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Evaluation of Photovoltaic Inverters Under Balanced and Unbalanced Voltage Phase Angle Jump Conditions

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Abstract **– In 2016, 1.2 GW of photovoltaic (PV) power tripped off in California during the "Blue Cut Fire" when PV inverters miscalculated the grid frequency during a line-to-line fault. In response, the 2018 edition of the IEEE 1547 interconnection standard was updated to mandate distributed energy resource (DER) devices "ride-through" voltage phase angle changes that appear during faults. This new requirement is designed to ensure bulk-system stability is not impacted by emergent DER misbehaviors triggered by local fault events. Transitory DER behaviors under phase changes may still significantly impact grid operations, so it is necessary to quantify the DER response to both balanced and unbalanced voltage phase angle shifts. To achieve this, two PV inverters were subjected to balanced and unbalanced phase jump changes defined in the IEEE 1547.1-2020 test protocol to validate compliance to IEEE 1547. Experimental results show that one DER inverter was compliant to IEEE 1547 and its "momentary cessation" behavior produced stable power system response. However, the other PV inverter failed the IEEE 1547.1 compliance test and tripped off during some of the phase jump experiments.**

Keywords – photovoltaic inverter, hardware-in-the-loop, IEEE Std 1547.1, phase jump, ride-through.

I. Introduction

With the increasing numbers of clean energy generators interconnected to the grid, interactions between renewable energy sources and the power system are becoming more critical to system reliability. Distributed energy resources (DERs) help reduce the dependency on conventional fossil fuel generation and reduce harmful carbon dioxide (CO_2) emissions. Despite their benefits, these systems can have unforeseen impacts on the electrical grid. On October 16th, 2016, the "Blue Cut Fire" incident caused a loss of 1.2 GW of photovoltaic (PV) power generation in the Southern region of California [1]. This loss of PV generation was caused by a miscalculation of frequency in the DER equipment due to a phase jump event created by a fault at the transmission level. Due to incidents such as this, the DER and power system community worked together to define acceptable electrical behavior (in IEEE Std 1547-2018 interconnection standard [2]) along with strict test protocols to ensure compliance (in IEEE Std 1547.1-2020 [3]). While the transmission system fault in the "Blue Cut Fire" had widespread impact, any fault on the system will cause a phase jump seen by nearby DER due to the change in the X/R ratio of the system with the fault resistance. Characterization of DER inverter response to fault scenarios has also become critical because modeling DER response to frequency changes, phase jumps, and voltage deviations are important to capture the power system dynamics under fault conditions [4].

In this work, a Power Hardware-in-the-Loop (PHIL) setup was used to evaluate DER device compliance with the IEEE Std 1547.1-2020 phase-angle change ride-through (PCRT) test sequence in a controlled laboratory environment [5]. These results were used to analyze the response of the PV inverters' phase locked loops (PLLs) to both balanced and unbalanced phase angle changes. Under distorted grid voltage conditions, PLLs are susceptible to miscalculations, which could cause PV inverters to trip [6]. PV inverter PCRT capabilities were studied to help provide insight into their performance when subjected to phase jump changes and to identify potential improvements that can be implemented to increase reliability [7].

This paper evaluates the performance of two PV inverters under IEEE Std 1547.1-2020 phase jump test sequences. Experimental results were obtained by subjecting an IEEE Std 1547-2018 PCRT-compliant PV inverter to unbalanced and balanced phase-jump conditions. A comparison is then made between these results and phase jump test results obtained from a PV inverter that is not compliant with the PCRT test sequence within IEEE Std 1547-2018.

II. Real-Time Power Hardware-in-the-Loop Setup

The use of PHIL enables a hardware component to be interfaced into a Real-Time (RT) simulation environment [8]. Fig. 1 illustrates an example of a RT PHIL setup with a hardware PV inverter as the device under test (DUT) [9]. This approach enables testing the interactions of a physical PV inverter under a variety of case scenarios such as fault conditions [10]. The performed RT PHIL tests subject a physical PV inverter to different types of voltage phase shifts based on IEEE 1547.1 standards.

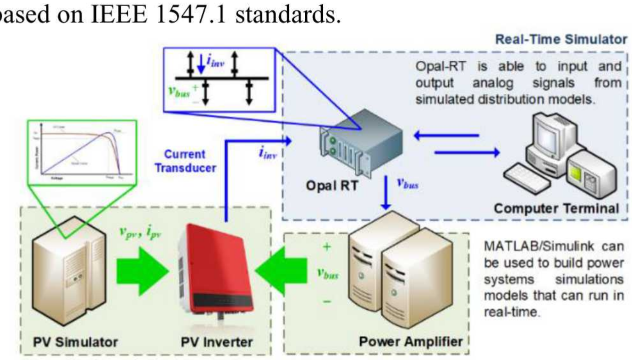

Fig. 1. Diagram of the Real-Time Power Hardware-in-the-Loop Setup.

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In the PHIL setup, three-phase voltage signals were generated utilizing a MATLAB/Simulink simulation model that could have the jump time, duration, and magnitudes adjusted for each of the phases. These parameters were configured using the open-source System Validation Platform (SVP) by communicating the simulation parameters to the RT-LAB simulation using the RT-LAB python API [11-13]. This implementation approach leveraged the work of a team of research laboratories who are creating test scripts to facilitate PV inverter compliance testing to the IEEE 1547.1 standard [14-15]. Scaled analog voltage signals were sent to a power amplifier from an OPAL-RT RT simulator to create the grid phase jump behavior. The DC power for the PV inverter was provided by a programable PV simulator. Current and voltage responses from the PV inverter were stored in MATLAB/Simulink and in the SVPs CSV files.

