Project Phase 1 Report

Reliability Assessment for Utility PV Inverter System

Project period: Dec 2021 – Dec 2022

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Project Scope

The reliability of power electronics is critical for energy conversion systems to maintain safety, efficiency, and uptime. PV inverters are regarded as one of the most fragile components in PV systems. Their failures can downgrade the system efficiency, cause catastrophic system breakdowns, and result in expensive economic losses. U.S. Department of Energy (DOE) Solar Energy Technologies Office (SETO) considered "improving reliability and efficiency of new and existing PV technology" as the key focus for increasing PV useful system life to 50 years while lowering the cost of energy. Based on DOE's recent PV system failure survey [1], occurrences of specific hardware issues are shown as percentage and in Fig. 1. PV inverters are associated with 40% or more of the service requests, representing the single largest category in the PV system failure causes.

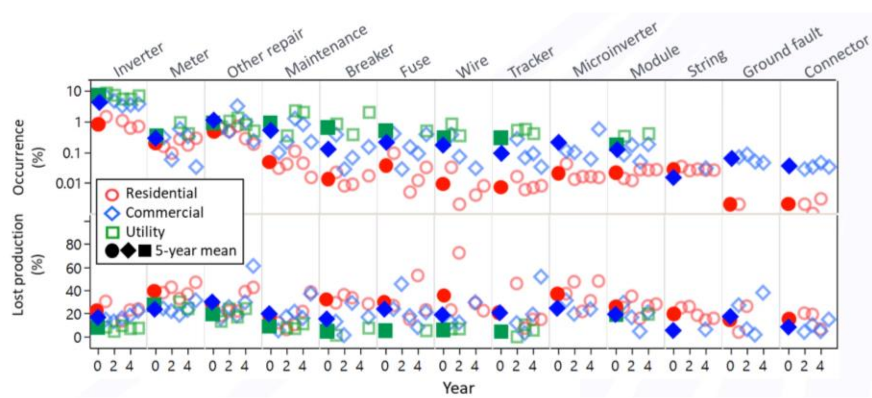


Fig. 1 PV system hardware failures (data based from100k+ systems in the U.S.) [1]

Among all the various failure causes investigated by researchers, thermal stress has been identified as one of the significant causes of PV inverter modules. The generated power due to the chaining irradiation usually has a large variation in a short duration. The solar inverters will bear such variation of the real power from hundreds of kilowatts to several megawatts. Subsequently, a fast-varying power loss is accompanied and aggregated, and a severe thermal cycling occurs in the power module of the converter. Both the bond-wire liftoff and the solder joint fatigue, two most frequent failure modes of power modules, have been justified related to this thermal stress.

This thermal stress accelerates the degradation of semiconductor devices, downgrades the system quality and efficiency, and eventually causes catastrophic system breakdowns and extensive economic losses. Therefore, it is critical to establish a **reliability assessment tool** to quantitively assess PV inviter's reliability based on the field data and support the development of safer and more reliable PV.

Project Achievements

The phase 1 project team has been focused on developing a reliability assessment tool to quantitively assess PV inverter's reliability based on Duke energy's field data at the Mount Holly PV system. Fig. 2 shows the overall framework of the proposed reliability assessment tool for PV inverter. The proposed approach introduces the PV system reliability-related information (such as energy mission profile, semiconductor temperature and stress, temperature, solar irradiation, etc.) into the inverter control system, therefore offers a universal platform to quantify and compare the reliabilities for PV inverter from different vendors with different control methods.

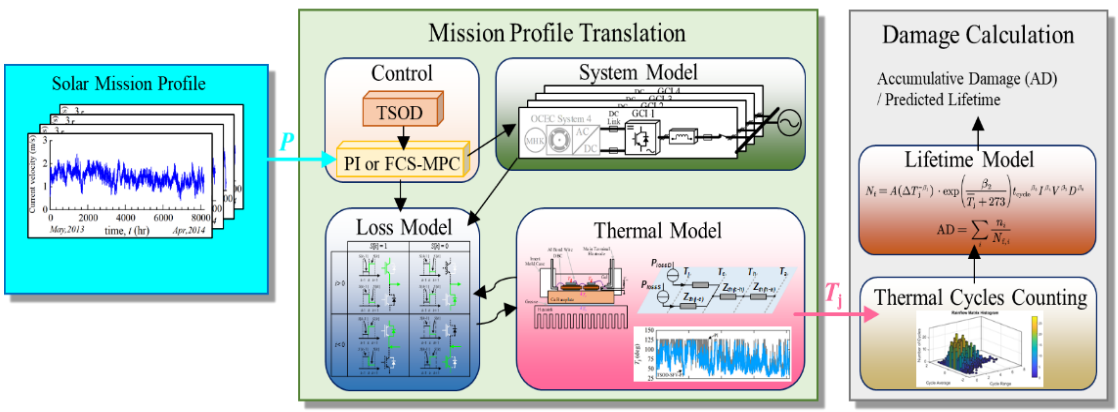
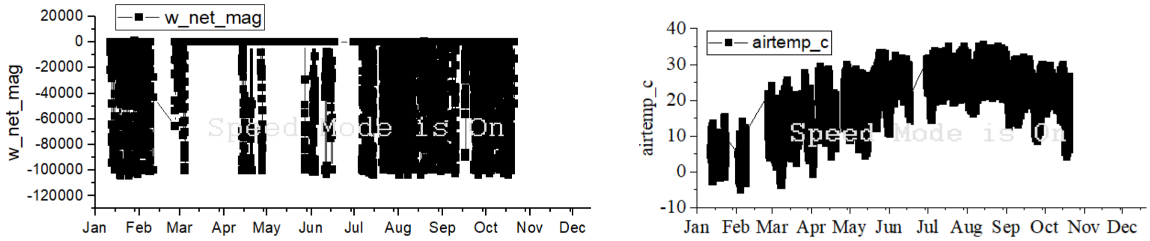


