Integrated AC Power Cycling Platform with Automated Characterization for T-Type Power Module in Photovoltaic Applications

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***Abstract*—The reliability of power electronic modules can be assessed by stress testing the devices and characterizing them. AC power cycling provides the platform to stress the devices in exact field conditions. This paper exhibits the existing state of the art in AC power cycling test benches and demonstrates the uniqueness of the newly developed test bench for PV inverter application. Characterizing is an essential part of the reliability model development. It becomes a challenge to characterize the T-type IGBT modules and visualize results because they are complex and time-consuming, especially for power modules based on a non-phase-leg configuration, such as T-type circuits, widely applied for PV inverters. This paper focuses on stress testing with a built-in characterization platform for easy and time-efficient characterization of T-type IGBT modules. First, state of the art in AC power cycling is presented. Second, the unique features of the stress testing platform are shown. Finally, the test result has been presented for the newly built platform.**

Keywords— AC power cycling, characterization, T-type neutral point clamped IGBT, reliability, static and dynamic characterization, automation.

I. Introduction

T-type power modules are a popular choice in Photovoltaic (PV) applications. According to PV power plant operators, the power electronics converter is responsible for most operation and maintenance (O&M) issues, ranging from 43% to 70% of service calls [1]. This emphasizes the critical need to assess power electronics' reliability in PV plants, as they can act as a bottleneck. Conducting a quantitative analysis of power module degradation can provide valuable insights into failure mechanisms and allow for more accurate lifetime assessment models.

Power module characterization has been extensively investigated in this paper, especially for a typical phase-leg configuration [2-7]. The contribution of this paper includes: (1) a newly developed AC power cycling platform for T-type IGBT modules for PV applications, (2) unique methodology to stress test the IGBT power modules in a similar field application setup, and, (3) integration of an automated characterization platform to perform static and dynamic characterization in the fastest possible way with experimental verification.

The paper is organized as follows: Section II presents the existing AC cycling platform's literature review and identifies the proposed platform's unique approaches compared to the existing state of the art. Section III introduces the newly designed AC power cycling platform which has unique techniques to increase the rate of change of junction temperautre as well as mean junction temperature. The unique considerations of the platform will be described in Section IV. Section V presents the automated integration of static and dynamic characterization platforms. Section VI illustrates the results received from the power cycling platform, and VII concludes the study.

II. Literature Review

AC power cycling platform has been a popular choice to stress test the power semiconductor modules as it provides stress patterns closer to the actual application [2-12]. Many state-of-the-art AC power cycling platforms have previously been developed with different topologies [13-14]. The design criteria for the existing AC power cycling platforms versus the uniqueness of the proposed platform are presented in Table I.

As shown in Table I, the main features of the platforms are categorized by topology, temperature control variables, temperature measurements, temperature control objectives, and collected data for reliability modeling. The comparison and research gap are presented in terms of the existing state of the art platforms and the features of the new proposed platform, which is also a very practical evaluation in PV applications.

TABLE I. STATE OF THE ART IN AC POWER CYCLING TEST BENCHES

Features	Comparison and research gap	
	State-of- the-Art platforms	***Proposed Platform***
Topology	• H-bridge two-level [2,12] • Three-phase two levels [3-11]	• T-type three-level, three-phase
Temperature control variable(s)	• The magnitude of the output current and voltage, power factor, switching frequency, and phase output frequency [2-12] • Increase of gate loop inductance[8]	• Beyond traditional means, programmable driving voltage control for active loss management
Temperature measurement	• Model-based [2] • IR camera and TSEPs [3-12]	• Hybrid sense + model method
Temperature control objective(s)	• Mean junction temperature (T_j) by ambient temperature control [2-12] • Junction temperature variation (ΔT_j) [3-6,8-9] • Rate of change of junction temperature ($\frac{dT_j}{dt}$) [10]	• Ambient temperature range from -20 ºC to 60 ºC for the PV application by dedicated mechanical design to ensure a condensation-free environment • Enhanced ΔT_j and flexible $\Delta T_j/dt$ regulation by the programmable driving voltage
Collected data for reliability modeling	• Static characterization [4-7] • Dynamic characterization [8]	• Integrated automated static and dynamic characterization for key parameters' degradation tracking and modeling

Based on the T-type three-level three phase inverter platform, the temperature has been measured through Negative Temperature Coefficient thermistor (NTC), under the range of -20°C to 60°C in PV application. For fast and time-efficient degradation experiment, the tunable V_{CC} of gate driver voltage has been designed for junction temperature control. It makes the realization very visible and programmable. Especially, to enable complete reliability testing, the designed characterization platform incorporates an automated system for static and dynamic characterization, enabling the characterization of twelve devices across three phases to track the change in their parameters over the stress testing period.