III. Experimental Results

The IEEE Std 1547.1-2020 phase jump angle test was developed to help determine if a PV inverter could perform a voltage phase angle "ride-through." The experimental tests deployed a sequence of phase angle changes. There was a total of five sequence combinations that were performed for this test. Three of these tests involved phase jumps on only one of the phase angles, while the remaining two changed all phase angles at the same time. The shift on one of the phases represents the response of the system to an unbalanced single-line-to-ground fault, and shifting all phases represents the response to a balanced three-phase-to-ground fault. Moreover, the duration of these events also plays a role in the PV inverter performance. Table I summarizes the different sequences for the IEEE Std 1547.1-2020 phase jump test procedure. In order to comply to with PCRT test sequence in IEEE Std 1547.1-2020, the PV inverter performance must adhere to criteria 5.5.6.4, which specifies the minimum time in which the DUT must respond and the RMS current percentage it must reach. For the balanced phase jump tests, (*A-E-A* and *A-F-A*), the duration of the event is significantly longer than for unbalanced phase jumps (*A-B-A*, *A-C-A* and *A-D-A*), as specified by IEEE 1547.1.

Table I.
IEEE 1547.1 Phase Jump Test Procedure

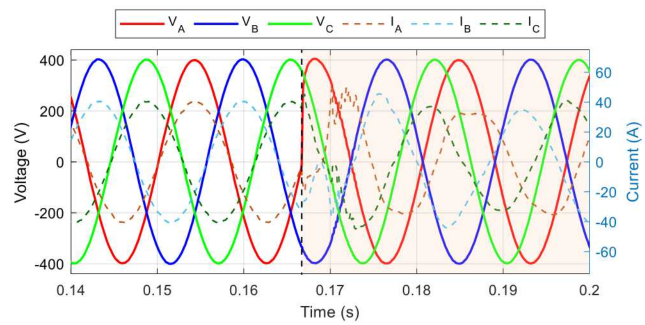
Test	Phase A	Phase B	Phase C	Time (s)
A	0˚	-120˚	120˚	30 - 40
B	60˚	-120˚	120˚	0.32 - 0.50
C	0˚	-120˚	180˚	0.32 - 0.50
D	0˚	- 60˚	120˚	0.32 - 0.50
E	20˚	-100˚	140˚	55-65
F	-20˚	-140˚	100˚	55-65

A. *IEEE 1547.1-2020 PCRT Compliant PV Inverter*

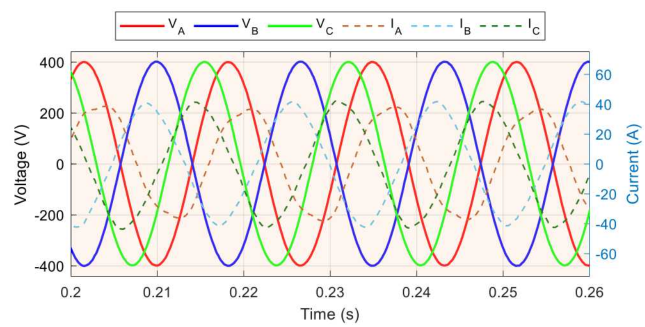
For these tests, the DUT is a three-phase PV inverter with a power rating of 24 kVA, operating at a L-N voltage of 277 V. The firmware on the device was listed to IEEE 1547a-2014 and, therefore, was not programmed specifically for the PCRT requirements in IEEE Std 1547-2018. However, the DUT does successfully pass each of the PCRT tests. For the experimental results, sequence *A-B-A* and *A-E-A* are presented. The instantaneous voltage and current is presented for all phases.

i) IEEE Std 1547.1-2020 Unbalanced Phase Jump Test A-B-A

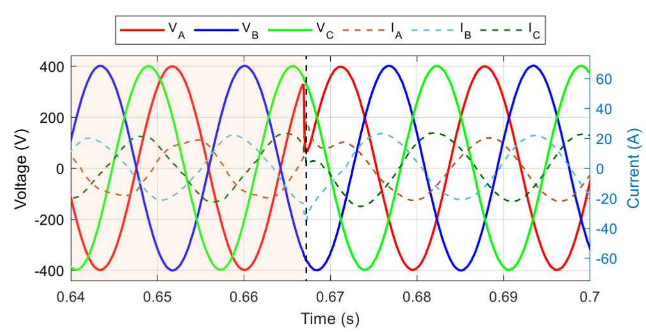
For the experimental results, phase jump combination *A-B-A* is performed. In this test procedure, phase A is shifted from 0˚ to 60˚ (either forward or backward) for a duration of 0.5 s. Then, phase A is shifted back to its original 0˚ phase angle. IEEE Std 1547.1-2020 criteria 5.5.6.4 specifies that the current must reach 80% of the pre-disturbance current in less than 0.5 s. Fig. 2 illustrates the experimental results obtained for the instantaneous voltages and currents. Fig. 3 illustrates the experimental results obtained for the RMS phase currents. Fig. 4 shows the symmetrical positive (I_1), negative (I_2) and zero (I_o) sequence currents. Fig. 5 illustrates the experimental results obtained for the active and reactive power of the PV inverter. Notice from these results that the PV inverter does not disconnect when subjected to a phase jump and is able to supply more than 80% of its pre-disturbance current within 0.5 s after the phase jump event is removed. The same results were observed when implementing the *A-C-A* and *A-D-A* phase jump tests. These are passing results in accordance to the IEEE Std 1547.1-2020 PCRT criteria.



(a)



(b)



(c)

Fig. 2. Experimental Results Obtained for Instantaneous 60˚ Voltage Phase Jump on Phase A. (a) Before Phase Jump Event. (b) During Phase Jump "Ride-Through". (c) After Phase Jump Event.

