoption in the near-term. MLPE devices consist of PV modules where power electronics are incorporated into unit. Such devices are also referred to as AC modules. Ability to support and work with a variety of MLPE manufacturers — in a similar manner to photovoltaic (PV) module manufacturers today — will be vital for both the economic and technology development of microgrids. Utilities, integrators and residential customers must be prepared to incrementally adopt new inverter and power electronics functions in their PV systems designs. The maturation of AC PV module technology will provide future smart grids with high-fidelity control of its power generation elements down to the individual module. Widespread implementation of optimized AC modules will accelerate their adoption into microgrids.

AC modules are gaining market share in the PV industry due to their promise to significantly improve safety and performance [1-3]. This enhancement is facilitated by low power levels, reduction of mismatch issues and improved

module-level control, using components which can be replaced easily.

While the change in topology from centralized inverters to MLPE offer numerous advantages, it exposes components to new reliability and warranty challenges. These include module and electronics thermal management issues as well as coping with environmental thermal stress. Harsh thermal environments can lead to accelerated component degradation [4] and arc-fault events [5-7]. To facilitate rapid industry acceptance, these reliability issues must be addressed to meet longer warranty requirements attached to the modules in which they are integrated.

The research in this paper connects short-term performance implications of inverter operation to long-term reliability. This link is based on benchmark experiments that utilize developed models to examine long-term reliability impacts. Tools are created to model the electrical performance of inverters, the thermal consequences of advanced inverter functionality, and the long-term reliability implications of such operating conditions.

Experimental measurements of both string inverters and MLPEs are used to validate the modeling results. Although centralized inverters have been well characterized to date [8], little work has been done to electrically and thermally analyze AC modules. This investigation examines AC modules under varying power generation levels and environmental conditions. The combination of the modeling tool and the simulation results will provide a rigorous approach for the PV industry to quantify the reliability of AC modules. Such capabilities will enable the industry to cost-effectively meet consumer reliability demand while navigating the market turbulence associated with rapid growth. Successful widespread implementation of AC modules will improve the performance of future microgrids.

II. MODELING RESULTS

The model addresses two challenges in developing a reliability prediction capability: 1) multi-physics simulation implementation; and, 2) multi-length time-scale calculation. While electrical performance of the MLPE is of primary concern, its long-term degradation is dependent on the thermal impact to the system and effectiveness of mitigation strategies. Furthermore, electrical performance, thermal effects, and reliability consequences each occur at different time scales. As a result, pure device-level simulation is impractical when faced with limited computational power.

This model takes a multi-physics approach in a computationally-efficient manner by using lumped elements for analyzing electrical and thermal performance. The parameters of these lumped elements are verified through

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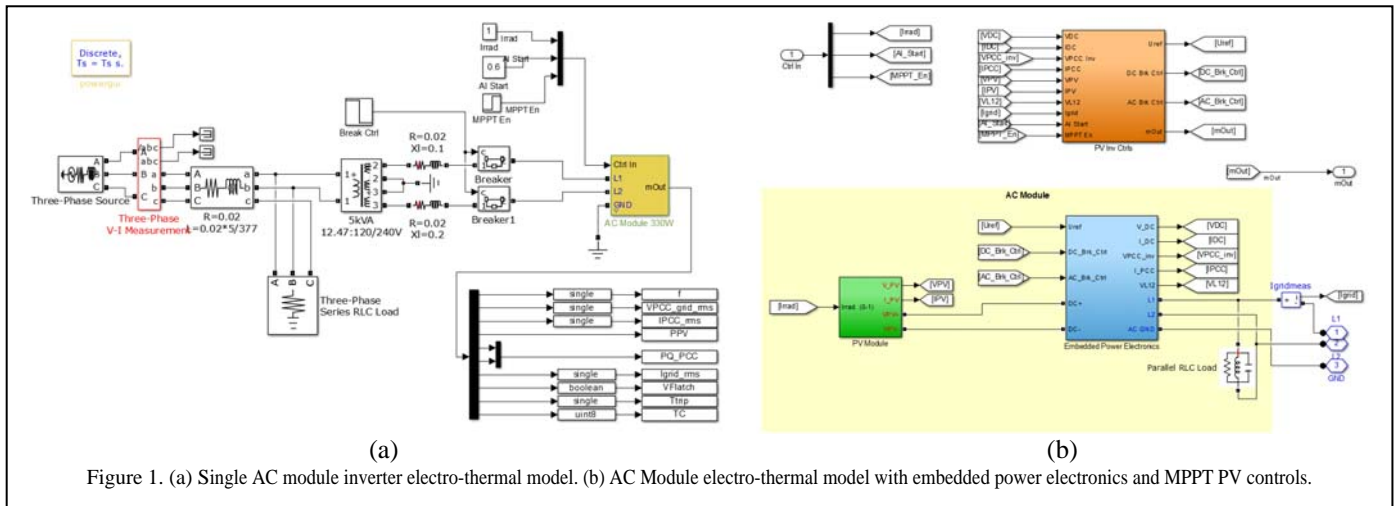