III. Overview Of The AC Power Cycling Platform

The proposed AC power cycling platform has been developed considering the complexity of T-type-based power semiconductor modules. The DC voltage is coupled for a three-phase power cycling platform. It recycles the DC supply, and the supply voltage only provides for the loss in the system. The current is sensed in the system to regulate junction temperature. dq frame control strategy has been implemented in this power cycling platform[13-14]. The thermal impedance model is employed in conjunction with the sensed temperature based on the module's NTC to estimate the device's junction temperature by thermal model[2]. The automated dynamic characterization platform is built into the system, and for the static characterization platform, the devices are connected with the Agilent B1505 curve tracer with an in-house assembled interface board. The AC power cycling test platform overview is presented in Fig. 1.

The load devices house the same power module devices used in the test module, which is a T-type neutral point clamped topology-based model rated for 1200V IGBT. DC link capacitor is used for the voltage balancing. The junction temperature is estimated using the NTC module built into the devices. A user can set a junction temperature swing profile to stress test the control devices. The feedback loop would constantly output the junction temperature and control the gate voltage along with the mechanical integration to ensure the desired junction temperature.

IV. Unique Considerations Of AC Power Cycling

The proposed AC power cycling platform has been used to stress the devices in terms of junction temperature, and therefore, the junction temperature is the feedback into the control system to assess the current flowing through it. In order to swing the junction temperature profile corresponding to time, the tunable V_{CC} function has been used. In terms of controls, the slope of the rise of junction temperature and mechanical integration has been used to regulate the mean temperature of the devices. As they are three-phase symmetrical AC outputs, the device degradation has been thought to be uniform for all the devices. The unique features implemented for junction temperature regulation are described in the following parts.

A. Enhanced ΔT_j and flexible dT_j/dt regulation by tunable V_{CC})

The tunable V_{CC} function with a customizable rise and fall rate has been integrated into the platform. The speed at which an IGBT turns on and off is directly proportional to the gate current [16]. The gate current can be calculated using the equation.

$$I_G = \frac{V_{CC}+V_{EE}}{R_G} \tag{1}$$

From (1), it can be seen that to change the gate current, the value of the gate resistor (R_G) or the supply voltage (V_{CC} or V_{EE}) must be changed. Previous research has shown that changes in V_{CC} have a more significant impact on switching losses and switching speed than changes in V_{EE} [16]. As shown in Fig. 2, the V_{CC} has been changed by digital resistor and controlled by DSP code. When the junction temperature is not achieved from NTC feedback, the turnable V_{CC} code will work to change the power supply of gate driver.