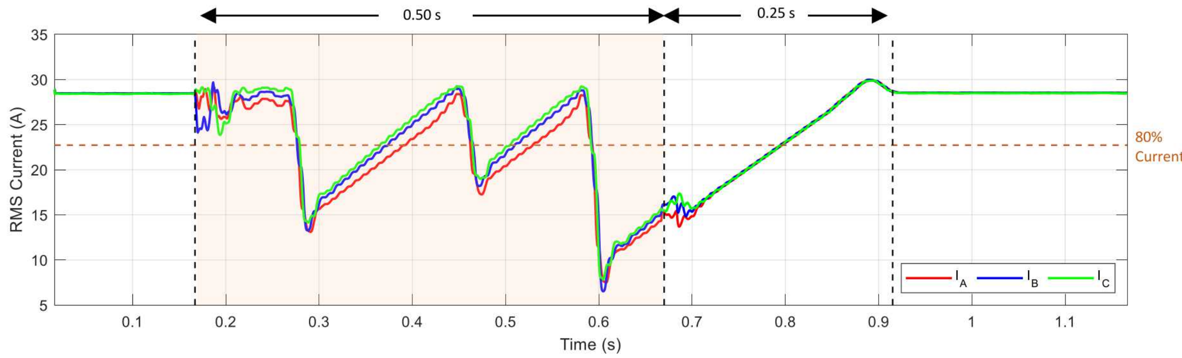


Fig. 3. RMS Phase Current for IEEE 1547.1 Phase Jump Experiment Shown in Fig. 2.

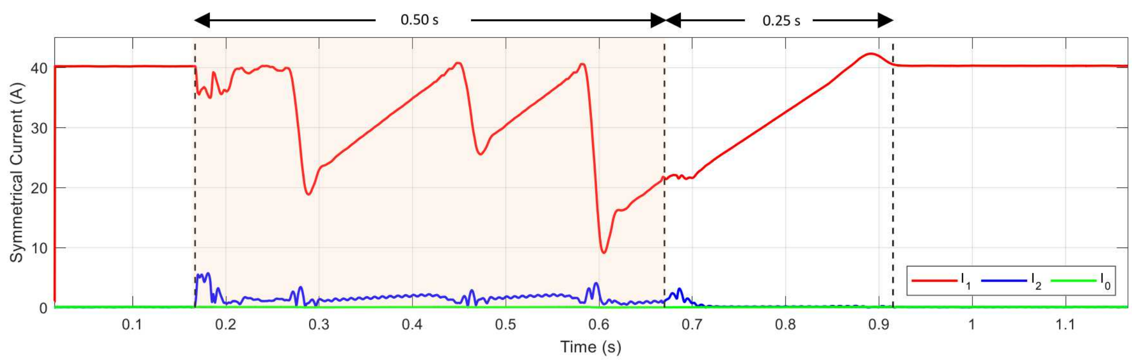


Fig. 4. Symmetrical Currents for IEEE 1547.1 Phase Jump Experiment Shown in Fig. 2.

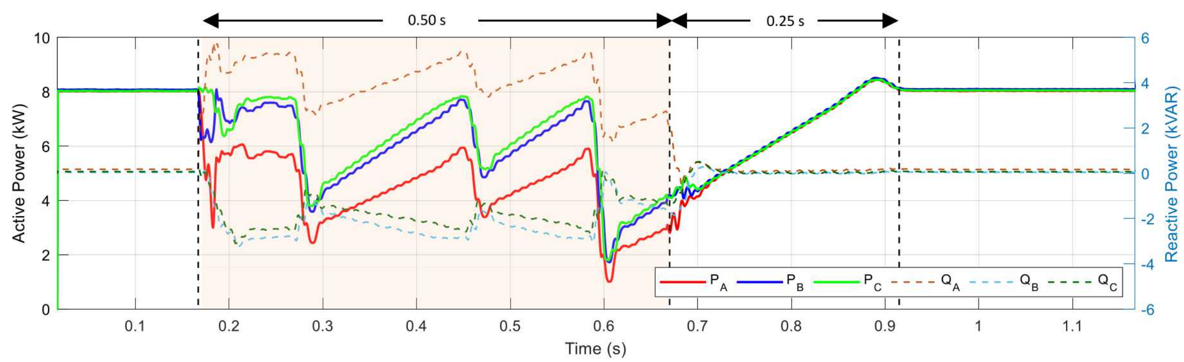


Fig. 5. Active and Reactive Power for IEEE 1547.1 Phase Jump Experiment Shown in Fig. 2.

Note from the experimental results presented in Fig. 2 that when a 60˚ phase jump is applied to phase A, phases B and C are slightly shifted in the opposite direction to maintain balanced current output. As seen in Fig. 4, the PV inverter controller regulates the currents to minimize the negative sequence current so that there is mostly only balanced positive sequence current injection [16]. The balanced current is reflected on the active and reactive power of the PV inverter, shown in Fig 5, with each phase absorbing or injecting reactive power while the total reactive power still sums to roughly zero. During the phase shift, for phase A, significant reactive power is generated while reactive power is absorbed from phases B and C. If the phase shift is applied in the opposite direction, there would be reactive power absorption in phase A. During the phase jump, there is reduction in the active power from phase A. Moreover, the active power drops and slowly ramps up. This pattern continues throughout the duration of the phase jump event.

ii) IEEE Std 1547.1-2020 Balanced Phase Jump Test A-E-A

To demonstrate the effects of a balanced phase jump on a PV inverter, the IEEE Std 1547.1-2020 phase jump test *A-E-A* is performed. This phase jump test introduced a balanced phase jump for a period of 60 s. Fig. 6 illustrates the experimental results obtained for the instantaneous PV inverter voltage and current when implementing the IEEE Std 1547.1-2020 *A-E-A* phase jump test. After the balanced 20˚ phase jump is applied, the current realigns with the voltage phase. For the 60 s duration of the IEEE Std 1547.1-2020 phase jump test, the PV inverters RMS phase currents return to their pre-disturbance value. Unlike the results obtained for an unbalanced phase jump test, these results show that there is no oscillatory behavior in the instantaneous current waveform. After the 20˚ phase jump is shifted back, the recovery time of the phase angles is within 50 ms. These results further reinforce that the PV inverter complies with the IEEE Std 1547.1-2020 test standard.