Figure 1. (a) Single AC module inverter electro-thermal model. (b) AC Module electro-thermal model with embedded power electronics and MPPT PV controls.

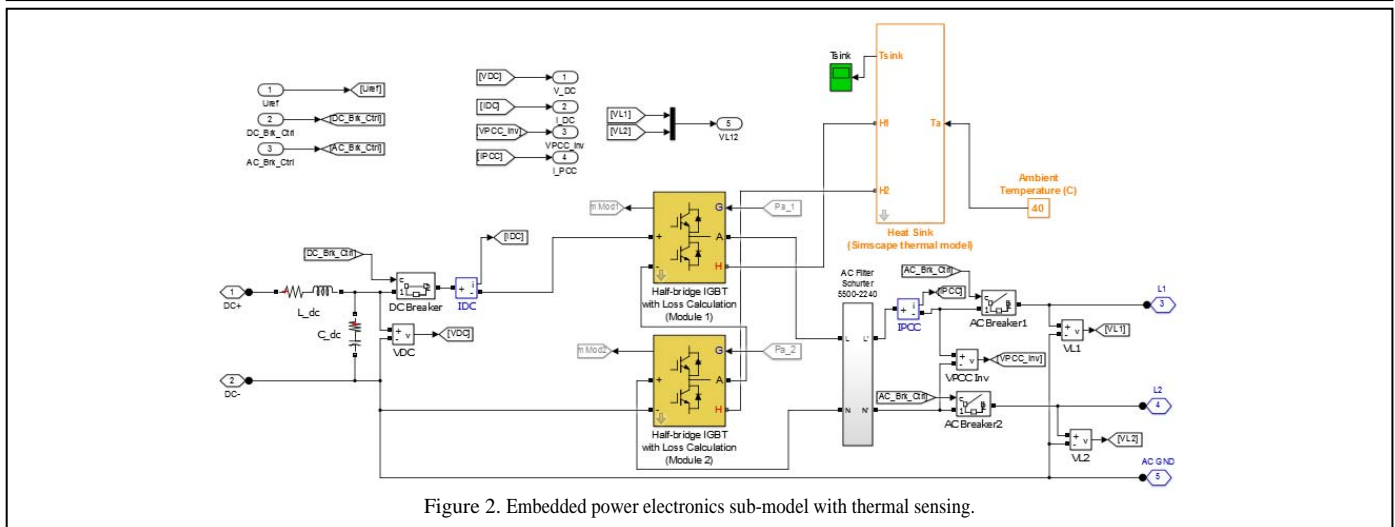


Figure 2. Embedded power electronics sub-model with thermal sensing.

lower-level simulations validated by experimental measurements on actual PV inverters.