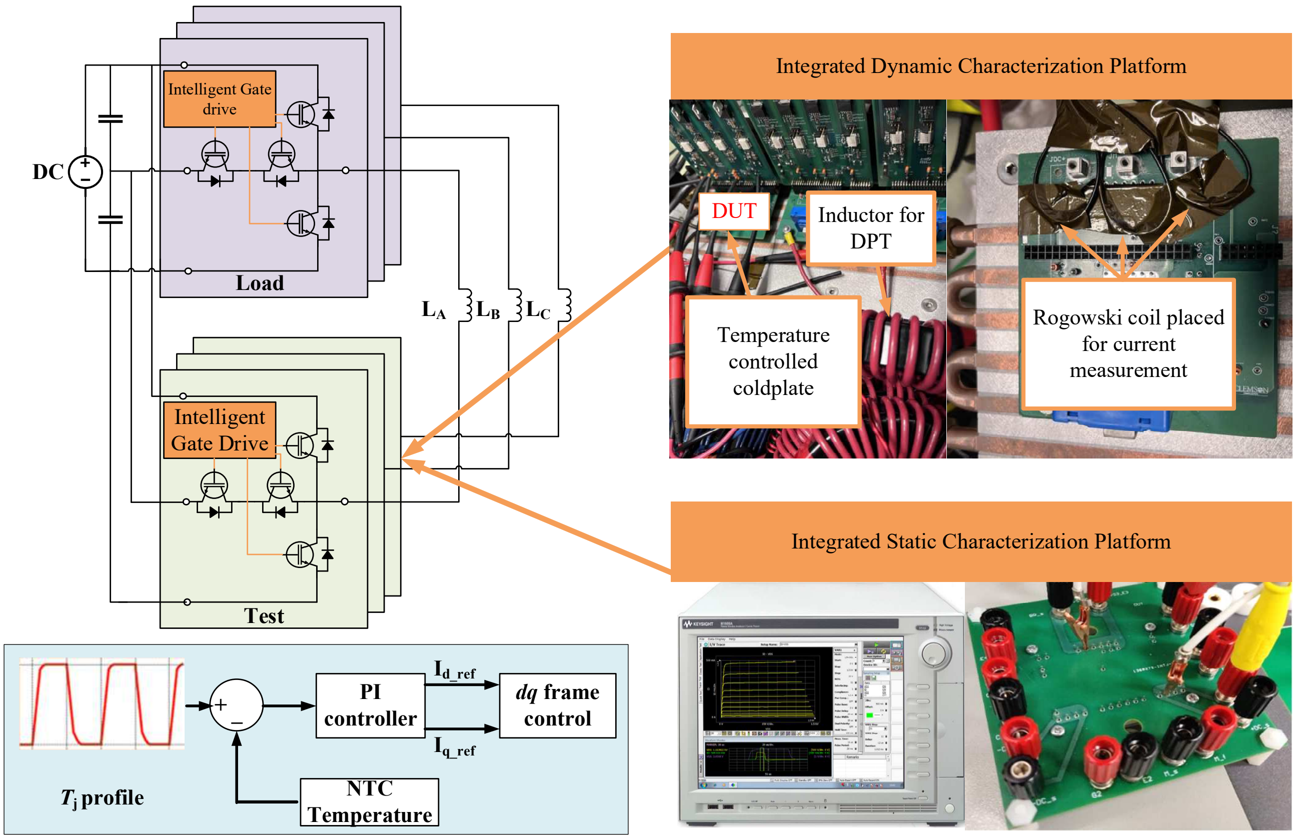


Fig. 1. Proposed AC power cycling platform

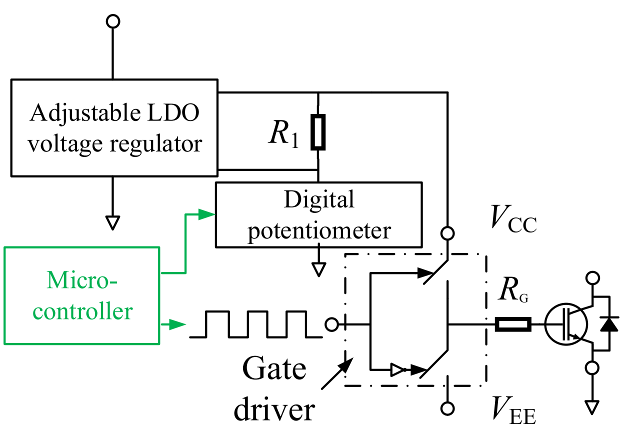


Fig. 2. Tunable V_{cc} operation

Therefore, the supply voltage could be used to control switching losses and regulate junction temperature; both dT_j/dt and ΔT_j. In this proposed power cycling platform, the V_{CC} can be changed dynamically to achieve the set junction temperature profile.

B. Mean T_j regulation by chiller with mechanical integration:

The power cycling platform is connected to a chiller that operates in the temperature range of -20°C to 60°C, relevant to the operating environment conditions of the PV inverters. The cold plates housing the devices are connected to a chiller. An enclosure is built to isolate the devices from the outside environment and controllable ambient constant temperature. Moreover the nitrogen gas can be regulated and the real time live images can be monitored using camera.

