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Effects of EMP Testing on Residential DC/AC Microinverters

Andy Fierro	University of New Mexico
Ken Le	University of New Mexico
David Sanabria	University of New Mexico
Ross Guttromson	Sandia National Laboratories
Matthew Halligan	Sandia National Laboratories
Jane Lehr	University of New Mexico

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico
87185 and Livermore,
California 94550

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ABSTRACT

Electromagnetic pulse (EMP) coupling into electronic devices can be destructive to components potentially causing device malfunction or failure. A large electromagnetic field generated from the EMP can induce large voltages and currents in components. As such, the effects of EMP on different devices needs to be understood to elucidate the effect of EMP on potentially vulnerable systems. This report presents test results for small-scale residential DC to AC solar panel microinverters that were subjected to high voltage impulses and currents. The impulses were intended to emulate an EMP coupling event to the AC and DC sides of the microinverter. State-of-health measurements were conducted to characterize device performance before and after each test.

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EXECUTIVE SUMMARY

The effects of electromagnetic pulses on power system devices are not completely understood. Many integrated components incorporate surge suppression technology but the response of these components to currents and voltages many orders of magnitude above their rated values from a high-altitude electromagnetic pulse is not yet fully quantified. As a result, critical devices on the power grid need to be studied to understand their vulernability when exposed to these types of impulses.

Residential microinverters which convert solar panel DC power to AC power are devices that could be vulnerable to EMP conducted insults via the power cables in and out of the microinverter. Ideally, the microinverters would be tested by insulting them while connected to a photovoltaic (PV) panel, but the microinverters were unavailable at the time of PV testing. Furthermore, to better control experimental values the microinverters were subjected to voltage insults in a laboratory setting with a known voltage pulse. These microinverters were tested at the University of New Mexico APERIODIC laboratory by insulting the them with voltages and currents at their input and output terminals, at levels greater than those expected by a HEMP. Devices were insulted in both common mode and differential mode test configurations while actively monitoring insult voltages and currents. State-of-health measurements were taken before and after applying a high voltage pulse to elucidate any effects on the operation of the microinverter.

Each microinverter was subjected to 5 separate tests. A total of 22 identical microinverters were tested in the configurations of AC differential mode, AC common mode, DC differential mode, and DC common mode. Voltages for the both AC common mode and differential mode tests were started at 20 kV and increased to 40 kV, 50 kV, and finally 60 kV. DC tests were limited to an insult voltage of 20 kV to limit the insult current to approximately 100 A. AC tests were used to emulate EMP coupling to the AC wires whereas the DC tests represent current injection from a PV panel exposed to a high altitude EMP.

Analysis of test results indicated that none of the microinverters tested experienced failures regardless of the test configuration they were subjected to.

The AC and DC side of the microinverters were tested independently of each other. In reality, EMP coupling would occur on both sides of the microinverter simultaneously. Future testing would need to focus on this testing aspect to determine if simultaneous insulting results in microinverter failure.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
DUT	Device Under Test
EMP	Electromagnetic Pulse
FWHM	Full-Width Half-Maximum
HEMP	High-Altitude Electromagnetic Pulse
Insult	High voltage pulse conducted to test the article which represents the effects of a potential HEMP conducted environment
MOV	Metal Oxide Varistor
PV	Photovoltaic
SOH	State-of-Health
UNM	University of New Mexico

1. EXPERIMENTAL SETUP

1.1. EMP Signal Generation

Figure 1 shows the high voltage pulser designed to produce a double-exponential waveform with a rise time on the order of 10 ns and full-width half-maximum (FWHM) of 50 – 75 ns [1]. Two series connected capacitors (1 nF each, 0.5 nF total) are charged with a high voltage power supply. A 0.5 uH inductor was connected to a self-triggered spark gap to influence the rise-time. Complete theoretical and simulation analysis of the pulser is demonstrated in [1]. An additional 150 Ohm and 50 Ohm resistor are used for pulse shaping and to generate the desired output.