Fig. 2 Reliability assessment framework for utility PV system

The reliability assessment framework was based on the real field data from Duke energy's Mount Holly PV system. Examples of the yearly three-phase current data are illustrated in Fig. 3. The data has been processed to generate the mission profile as the input to the reliability assessment framework. The output of the framework is the accumulative damage (AD) and predicted lifetime of the semiconductors. The quantified accumulative damage is highly related to the semiconductor specs, PV inverter topology, package and cooling system, and ambient temperature variation. The results are representative and will be refined once we have the detailed design and specifications from the inverter vendor. The framework provides a universal tool to quantitatively compare the reliabilities for PV inverters from different vendors with different control methods. The lifetime prediction for the PV inverter leads to a better understanding of the thermal stress impact to inverter failure. Based on this reliability assessment platform, predictive maintenance and reliability-oriented control and operation methods, such as active thermal control, can be evaluated to extend the lifetime of PV inverters.



(a) w_net_mag: Active power

(b) airtemp_c: ambient temperature

Fig. 3 Yearly mission profiles from Mount Holly PV system

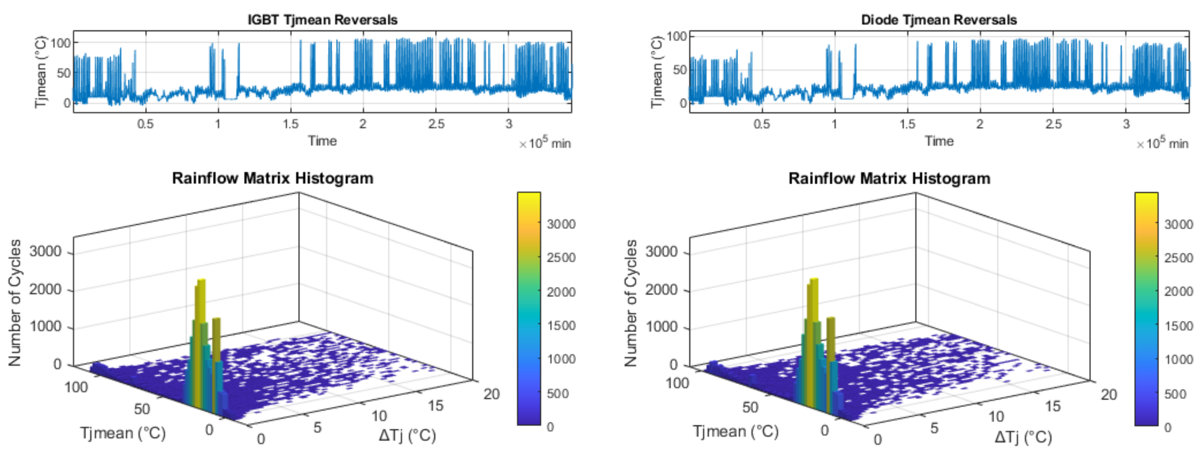


Fig. 4 Rainflow counting results and the mean junction temperature profiles.

In Phase 2 of the project, the team plans to evaluate the PV inverter reliabilities for different control and operation strategies and provide lifetime extension recommendations based on the case study of the Mount Holly PV system. The team will also investigate arc safety and fire resilience for PV and utility energy storage systems to support the development of safe and reliable utility PV and energy storage systems.

More details about the reliability assessment are given in the **Appendix (technology descriptions**).

Acknowledgments

The team would like to thank Dr. Kevin Chen, Tom Fenimore, and Dwayne Bradley from Duke Energy for their valuable guidance and technical discussions and for providing field data to this project.