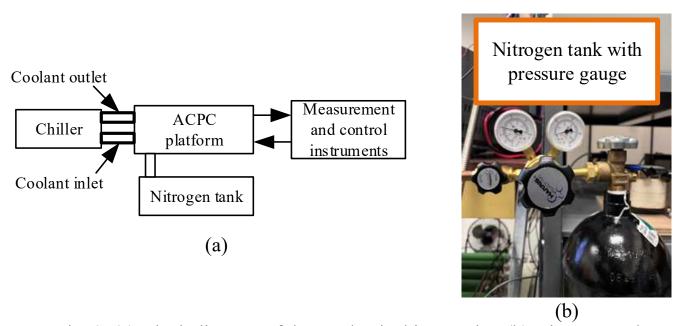


Fig. 3. (a) Block diagram of the mechanical integration (b) Nitrogen tank

Sub-zero temperatures are known to cause vapors and condensations in the pipes and cold plates. Nitrogen gas is introduced to flush out the air from the enclosure, allowing a condensation-free environment. The block diagram for the mechanical integration has been presented in Fig. 3(a). The nitrogen tank is placed outside the enclosure, as seen in Fig. 3(b). Real-time condensation mitigation inside the enclosure versus water droplets outside can be observed in Fig. 4.

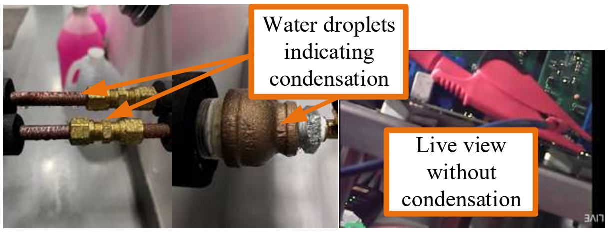


Fig. 4. Real-time condensation mitigation inside the power cycling platform

V. INTEGRATED AUTOMATED CHARACRACTERIZATION

Typically, the T-type power modules' static and dynamic characterization is complex, time-consuming, and requires special attention. In order to efficiently characterize the devices, automation can be integrated into the power cycling platform. The research presented in [17] discusses the automation technique that can be implemented for T-type modules with special consideration.

A. Static Characterization

The automated static characterization of four devices in a single phase can be done with a single button click on this platform. The basic configuration presented in [17] is used as the foundation to develop a relay configuration that can be controlled using a microcontroller. With the help of a Human Machine Interface (HMI), when a testing trigger is generated, it sends the signal to control the relay for the specified DUT. After selecting the device, it would send a command to the curve tracer which would generate a test signal and collect the data for the set test. This design eliminates the change of Kelvin terminals manually. Moreover sequentially selects DUT and retrieves the results. Apart from collecting the testing results, the HMI would plot them and track the changes in device parameters over the degradation cycle.

T1 and *T4*, device characterization tests are conducted similarly to phase leg tests. As *T2* and *T3* devices are connected in the middle phase and can handle lower voltages than *T1* and *T4* devices, the characterization of these devices needs special attention. Apart from that, the current handling ability for the "*C*" terminal is low compared to other terminals. Therefore conventional characterization is tricky for *T2* and *T3*, and a new characterization technique is necessary.

IGBT *T2* characterization is done by keeping the gate and emitter terminals as usual, but the curve tracer's "Collector Force" terminal is moved to the emitter pin of IGBT *T3*, and the "Collector Sense" terminal is connected with the collector pin or "*C*" pin of the *T2* device as shown in Fig. 6. This ensures the "*C*" pin remains only as a measurement terminal and won't handle the higher voltage, and the forward diode drop in *T3* can be excluded from the measurement results. This configuration makes testing the output characteristics much more accurate and reliable. A similar setup is also used for the measurement of the output characteristics of *T3*.

The forward voltage characteristics of the diode associated with *T2* can be measured by shorting the gate and emitter pin of the DUTs and turning on the *T3* device. The collector and emitter terminals remain the same as the previous configuration; the only change would be the DUT IGBT device off and the other one on. Silimar configuration can be implemented for *T3* devices.