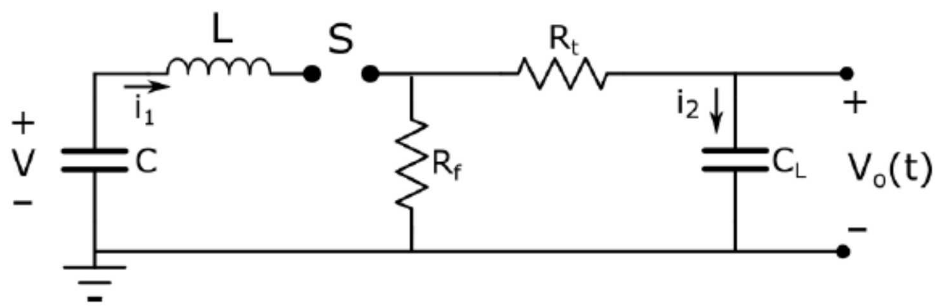


Figure 1: Schematic of the high voltage pulser used to insult microinverter devices [1].

To generate different output voltages, the spark gap is pressurized with air to increase output voltage. The minimum output voltage for the pulser under open circuit operation is approximately 20 kV at atmospheric pressure inside the spark gap. Lower voltages can potentially be achieved by applying a vacuum to the spark gap, shifting the operating regime to a lower potential on the Paschen curve. If the spark gap is pressurized to 25 PSI, the open circuit output voltage increases to approximately 40 kV. The maximum open circuit output of the high voltage pulser is 100 kV, although in this testing the maximum voltage used is 60 kV. Representative waveforms are shown in Figure 2 for the charging voltage indicated into an open circuit load.

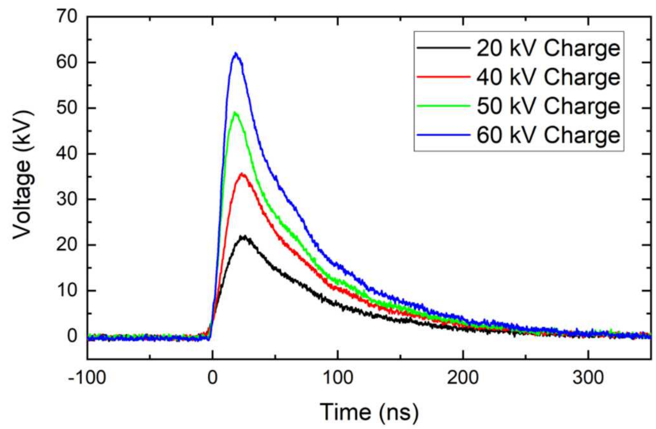


Figure 2: Open circuit voltage waveforms measured for different charging voltages.

1.2. Microinverter Specifications

The microinverter used for testing is an Enphase Energy M250-60-2LL-S22. Specifications for the microinverter are shown in Table 1.

Table 1: Microinverter Specifications

Input Data (DC)	
Commonly used module parings	210 – 350+ watts
Compatibility	60-cell PV modules
Maximum input DC voltage	48 V
Peak power tracking voltage	27-39 V
DC Operating range	16–48 V
Min/Max start voltage	22-48V
Max DC short circuit current	15 A
Output Data (AC)	
Peak output power	250 W
Maximum continuous output power	240 W

Nominal output current	1.15 A @ 208 VAC; 1.0 A @ 240 VAC
Nominal output voltage/range	184-229 V @ 208 VAC; 211-264 V @240VAC
Nominal frequency/range	60 / 57-61 Hz
Maximum output fault current	850 ma rms for 6 cycles
Efficiency	
Peak inverter efficiency	96.5%
Night time power consumption	65 mW max

1.3. Complete System Design

A schematic of the experiment is shown in Figure 3. The microinverter is powered by 3, 12 V automotive batteries connected in series producing a total voltage of approximately 36 V. A 208 L-L three-phase outlet is connected to a 150 Ohm load capable of dissipating 1000 W. Only 2 of the 3 phases are used for all testing. The microinverter output is also connected to the load. In this configuration, the microinverter ideally outputs its rated 240 W, with a maximum rated output power of 250 W with the rest of the power being supplied by the wall outlet.