A variable time-step strategy enables the model to answer questions at time scales relevant to electrical, thermal, and reliability performance. Fundamental equations are used to calculate nonlinearities that occur during events such as advanced inverter functionality. This nonlinear approach allows precise computation over the electrically relevant time scales, which is on the order of milliseconds or less. These simulations are extended into the thermal time scale of minutes to hours to quantify heat transfer impacts under an inverter's thermal management design.

A lumped electro-thermal circuit approach incorporates the above results and extends this simulation into to the reliability time scale of multiple years. This systems-level approach enables propagation of thermal effects over long periods with effective use of computational resources.

The transient model incorporates a piecewise linear simulation methodology to investigate electrical and thermal physics simultaneously. The single-phase inverter model was implemented in MATLAB/SIMULINK using SimPower Systems and SimElectronics libraries. These tools were employed to provide component- and system-level analysis of a PV module with embedded power electronics. The power

electronics components were modeled based on actual circuits with minimal idealities used in the AC module test-bed experiments performed at the Sandia National Laboratories (SNL) Distributed Energy Test Laboratory (DETL) facility. A schematic overview for the laboratory prototype used for testing and analysis is presented in Figure 1 (a) and (b). The DC portion of the system primarily consists of a PV module. The AC output of the inverter, in combination with the LCR circuit, forms a sub-grid in which the voltage can be controlled independently from the voltage of the external grid [9].

The electro-thermal modelling of the semiconductor devices — such as insulated-gate bipolar transistors (IGBT) and power diodes — have terminals that are connected to an electrical network. It also has respective thermal terminals attached to a loosely-coupled, discretized, heat transfer network. The thermal nodes have units of temperature (K) across the nodes, and units of power (W) flowing through the nodes, whereas the electrical circuit's analog has respective units of voltage and current. In this electro-thermal simulation methodology, the model is represented as an interconnection of thermal, electrical, and semiconductor networks where each component represents an individual building block used by the designer for comprehensive analysis. The 330W AC module

itself is composed of a submodel, shown in Figure 2, whereby a defined input irradiance curve is loaded producing an IV curve based on the Sandia Array Performance Model [10].

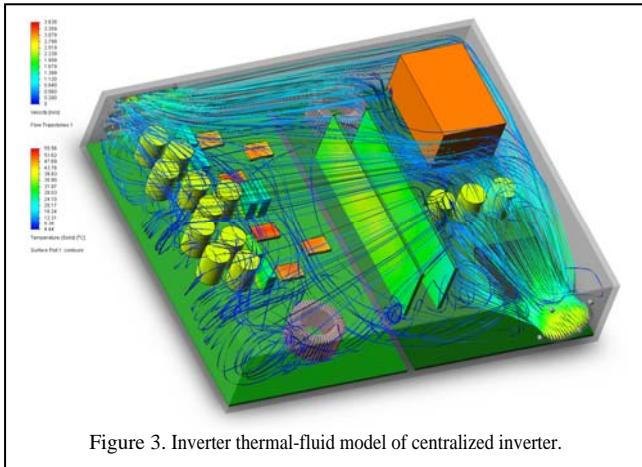


Figure 3. Inverter thermal-fluid model of centralized inverter.

Heat sink ambient temperature values are determined from a Navier-Stokes analysis which is based on the component internal topology of the inverter. A preliminary analysis shows that the simplified inverter components in Figure 3 are very sensitive to direction and speed of air flow within the inverter as facilitated by the external fan. This finding is especially the case with the six-IGBT configurations.

Preliminary results of the electro-thermal model, as shown in Figure 4 demonstrate the capability of investigating the losses and respective temperature fluctuations during a contingency event from an IGBT module failure. This example, as well as other nominal and contingency events, is currently being validated at the Sandia DETL facility through accelerated testing.