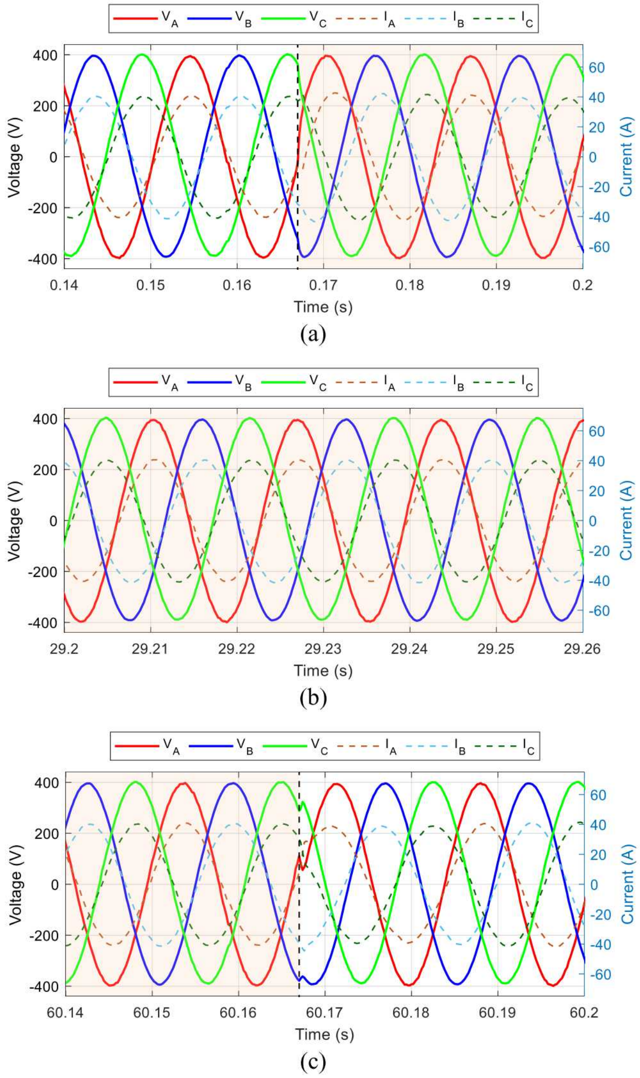


Fig. 6. Experimental Results Obtained for Instantaneous 20˚ Voltage Phase Jump on All Phases. (a) Start of Phase Jump Event. (b) During Phase Jump “Ride-Through”. (c) End of Phase Jump Event.

Fig. 7 illustrates the experimental results obtained for the PV inverters RMS phase currents for a balanced phase shift. In contrast to the effects observed in the *A-B-A* phase jump test, when performing the *A-E-A* combination, there is a slight disturbance in the PV inverters RMS phase currents, but they do not fall under the 80% of the pre-disturbance current threshold. The recovery time of the PV inverter current is much faster than the unbalanced cases. Fig. 8 illustrates the experimental results obtained for the symmetrical components of the current when applying a balanced phase jump. As expected, most of the symmetrical current is provided by the positive sequence, although there is also slight contribution from the negative sequence when the phase jump is applied and later shifted back. Fig. 9 illustrates the experimental results obtained for the active and reactive power of the PV inverter when applying a balanced phase jump. Once a 20˚ phase shift is applied, there are slight oscillations in active power generation. These effects on the active power are also observed when the phases are shifted back to normal.

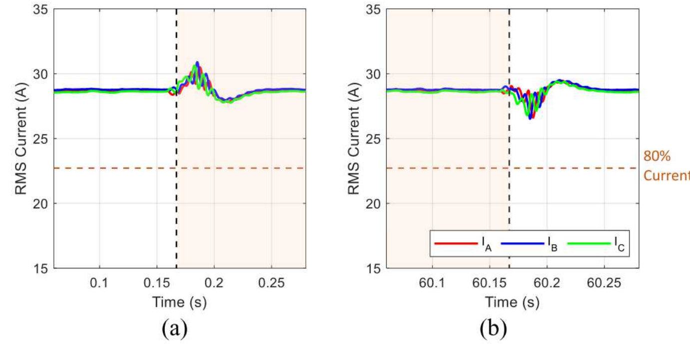


Fig. 7. Experimental RMS Phase Current Results Obtained for 20˚ Voltage Phase Jump on All Phases. (a) Start of Phase Jump Event. (b) End of Phase Jump Event.

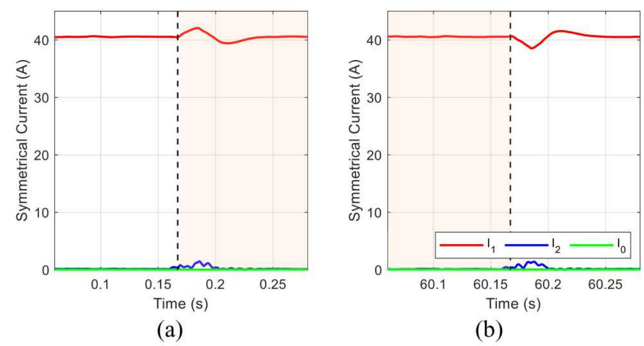


Fig. 8. Experimental Symmetrical Current Results Obtained for 20˚ Voltage Phase Jump on All Phases. (a) Start of Phase Jump Event. (b) End of Phase Jump Event.