Appendix: Technology Descriptions

I. Technology Description

The lifetime of power converters in PV systems suffers from intermittent renewable energy generation which is highly affected by instantaneous environmental conditions. The generated power or the mission profile usually has a large variation in a short duration [2]. Because of the inline structure, power converters will bear such variation of the real power from hundreds of kilowatts to several megawatts. This variation not only induces the surge and the slump of the power flow on the converter, which increases control requirements in both transient and steady states, but also arises a fast-varying power loss across the power converter. This varying power loss is rapidly aggregated inside of the power module in the form of heat which produces a severe thermal cycling in the power converter over the mission profile. Fig. 5 shows the overall framework of the proposed reliability assessment tool for PV inverter. Fig. 6 demonstrates the lifetime prediction procedure of semiconductor modules.

There are mainly four steps in the lifetime prediction process of the power semiconductor devices in the PV inverter applications. In the first step, loss model will be established from the input data, such as device characteristics, converter features. Then, in the second step, a junction temperature look-up table will be established with the thermal characteristics of the power semiconductor devices and the mission profiles of PV inverter applications. In step 3, the different thermal stress factors, such as junction temperature swing (ΔT_j) and mean junction temperature ($\overline{T}_{\mathrm{j}}$), are obtained from the junction temperature profiles by using Rainflow counting algorithm. Finally, the lifetime of the power semiconductor devices is obtained based on linear damage accumulation rule.

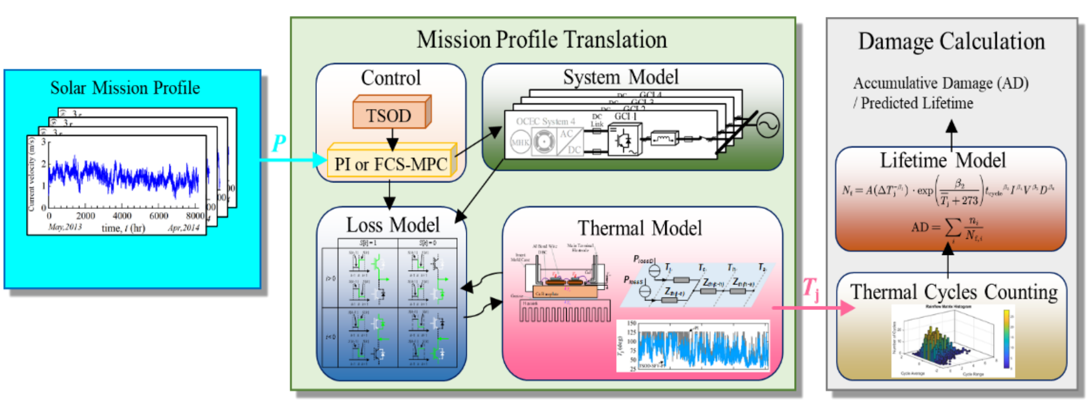


Fig. 5 Reliability assessment framework for utility PV system

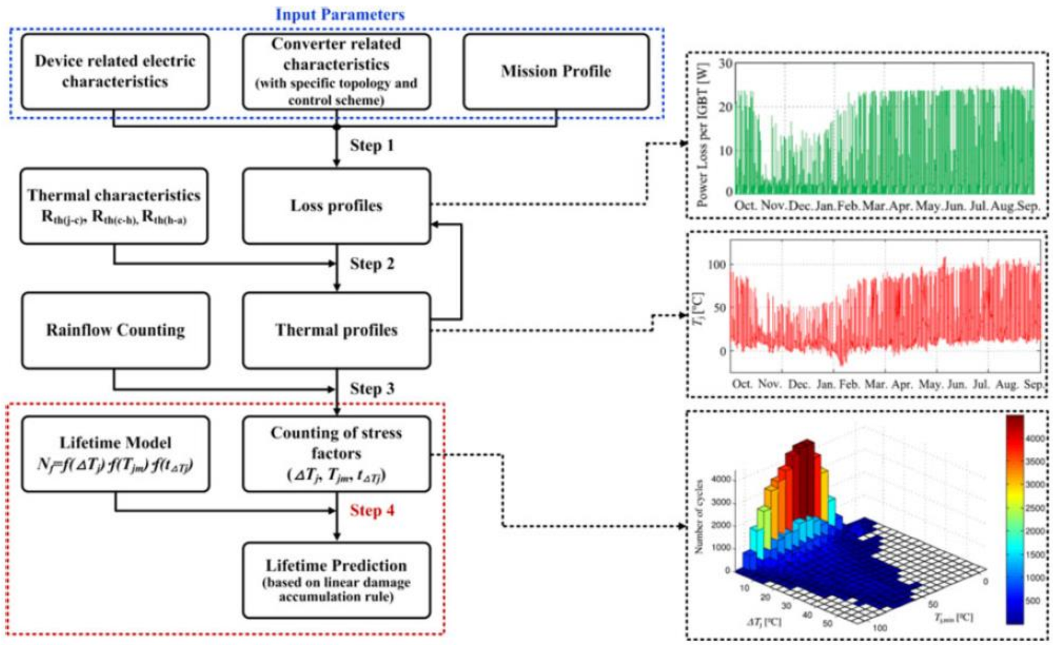


Fig. 6 Lifetime prediction procedure of IGBT modules in PV inverter applications [3].