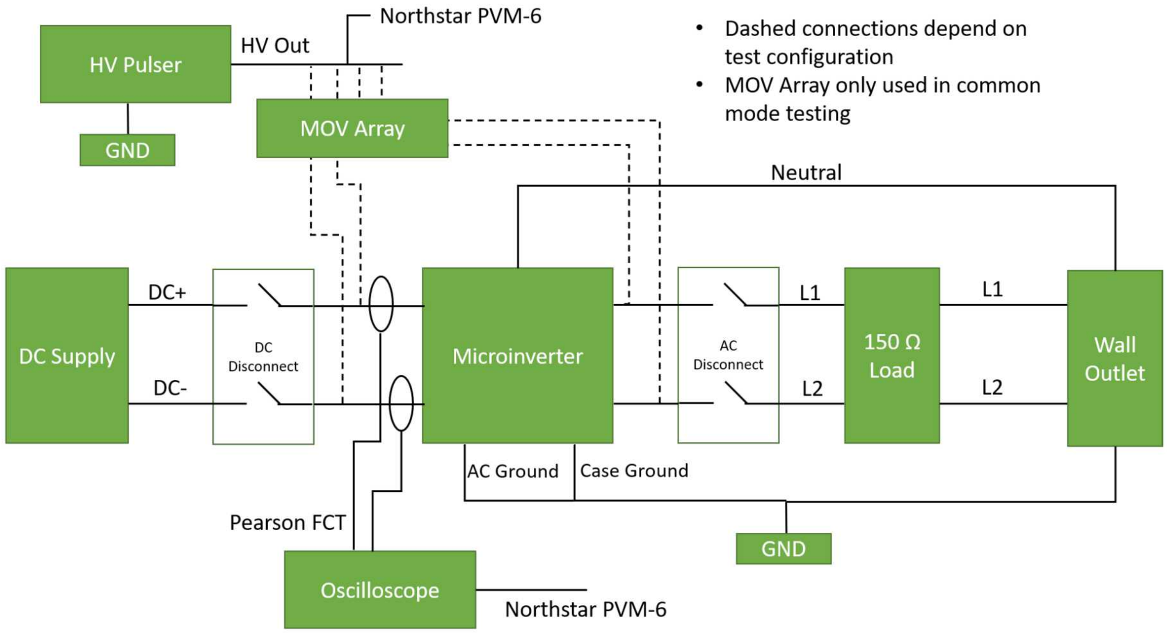


Figure 3: Test schematic for connections of microinverter to DC, AC, and Pearson current measuring points.

An Enphase® Engage cable is used to connect to the microinverter to the 208 V AC power and load [2]. This cable has 4 pins, two for the individual phases, one for neutral, and a final one for ground. In Figure 3, the Engage cable 4 connections from the microinverter are the AC ground, Neutral, L1, and L2. See Figure 4 for a pin out for each Enphase® Engage cable. In the experimental configuration, only phase A-B are used, for example, as only a single microinverter configuration was tested.

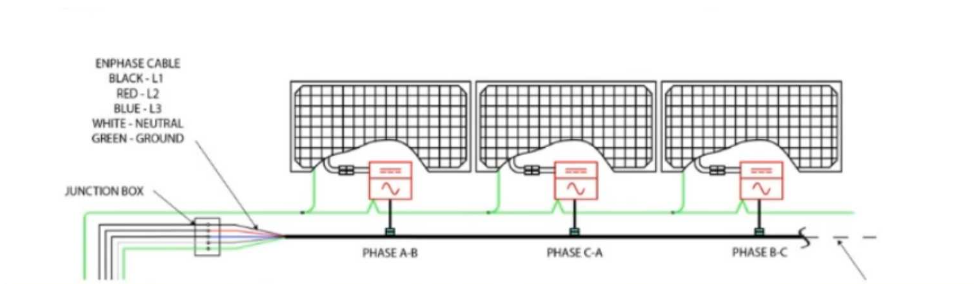


Figure 4: Enphase® Engage 208V, three-phase cable wiring schematic.

One end of the Engage® cable was connected to a two-pole, single throw switch for disconnection/connection from the 208 AC load/power. The other end was open-ended and fitted with Banana plugs to feed in the high voltage pulse to L1, L2, and/or neutral. See the Figure 5 for the modified cable for connection to the microinverter. From the wall outlet, the ground and neutral were connected to the Engage® cable ground and neutral with no interruption circuit.