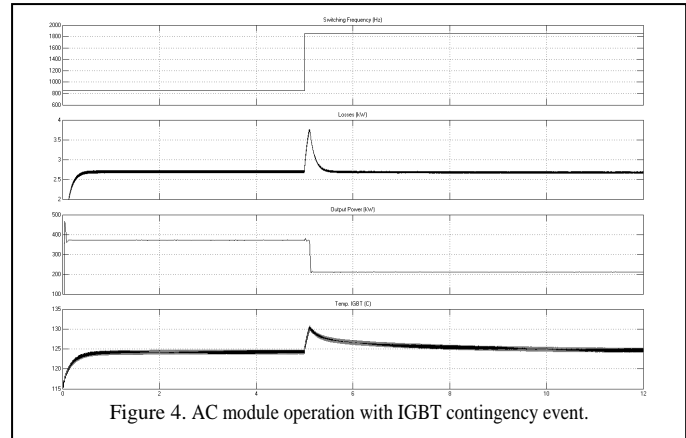


Figure 4. AC module operation with IGBT contingency event.

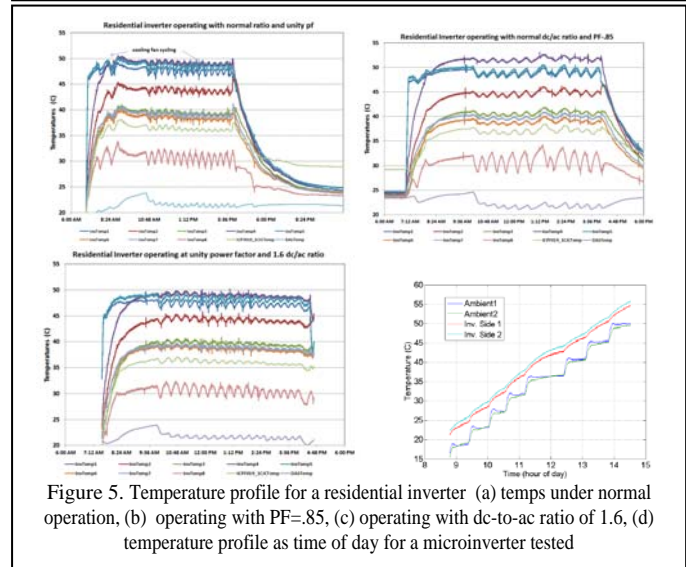


Figure 5. Temperature profile for a residential inverter (a) temps under normal operation, (b) operating with PF=.85, (c) operating with dc-to-ac ratio of 1.6, (d) temperature profile as time of day for a microinverter tested

III. EXPERIMENTAL RESULTS

A. Results from thermal management study

We have conducted thermal tests to monitor the operational efficiency of both residential-scale string inverters and microinverters under a range of temperatures. Laboratory experiments that were conducted utilized an Accelerated Lifetime Test (ALT) plan to quantify the thermal capabilities of the device under test. Both residential string and microinverters were investigated and monitored. Further details of the experimental setup and conditions will be presented at the time of the conference.

The DC power and input voltage are important factors affecting the operational efficiency of inverters. The experiments shown in Figure 5 found that high DC-to-AC ratio operation resulted in earlier fan turn on, increased fan cycling, higher temperatures on critical components, lower efficiency, and higher operating DC voltage.

These experiments set the baseline for the thermal performance of the inverter while operating at normal conditions. The following two subsections present measurements at high DC-to-AC ratio and at non-unity power factor.

B. Advanced functionality operation

A 3-phase inverter was put in operation with the addition of thermocouples. Figure 6 (a) describes 6 hours of inverter operation at rated power. For this test, the PV array simulator delivered DC power at approximately the rated value while still allowing margin for maximum power point tracking (MPPT). Testing conditions were at room temperature and unity power factor operation. Figure 6 (b) shows the temperatures with the inverter operating at 0.85 power factor. While the real power generated by the inverter is less when non-unity power factor operation, the temperatures are slightly higher and fan cycling is increased.