A. Loss Model

An energy-based loss model of the power module has been established in the project. The power loss in power modules consists of two parts, the conduction loss and the switching loss, coming from the active switch (IGBT, MOSFET, etc.,) and the antiparallel diode, respectively. The conduction state and switching events for the half-bridge semiconductor devices against the current and the switching state are shown in Fig. 7, where it covers both upper and lower level switches. All dynamic actions are summarized for the hard switching on the half bridge.

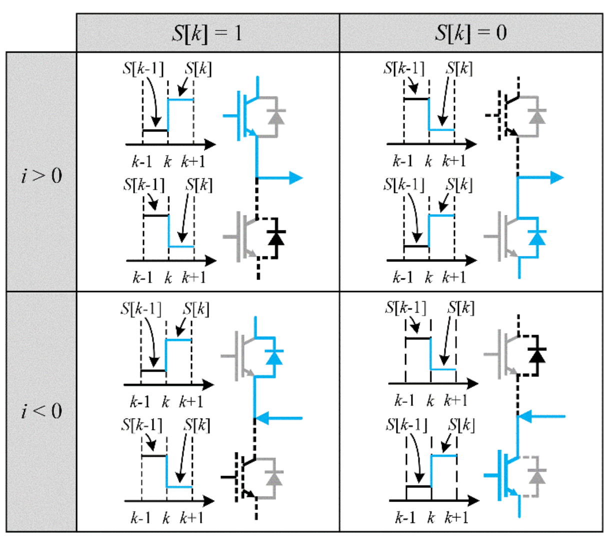


Fig. 7 Conduction states and switching events of the grid-tied inverter.

Switching loss in terms of the pulse energy happens when the semiconductor device turns on or off for the current commutation. This switching loss can be calculated by using the curve fitting and the behavioral loss model [4].

$$E_{switch} = \begin{cases} E_{on}(\boldsymbol{i}_{abc}, T_j) \cdot V_{CE} / V_{CE,rated}, & \triangle \boldsymbol{s}_{abc} = 1 \\ 0, & \triangle \boldsymbol{s}_{abc} = 0 \\ E_{off}(\boldsymbol{i}_{abc}, T_j) \cdot V_{CE} / V_{CE,rated}, & \triangle \boldsymbol{s}_{abc} = -1 \end{cases} \tag{1}$$

where the switching loss depends on the line current $\boldsymbol{i}_{abc}$ for each phase, the blocking voltage V_{CE} that is V_{DC} in the two-level converter, the junction temperature T_j and the successive switching states.

Conduction loss is the power dissipated on the semiconductor device during the device on-state. The conduction loss can be estimated in terms of the uniform energy [4].

$$E_{cond} = \begin{cases} T_s \cdot P_{cond} = T_s \cdot v_{CE,ON}(\boldsymbol{i}_{abc}, T_j) \cdot \boldsymbol{i}_{abc}, & \boldsymbol{s}_{abc}[k+1] = 1 \\ 0, & \boldsymbol{s}_{abc}[k+1] = 0 \end{cases} \tag{2}$$

where $v_{CE,ON}$ is the voltage drop on the semiconductor device during the on-state which is determined by curve fitting with the current $\boldsymbol{i}_{abc}$ and the junction temperature T_j.

Then, the total energy-based power loss for all bridges can be calculated in the sum of the switching loss and conduction loss.

$$\boldsymbol{E}_{abc}[k] = \sum_{a,b,c} (E_{switch}[k] + E_{cond}[k]) \tag{3}$$

It is noted that both switching loss and conduction loss vary with the junction temperature. The amount of power loss would change significantly over a broad range of the junction temperature, even if the converter is operating under the same power loading. Furthermore, the power loss would have feedback on the junction temperature, which complicates the system dynamic analysis. Therefore, the junction temperature of the power model has to be identified in the proposed control method.