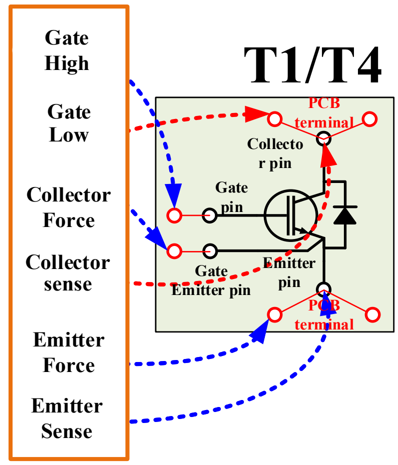


Fig. 5. Static characterization configuration of T1 and T4 devices [17]

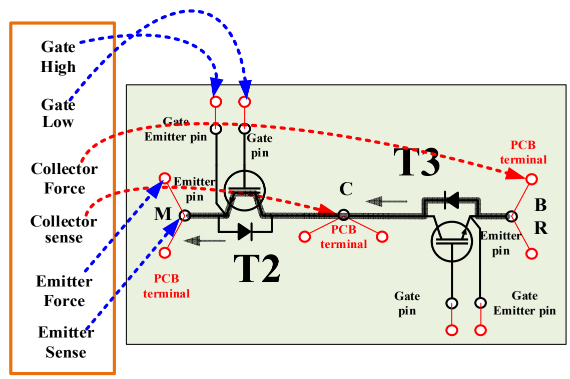
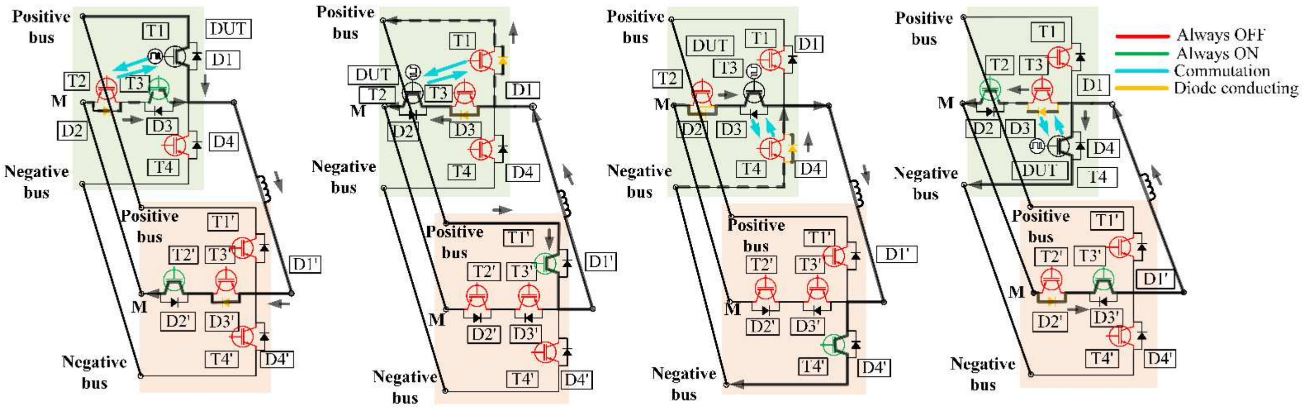


Fig. 6. Static characterization configuration of T2 and T3 devices [17]

B. Dynamic Characterization

Dynamic characterization can be performed by using the technique provided in [17] for all the test devices. In this testing, the DUT is the test device module, and the load device module connected through an inductor is selected as the relay. The double pulse duration is automatically adjusted and implemented for the devices according to the current rating provided by the user. The measurements are done through an oscilloscope that sets the resolution and triggers according with the generated pulses.



(a) (b) (c) (d)

Fig. 7. Dynamic characterization configuration of (a) T1 (b) T2 (c) T3 (d) T4 devices [17]

As there are no hardware connection changes, it can instantly characterize all the devices in each phase and generate the switching data Instantaneously. The gate signal and the measurement being automated reduce time and human error. Although the dynamic characterization is automated to characterize all four devices, special considerations are given to eliminate open circuit faults.

VI. Experimental Results

A unique AC power cycling platform has been prototyped, incorporating distinct design considerations with integrated implementations. A MATLAB-based HMI was developed to control the AC power cycling platform.