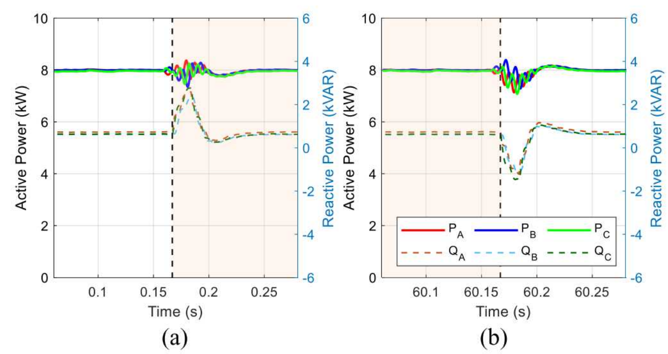


Fig. 9. Experimental Active and Reactive Power Results Obtained for 20˚ Voltage Phase Jump on All Phases. (a) Start of Phase Jump Event. (b) End of Phase Jump Event.

Although the PV inverter is operating at unity power factor, when all phases are shifted 20˚ in the same direction, there is a temporary balanced generation of reactive power for all phases. When the phase jump combination performed was *A-F-A*, there is temporary reactive power absorption instead of generation.

B. IEEE Std 1547.1-2020 PCRT Non-Compliant PV Inverter

For the following tests, the DUT used was a three-phase PV inverter with a power rating of 10 kVA (operated at 20% rated power), at a L-N voltage of 120 V. This device was not designed to be compliant with IEEE Std 1547-2018. Sequences *A-B-A, A-C-A* and *A-E-A* are presented for this PV inverter.

i) IEEE Std 1547.1-2020 Unbalanced Phase Jump Test A-B-A

To demonstrate the effects of an unbalanced phase jump on a PV inverter, the IEEE Std 1547.1-2020 phase jump test *A-B-A* is performed. Fig. 10 illustrates the experimental results obtained for the instantaneous PV inverter voltages and currents when implementing the IEEE std 1547-2020 *A-B-A* phase jump test.

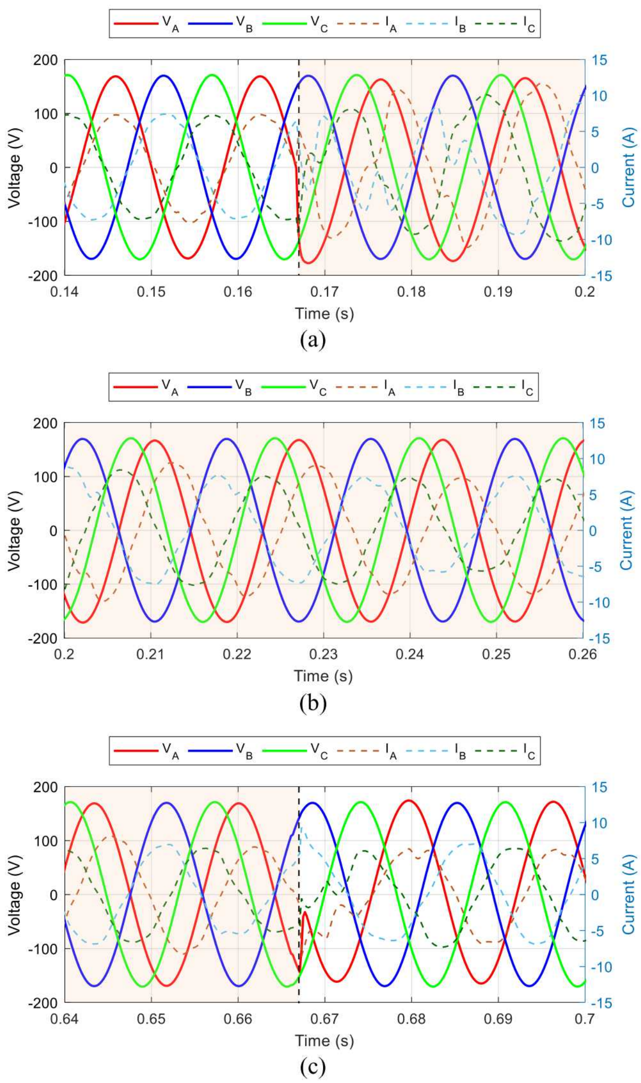


Fig. 10. Experimental Results Obtained for Instantaneous 60˚ Voltage Phase Jump on Phase A (a) Start of Phase Jump Event. (b) During Phase Jump "Ride-Through". (c) End of Phase Jump Event.

Note from the instantaneous experimental results in Fig. 10, that it appears that the PV inverter rides through the phase jump event. Fig. 10 (a) illustrates that applying a phase shift to phase voltage A pushes the phase A current waveform in the opposite direction. Alternatively, phase currents B and C are pushed in the opposite direction as phase current A. During the events of the phase jump, oscillations in the instantaneous current waveform are observed, as illustrated in Fig. 10 (b). When the phase shift is removed, the reverse effects of what is observed in Fig. 10 (a) occur, as illustrated in Fig. 10 (c).

Fig. 11 illustrates the experimental results obtained for the PV inverter RMS phase currents for an unbalanced phase shift. Results for the PV inverter RMS phase currents demonstrate an increase in current when the phase jump is applied. There is a phase imbalance, with phase A current being slightly higher. Although the PV inverter does not disconnect, after the phase angle is restored, the PV inverter current oscillates around 80% of its pre-disturbance current. This demonstrates that although the PV inverter can operate during and after the phase jump event, clearly it does not comply with IEEE Std 1547-2018 requirements.

Fig. 12 illustrates the experimental results obtained for the symmetrical components of the current when applying an unbalanced phase jump. As expected, during the phase jump event the majority of the symmetrical sequence current is provided by the positive sequence current. There is also slight symmetrical current from the negative sequence. After the phase jump is removed, there is reduction in positive sequence current. Moreover, after the phase jump event is removed, there is slight oscillation present in positive sequence current.