B. Thermal Model

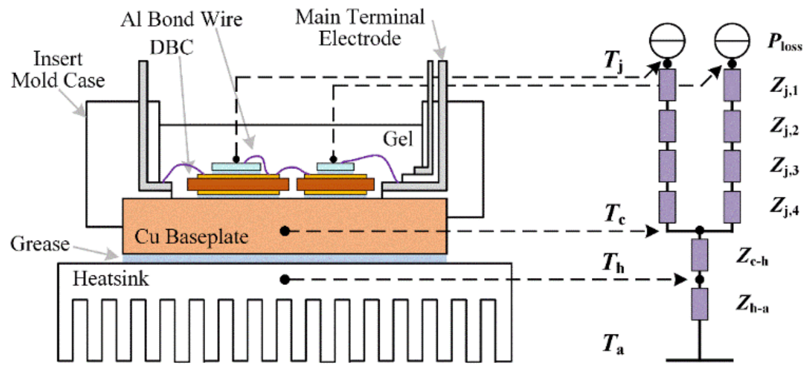


Fig. 8 Structure of the power module and its Foster-type RC thermal model

The junction temperature of the power module is retrieved through the real-time estimation in the most scenarios. The common way to estimate it is through a thermal resistance and capacitance (RC) model and a simple case or heatsink temperature feedback [5]. Fig. 8 shows a Foster-type RC model of power modules, including four layers of the junction-to-case thermal impedance, one layer of the case-to-heatsink thermal impedance and one layer of the heatsink-to-air thermal impedance. Each thermal impedance consists of one lumped RC which only infers the mathematical fitting of the temperature curve and has no physical meanings.

The parameters of the Foster-type RC thermal model are provided based on the transient thermal impedance curve in the datasheet provided by the manufacturer. Thermal resistance and thermal capacitance are used to obtain the frequency domain representation of the thermal impedance. And the junction temperature of the power module is estimated as

$$T_j = P_{loss} \sum_{i=1}^{n} Z_{j,i} + T_c = P_{loss} \sum_{i=1}^{n} \frac{R_i}{\tau_i s + 1} + T_c \tag{4}$$

where P_{loss} is the output from the loss model, R_i and τ_i are the thermal resistance and time constant for the layer i of thermal model, T_c is the case temperature feedback which can be measured through a low-bandwidth thermocouple or a linear thermal sensor.

C. Lifetime Prediction

The reliability assessment is conducted by accumulative damage and lifetime prediction. In this project, the Bayerer's IGBT lifetime model and Miner's rule are used to calculate the accumulative damage (AD) and the predicted lifetime based on the thermal cycles counting results [6].

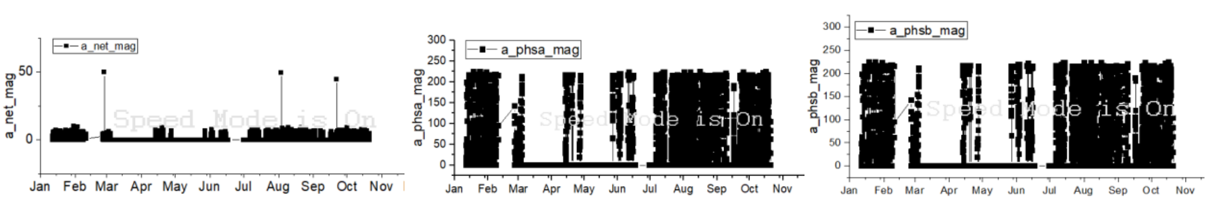
$$N_{\mathrm{f}} = A(\Delta T_{\mathrm{j}}^{-\beta_1}) \cdot \exp\left(\frac{\beta_2}{\overline{T}_{\mathrm{j}} + 273}\right) t_{\mathrm{cycle}}{}^{\beta_3} I^{\beta_4} V^{\beta_5} D^{\beta_6} \tag{5}$$

$$\mathrm{AD} = \sum_i \frac{n_i}{N_{\mathrm{f},i}} \tag{6}$$

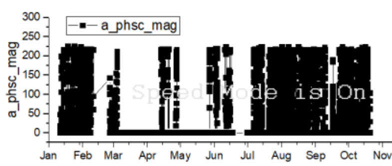
where N_{f} is defined as the number of cycles to failure for the specific thermal stress ($\overline{T}_{\mathrm{j}}$, ΔT_{j}, t_{cycle}), n_{i} is the number of this thermal stress, I is the current per wire bond, V is the voltage class, and D is the diameter of the bond wire. Parameters A and $\beta_{1\text{-}6}$ are device dependent constants according to the aging data provided by manufacturers [6]. The lifetime prediction is calculated by reciprocal of AD. When AD equals to one, the device is regarded to be fully failure out.

II. Reliability Accessment

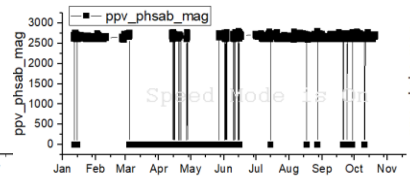
The first step of the reliability assessment is to determine the mission profiles of PV inverters. Fig. 9 shows the yearly PV system current, voltage, and weather data from Mount Holly PV system. Fig. 10 represents the active power and ambient temperature mission profiles. The power rand temperature data are utilized to the reliability assessment project. Due to some missing data in ambient temperature mission profiles, assumptions have been made in the ambient temperature mission profile to fill up some of the missing temperatures. For example, there is no data recording of the ambient temperature from Feb. 9 to Feb. 24, the adjacent weeks' ambient temperatures are added in these blank positions.