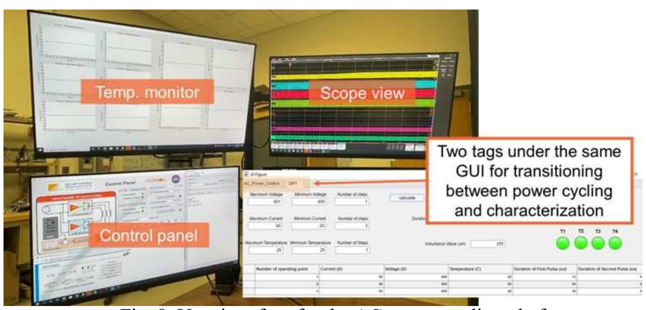


Fig. 8. User interface for the AC power cycling platform

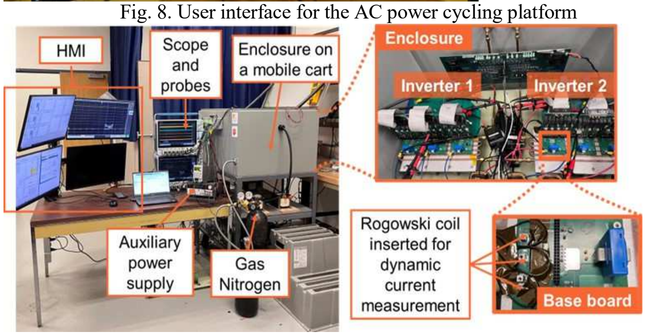


Fig. 9. Hardware setup of the power cycling platform

The HMI controls all the operations and plots the real-time temperature observed from the NTC and the cold plates for junction temperature estimation. The HMI controls the microcontroller, oscilloscope, high-voltage power supply, and temperature-controlled chiller to conduct the power cycling and the characterization test, as seen in Fig. 8. The HMI has an easy, user-friendly feature to transition between the power cycling and characterization tests. Fig. 9 presents the entire test setup. The enclosure houses the PCB assembly for both inverters and also the microcontroller. An insulated cutout was used for the measurement probe, and auxiliary power cables were incoming and outgoing. The in-house designed baseboard houses the T-type modules for the platform, which are attached to the chiller-integrated cold plates. The base board terminals are designed to attach the Rogowski coil for current measurement during the dynamic characterization testing.

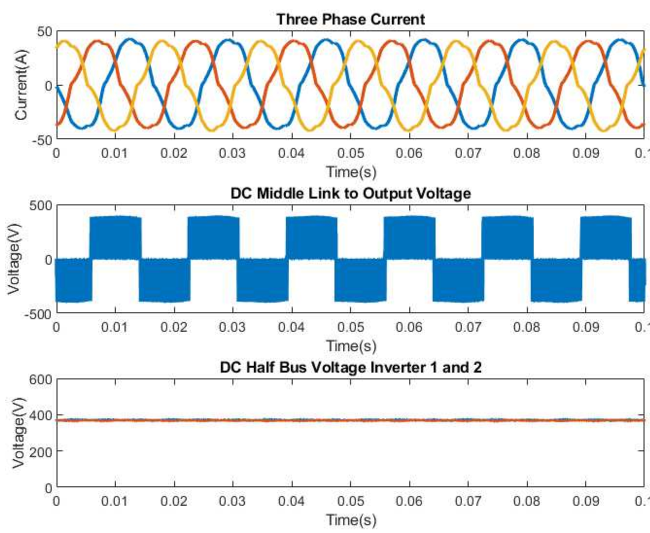
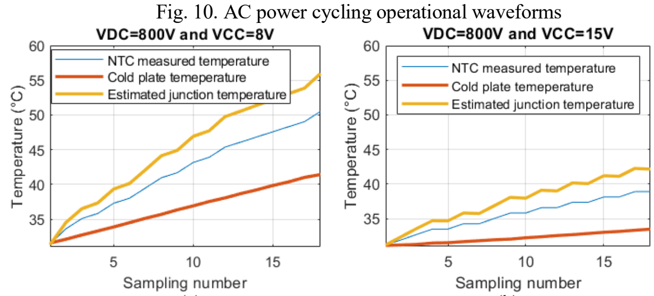