Fig. 13 illustrates the experimental results obtained for the active and reactive power of an unbalanced phase jump test. Experimental results illustrate that there is active power reduction during the phase jump event. There is also significant oscillation in the active power waveform. During the phase jump event, there is power imbalance, with phase A providing slightly larger active power in comparison with phases B and C. Once the phase jump event is removed, there is additional active power reduction. Active power oscillations continue after the phase jump event is removed. Although operating at unity power factor, after the first phase jump there is reactive power generation from phase A, and reactive power absorption from phases B and C throughout the phase jump duration. After the second phase jump, there is neither absorption nor generation of reactive power.

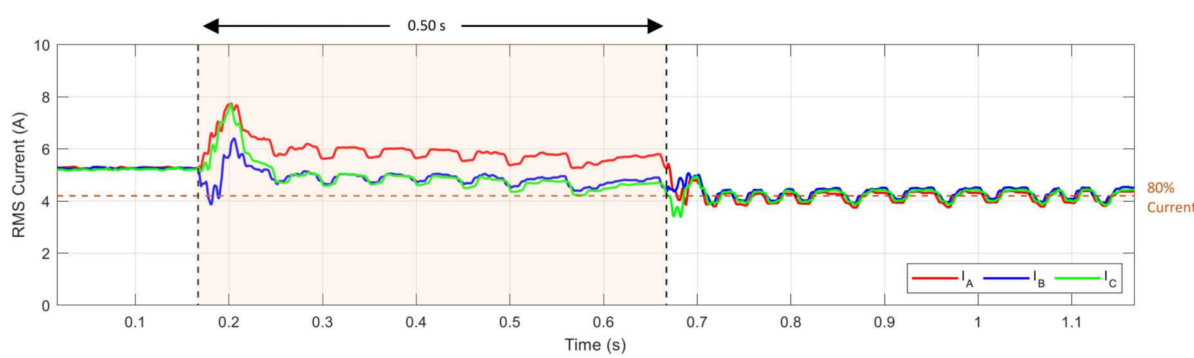


Fig. 11. RMS Phase Current for IEEE 1547.1 Phase Jump Experiment Shown in Fig. 10.

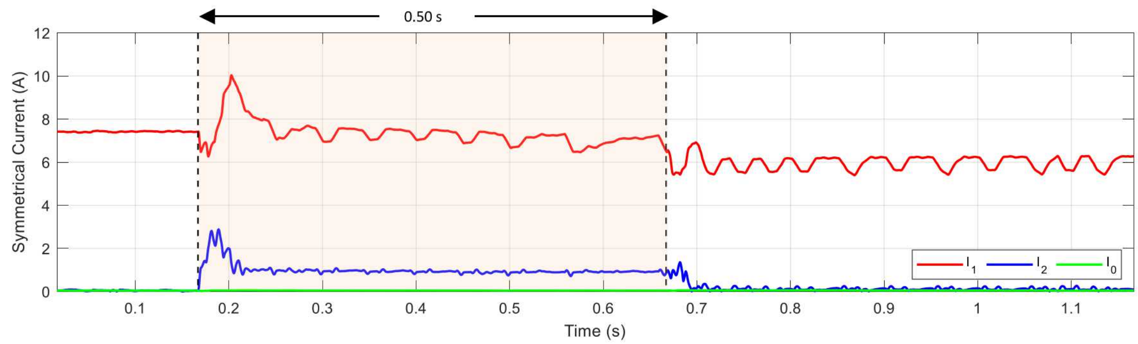


Fig. 12. Symmetrical Currents for IEEE 1547.1 Phase Jump Experiment Shown in Fig. 10.

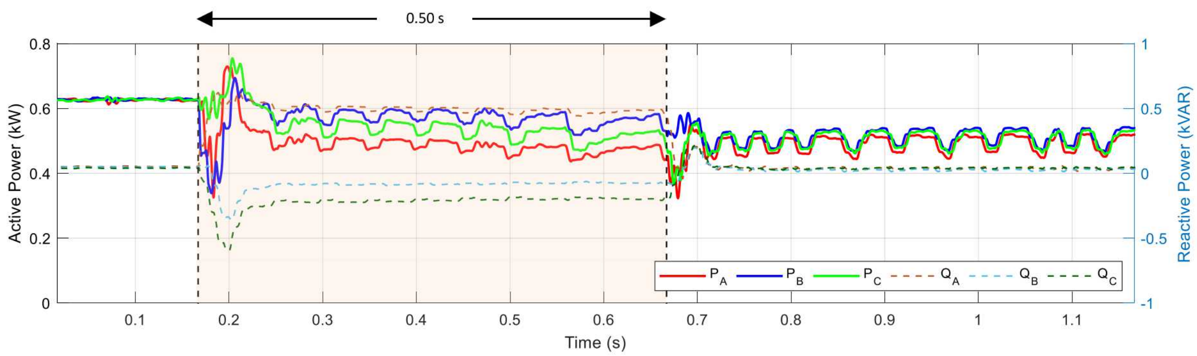


Fig. 13. Active and Reactive Power for IEEE 1547.1 Phase Jump Experiment Shown in Fig. 10.

ii) IEEE Std 1547.1-2020 Unbalanced Phase Jump Test A-C-A

Phase jump sequences *A-C-A* and *A-D-A* caused the PV inverter to trip with an overvoltage error code. This could be the result of an RMS voltage calculation error caused by the phase jump. Fig. 14 illustrates the results for the instantaneous PV inverter voltage and current for an *A-C-A* phase jump.