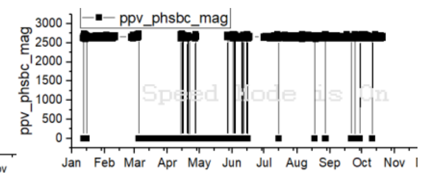
(a) a_net_mag: three-phase current (b) a_phsa_mag: Phase A current (c) a_phsb_mag: Phase B current



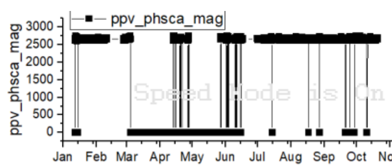
(d) a_phsc_mag: Phase C current



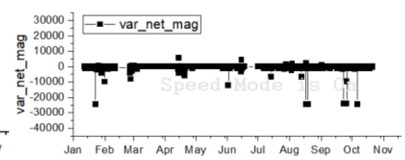
(e) ppv_phsab_mag: Vab



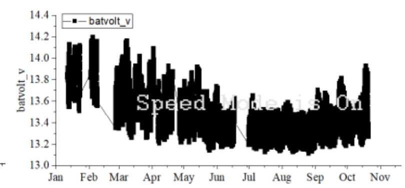
(f) ppv_phsbc_mag: Vbc



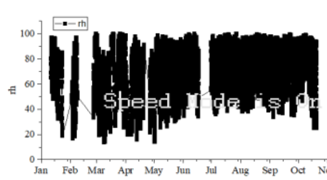
(g) ppv_phsca_mag: Vca



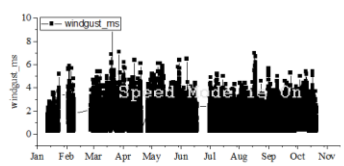
(h) var_net_mag: Reactive power



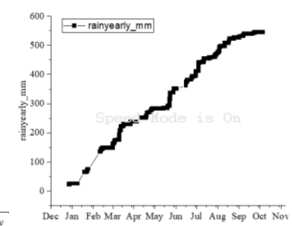
(i) batvolt_v: Battery voltage



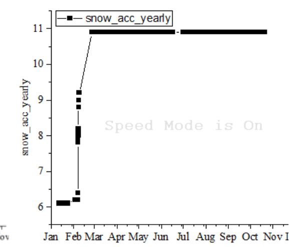
(j) rh



(k) windgust

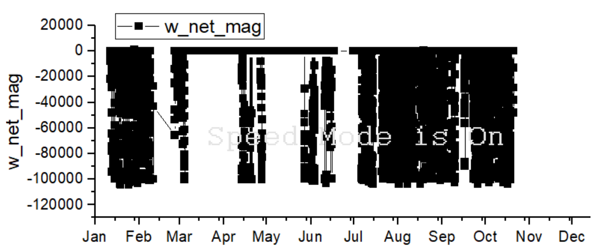


(l) rain

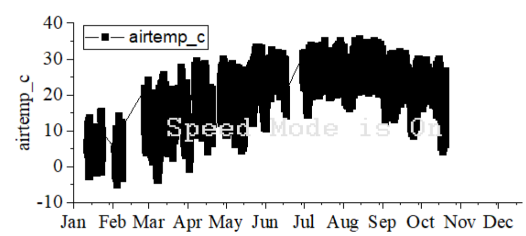


(m) snow

Fig. 9 Yearly mission profiles from Mount Holly PV system



(a) w_net_mag: Active power



(b) airtemp_c: ambient temperature

Fig. 10 Active power and ambient temperature mission profiles

Simulations are developed in MATLAB/Simulink and PLECS environment according to the PV grid-tied inverter topologies shown in Fig. 11. The active power shown in Fig. 10 (a) is no more than 110kW, and the range of ambient temperature shown in Fig. 10(b) is from -10°C to 40°C. Therefore, the simulation parameters are selected from Table I. The thermal model of Infineon FF300R12RT4 IGBT module including IGBT device and anti-parallel diode is applied in the simulation procedure. The mean junction temperature look-up tables of IGBT device and anti-parallel diode are obtained by simulating with different power loadings and ambient temperature. As illustrated in Table II and III, the simulation results cover all the operating conditions of PV inverter in this project.

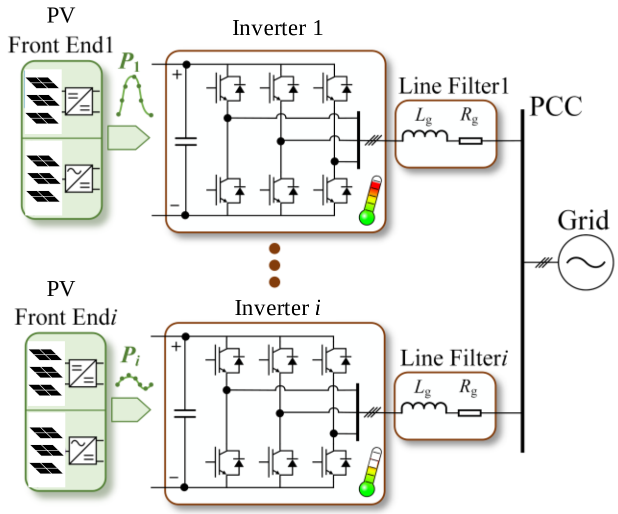


Fig. 11 PV grid-tied inverter topologies.