Non-unity power operation resulted in earlier fan turn on and greater amounts of fan cycling. The associated temperature measurements are shown in Figure 7. This configuration in turn resulted in higher temperature on critical components, lower efficiency and higher operating DC voltages. While fans are effective at managing temperature under different operating conditions, the additional stresses placed on the thermal management devices will have an impact on reliability [4].

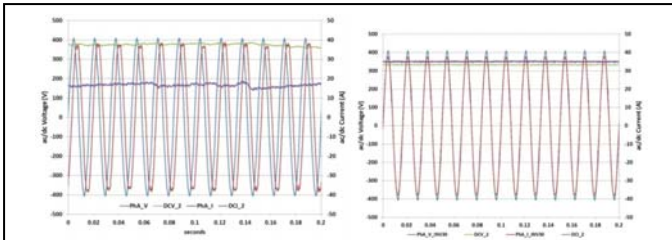


Figure 6. AC/DC voltage and current waveforms during (a) inverter operating at unity power factor, (b) inverter operating at non-unity power factor.

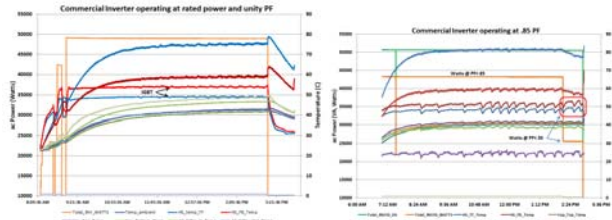


Figure 7. Temperature profile of a commercial inverter (a) under steady state normal operation, (b) with inverter operating at .85 power factor and for short time at 0.50 power factor.

Both FETs failed during start-up



Figure 8. Residential inverter failure occurred while restarting after ~8hrs of non-unity operation.

The DC voltage, AC voltage and current parameters are captured in the waveforms shown in Figure 6. While operating at unity power factor and MPPT, the DC voltage shows minimal ripple and operates at approximately 80% of the open circuit voltage. With the inverter operating at a power factor of 0.85, the DC voltage increased to 90% of the open circuit voltage (V_{oc}) and exhibited a 60% increase in ripple. System designs often operate close to the maximum V_{oc} . The addition of DC ripple can thus result in voltages that approach or exceed the rated values of DC bus capacitors, accelerating degradation [11].

We will report on examples of operational failures including an inverter failure that occurred during non-unity power factor operation. The inverter in question failed after 8 hours of operation upon restart after a planned shutdown. A photograph of the failed inverter and damaged field effect transistor is shown in Figure 8. The cause of the failure is under investigation and will be reported at the time of the conference with additional life testing results.

IV. SUMMARY AND CONCLUSIONS

Module-level power electronics are very likely to be a major technology thrust for PV modules in the future. They

have great potential for performance enhancements and safety improvements. Therefore, MLPE will likely gain significant PV market share, especially in the residential segment. The new functionality provided by MLPE, combined with interactive effects between MLPE and PV component operating environments, will likely result in new failure mechanisms and modes. Additionally, common failure modes for conventional PV components may change.

These failure modes may be exacerbated by exposure to harsher environmental conditions for MLPEs when compared to centralized inverters. For example, MLPE may experience greater diurnal temperature variations due to electronics being directly adjacent to the PV module. The MLPE may also be exposed to elements (vibration, thermal cycling, moisture, etc.), differentiating it from centralized inverters, which are often sheltered indoors. Several prevalent failure mechanisms (e.g., conductive anodic filaments, electrochemical migration, and corrosion [12-14]) in power electronics devices can be further accelerated by corrosive mechanisms. Such conditions may exist in a number of environments: coastal salt spray, industrial environments such as farms or factories, or international locations with reduced air quality standards.

Major gaps remain in understanding the reliability of MLPEs in AC modules. Specifically, the operating environment of a PV module is quite different from standard applications of power electronics. Research efforts focused on identifying failure modes, rates, and mechanisms for MLPE are needed to ensure that major and unexpected problems do not adversely affect the continued rapid growth of this technology.

V. ACKNOWLEDGMENTS

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