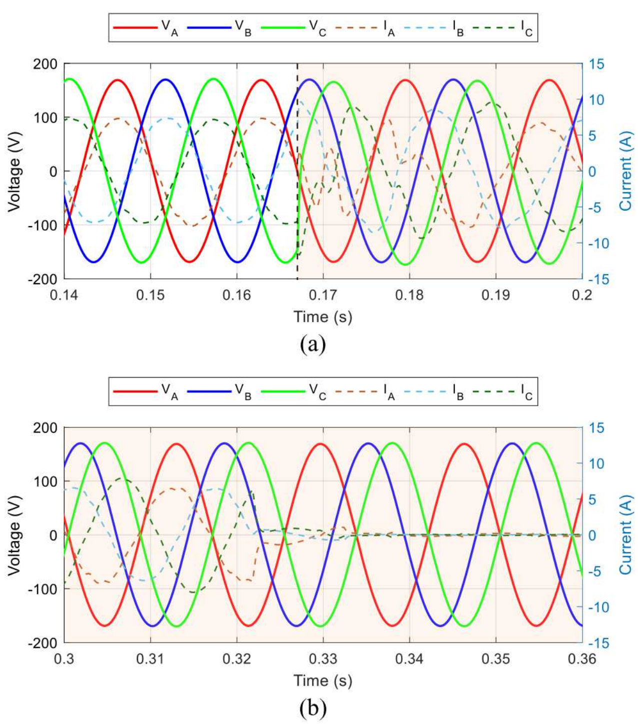


Fig. 14. Experimental Results Obtained for Instantaneous 60˚ Voltage Phase Jump on Phase C. (a) Start of Phase Jump Event. (b) During Phase Jump "Ride-Through".

Fig. 15 illustrates the PV inverter RMS phase currents. The PV inverter trips after 0.16 s of the phase jump event being introduced, a typical response for some PV inverters [17]. Fig. 16 illustrates the results obtained for the symmetrical sequence currents. Most of the symmetrical current is provided by the positive sequence, while there is some negative symmetrical current present. Fig. 17 illustrates the results obtained for the active and reactive power of an unbalanced phase jump. In comparison with phase jump sequence *A-B-A*, there is an active power sag before the PV inverter trips.

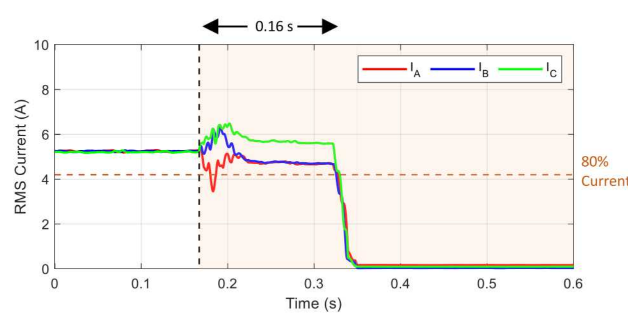


Fig. 15. RMS Phase Currents for IEEE 1547.1 Phase Jump Experiment.

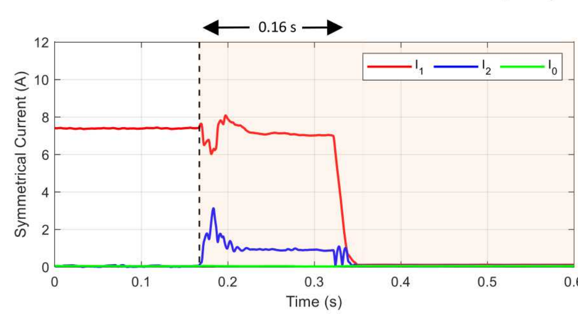


Fig. 16. Symmetrical Currents for IEEE 1547.1 Phase Jump Experiment.

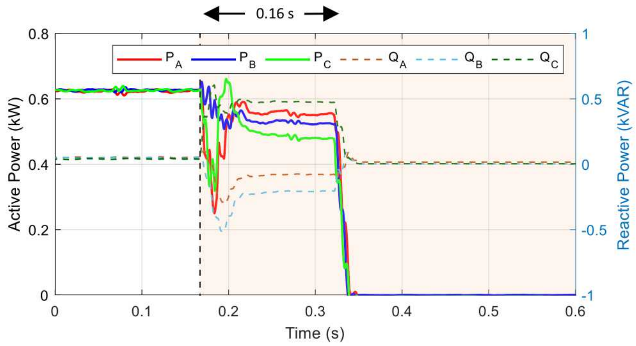


Fig. 17. Active and Reactive Power for IEEE 1547.1 Phase Jump Experiment Shown in Fig. 14.

iii) IEEE Std 1547.1-2020 Balanced Phase Jump Test A-E-A

To demonstrate the influence of a balanced phase jump on the second PV inverter, the IEEE Std 1547.1-2020 phase jump test *A-E-A* was performed. Fig. 18 shows the experimental results obtained for the instantaneous PV inverter voltages and currents when performing the *A-E-A* phase jump test.