TABLE I SIMULATION PARAMETERS

Rated power P	110kW
Rated DC bus voltage V_{dc}	800V
Grid frequency f	60Hz
Rated AC grid voltage $\boldsymbol{e}_{abc}$ (V_{LN}/V_{LL})	160/277V
Line current $\boldsymbol{i}_{abc}$ (RMS)	230A
Line inductance L_g	3mH
DC bus capacitance C	940µF
IGBT module	Infineon FF300R12RT4

TABLE II JUNCTION TEMPERATURE OF IGBT LOOK-UP TABLE

T_a / P_{load}	-10°C	-5°C	0°C	5°C	10°C	15°C	20°C	25°C	30°C	35°C	40°C
0kW	-10	-5	0	5	10	15	20	25	30	35	40
10kW	-3.5	1.6	6.8	11.9	17.0	22.2	27.3	32.4	37.6	42.7	47.9
20kW	2.5	7.8	13.0	18.3	23.5	28.8	34.0	39.3	44.5	49.8	55.0
30kW	8.2	13.5	18.9	24.2	29.6	34.9	40.1	45.6	51.0	56.4	61.8
40kW	14.0	19.4	24.9	30.6	35.8	41.2	46.7	52.2	57.7	63.2	68.8
50kW	20.3	25.9	31.5	37.0	42.6	48.1	53.8	59.4	65.0	70.7	76.4
60kW	26.8	32.5	38.2	43.8	49.5	55.3	61.1	66.8	72.6	78.5	84.4
70kW	33.9	39.7	45.5	51.4	57.3	63.2	69.2	75.1	81.2	87.2	93.3

80kW	41.4	47.3	53.3	59.4	65.4	71.5	77.7	83.9	90.2	96.5	102.9
90kW	49.3	55.5	61.7	67.9	74.3	80.7	87.1	93.6	101.1	106.9	113.6
100kW	51.1	57.2	63.2	69.5	75.8	82.2	88.5	95.0	101.5	108.4	114.9
110kW	52.7	58.9	65.1	71.3	77.6	84.0	90.3	96.7	103.3	109.9	116.5

TABLE III JUNCTION TEMPERATURE OF DIODE LOOK-UP TABLE

T_a \ P_{load}	-10°C	-5°C	0°C	5°C	10°C	15°C	20°C	25°C	30°C	35°C	40°C
0kW	-10	-5	0	5	10	15	20	25	30	35	40
10kW	-4.1	1.0	6.3	11.5	16.7	21.8	27.0	32.2	37.4	42.6	47.8
20kW	1.4	6.8	12.2	17.5	22.9	28.3	33.7	39.0	44.4	49.8	55.2
30kW	6.5	12.0	17.5	23.3	28.5	34.1	39.6	45.1	50.6	56.1	61.7
40kW	11.5	17.2	22.8	28.5	34.1	39.8	45.5	51.1	56.8	62.4	61.2
50kW	16.9	22.7	28.5	34.3	40.5	45.8	51.6	57.4	63.3	69.1	74.9
60kW	22.3	28.2	34.1	40.0	45.9	51.9	57.8	63.8	69.7	75.7	81.7
70kW	28.1	34.1	40.2	46.2	52.3	58.4	64.5	70.6	76.7	82.9	89.0
80kW	34.0	40.1	46.4	52.6	58.8	65.0	71.3	77.6	83.9	90.2	96.6
90kW	40.2	46.6	52.9	59.3	65.7	72.2	78.6	85.1	91.6	98.1	104.7
100kW	39.9	46.2	52.3	58.6	64.9	71.2	77.7	83.9	90.2	96.7	103.2
110kW	39.9	46.1	52.2	58.2	64.5	70.5	76.9	83.0	89.3	95.7	102.0

After the simulation, junction temperature swing ΔT_j and mean junction temperature T_{jmean} are obtained by using Rainflow counting method, and the results are illustrated in Fig. 12. The mean junction temperature mission profiles of IGBT and anti-parallel diode is from January of 2021 to October of 2021. The rainflow matrix histogram shows the cycle counts of corresponding thermal stress (The mean junction temperature and the junction temperature swing).