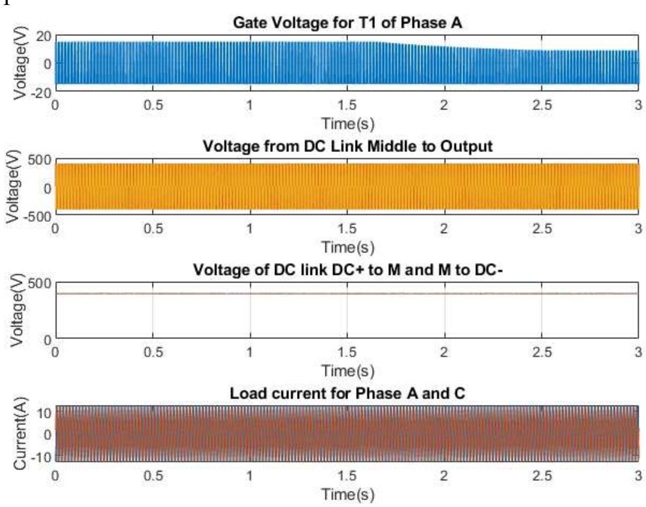
Fig. 10. AC power cycling operational waveforms



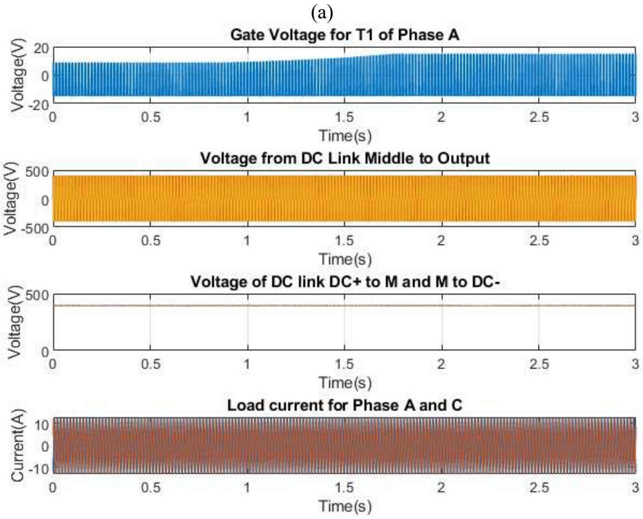
(a) (b)

Fig. 11. Junction temperature change in 15 V Vcc and 8 V Vcc

These Rogowski coils have high bandwidth to measure the current transients associated with switching of the devices. Fig. 10 presents the operation of AC power cycling platform output waveforms. In terms of three-phase current, DC middle link to the output voltage and the common DC half link bus voltage measured at 400V. As tunable V_{CC} for dynamic junction temperature control and mechanical integration for mean temperature control has been introduced as one of the prominent features of this AC power cycling platform, Fig. 11 presents the change in estimated junction temperature corresponding to the change in V_{CC}. Thermocouples were connected to the cold plates to measure the temperature. At 8V V_{CC} from Fig. 11(a), it can be seen that the temperature change is great, whereas, at 15 V $V_{CC,}$ the change in temperature is lower as intended. During this time, the chiller was kept off, and cold plates were used to measure the temperature only as they housed the devices firmly with a non-conductive thermal pad.



(a)



(b)

Fig. 12. Dynamic tunable Vcc operating (a) 15 to 8 V and (b) 8 V to 15 V

Fig. 12 presents the change in tunable Vcc during operation with constant load current, and voltage. As the V_{CC} is changed, they do not impact the operation of the inverter but introduce losses in the system.

VII. Conclusion

The paper highlighted the newly developed AC power cycling platform that can be used to stress test the IGBT modules primarily used in PV applications. The design criteria of AC power cycling platforms have been presented with their unique capability to regulate dTj/dt and ΔTj using the tunable V_{CC} function along with mechanical integration. Furthermore, results have been presented to demonstrate the platform's working capabilities. Moreover, as the reliability model is significant to understand reliability, an integrated characterization platform was designed to reduce complexity and reduce the time taken to characterize each device. Other widely used power modules' stress testing and characterization platform can be developed by implementing the AC power cycling test bench.

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