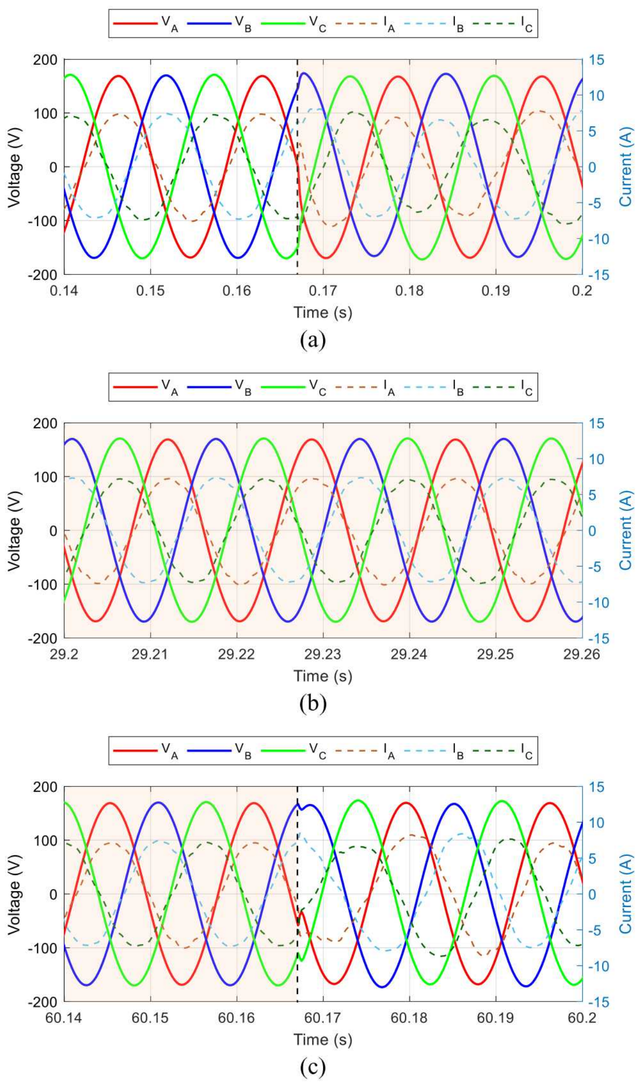


Fig. 18. Experimental Results Obtained for Instantaneous 20˚ Voltage Phase Jump on All Phases. (a) Start of Phase Jump Event. (b) During Phase Jump "Ride-Through". (c) End of Phase Jump Event.

The experimental results reveal that the PV inverter continues to operate even though the PV inverter is not designed to be compliant with IEEE Std 1547-2018 PCRT requirements. Fig. 19 illustrates the experimental results obtained for the PV inverter RMS phase currents for a balanced phase shift. When applying a balanced phase jump, the PV inverter current is always above 80% of its pre-disturbance current value. Fig. 20 illustrates the experimental results obtained for the symmetrical components of the current when applying a balanced phase jump. Fig. 21 illustrates the results obtained for the active and reactive power of a balanced phase jump. There are slight active and reactive power fluctuations when the phase jump is applied.

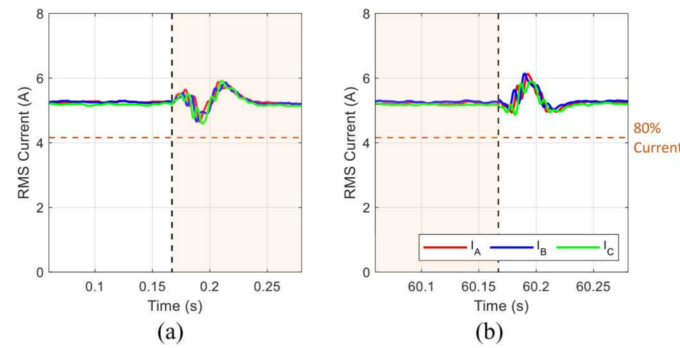


Fig. 19. Experimental RMS Phase Current Results Obtained for 20˚ Voltage Phase Jump on All Phases. (a) Start of Phase Jump Event. (b) End of Phase Jump Event.

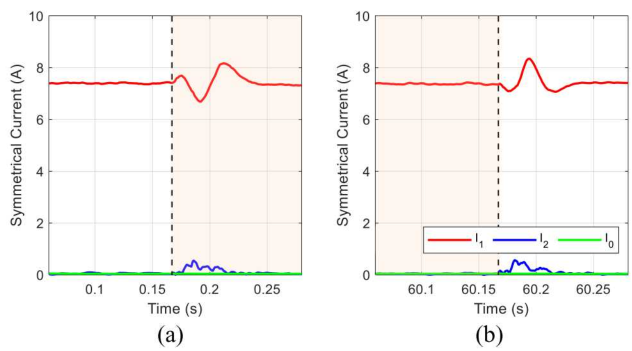


Fig. 20. Experimental Symmetrical Current Results Obtained for 20˚ Voltage Phase Jump on All Phases. (a) Start of Phase Jump Event. (b) End of Phase Jump Event.

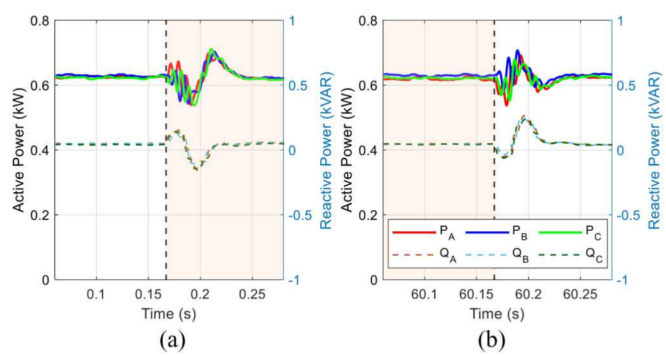


Fig. 21. Experimental Active and Reactive Power Results Obtained for 20˚ Voltage Phase Jump on All Phases. (a) Start of Phase Jump Event. (b) End of Phase Jump Event.

IV. Conclusion

This paper presents experimental results obtained from implementing the IEEE Std 1547.1-2020 PCRT tests on two PV inverters. It was found that one of the devices was compliant to the standard and reached 80% of its pre-disturbance current within the required time specified in the IEEE Std 1547.1-2020 standard. The second device was not able to reach the 80% of its pre-disturbance current in the required time and tripped off during the *A-C-A* and *A-D-A* tests that shift phase B and C voltages. These experimental results indicated that there are a range of performance characteristics for DER hardware on the market. In some cases, the equipment is compliant with the certification standard, but in other cases, DER manufacturers will need to redesign their firmware to meet the revised standard.

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