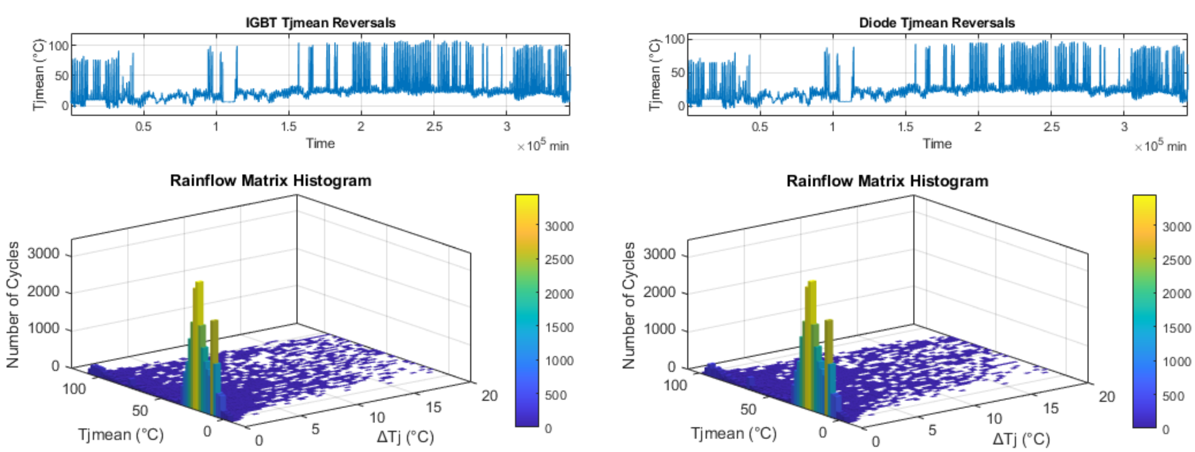
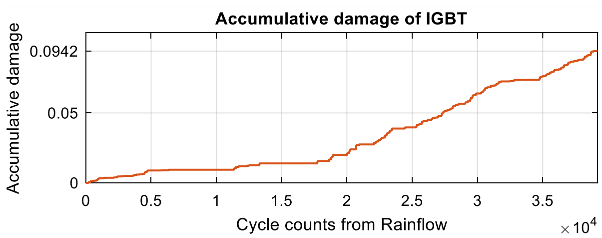


Fig. 12 Rainflow counting results and the mean junction temperature profiles.

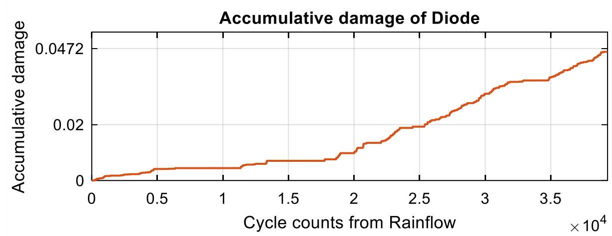
TABLE IV SIMULATION PARAMETERS

β_1	-4.416
β_2	1285
β_3	-0.463
β_4	-0.716
β_5	-0.761
β_6	-0.19
t_{cycle}	400
V	1200
D	$150*10^{-5}$
A	$9.34*10^{14}$

In the final step, lifetime prediction is conducted by equations (5) and (6) in the MATLAB/Simulink environment. The simulation parameters are presented in Table IV [6].



(a) Accumulative damage of IGBT



(b) Accumulative damage of Diode

Fig. 13 Accumulative damage results.

Fig. 13 shows the estimated accumulative damage results. It can be seen from Fig. 10(a) that the accumulative damage of IGBT is 0.0942 (from 10 months of accumulation), and its corresponding lifetime is about 8.84 years. Similarly, the accumulative damage of diode is 0.0472 (From 10 months accumulation) in Fig. 10(b), and its corresponding lifetime is about 17.6 years. Please note that these parameters are inverter specific, so for PV inverters from different vendors the parameters are related to the semiconductor specs, PV inverter topology and rating. The team currently does not have all the specs for the PV inverters in the Mount Holly system, so the results are representative and will be refined once we know more about the detailed design and specifications from the inverter vendor.

In summary, the framework of the proposed reliability assessment tool for PV inverters by utilizing the PV system reliability-related information (such as energy mission profile, semiconductor temperature and stress, temperature, etc.) to quantify and compare the reliabilities for PV inverter from different vendors with different control methods. The lifetime prediction for the PV inverter leads to a better understanding of number of thermal cycles to failure. And the remaining lifetime of main components (IGBT, Diode, MOSFET, etc.,) can be estimated forewarningly. Based on this reliability assessment platform, predictive maintenance and reliability-oriented control and operation methods, such as active thermal control, can be implemented to extend the lifetime of PV inverters.

In Phase 2 of the project, the team plans to evaluate the PV inverter reliabilities for different control and operation strategies and provide lifetime extension recommendations based on the case study of Mount Holly PV system. The team will also investigate arc safety and fire resilience for PV and utility energy storage systems to support the development of safe and reliable utility PV and energy storage systems.

III. REFERENCE

[1] Jordan D.C, Marion B., Deline C. Barnes T., Bolinger M., PV field reliability status—Analysis of 100 000 solar systems, Progress in PV 28 (8), 2020, 739 – 754.

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