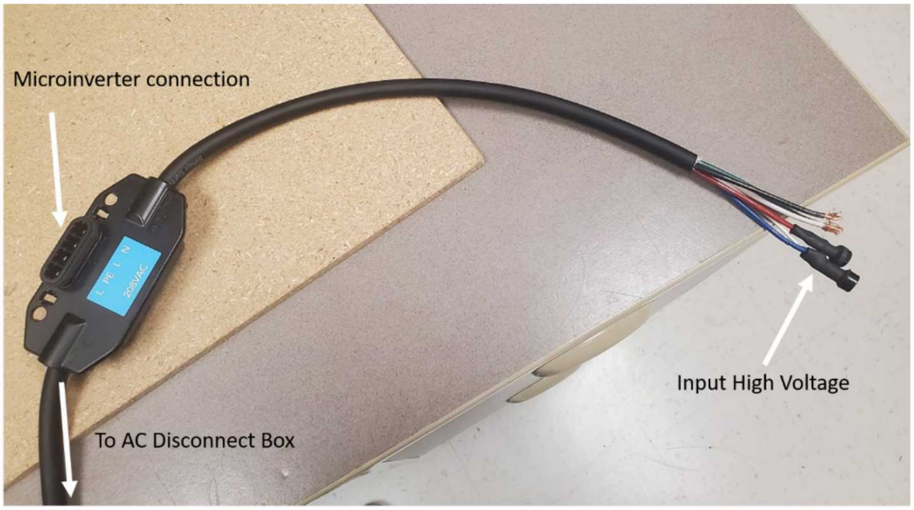


Figure 5: Enphase® Engage cable. Also shown are the connections of the high voltage insult pulse to a microinverter.

For DC testing, a two-pole, single-throw switch was also used to disconnect/connect DC power to the microinverter. The connections to the microinverter were modified with banana jacks to connect the high voltage pulser. The modified connections are shown in Figure 6.

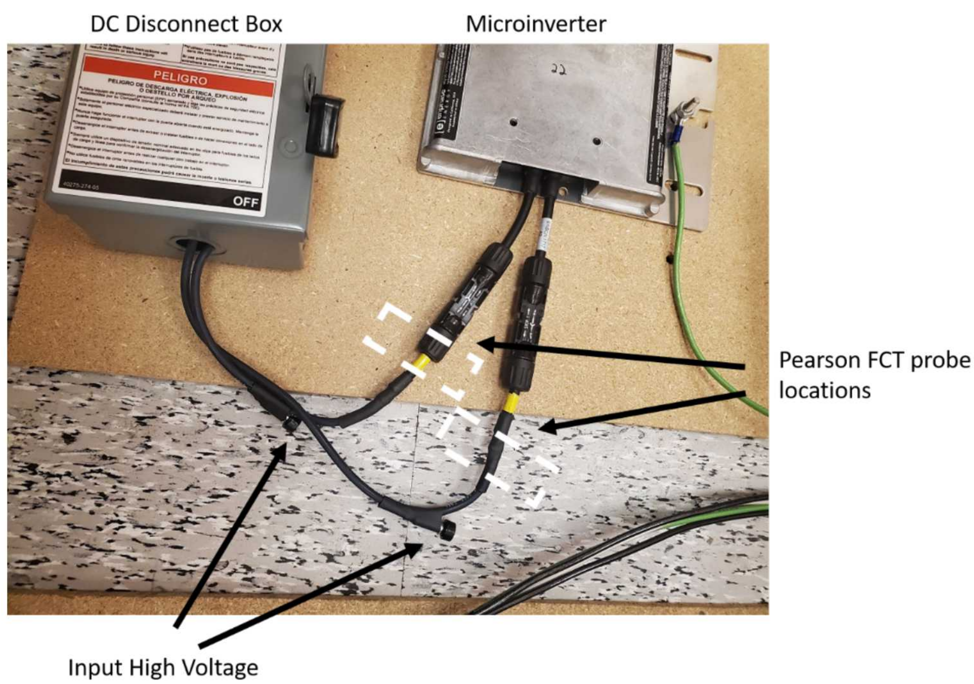


Figure 6: Connections for high voltage input into the DC common/differential mode configurations.

In common mode testing, connection of the single high voltage pulser output directly to either the DC+ and DC- terminals, or L1 and L2 would result in a short circuit. As a result, a high impedance must be placed on the output of the high voltage pulser, but it must become a low impedance when the pulser's high voltage is applied. Metal Oxide Varistors (MOVs) are solid-state components that transition from high to low impedance above a certain voltage threshold through an avalanching process. As a result, common mode tests were performed by using MOVs between the high voltage output and the load lines. The MOV test fixture produces the same wave shape with reduced amplitude as without the test fixture (see Figure 8). Thus, the frequency content of the high voltage pulse is the same but the incident current and voltage into the DUT is reduced. his fixture was provided by Sandia National Laboratories to UNM.

The MOV fixture has a total of 7 MOVs. In the DC common mode tests, only two MOVs were utilized, one for each of the two DC leads on the inverter. AC common tests utilized either 2 or 3 MOVs depending on if the neutral line was connected as well. The remaining MOVs were left open-circuited. The test schematic can be seen in Figure 7 for both the AC and DC common mode tests.

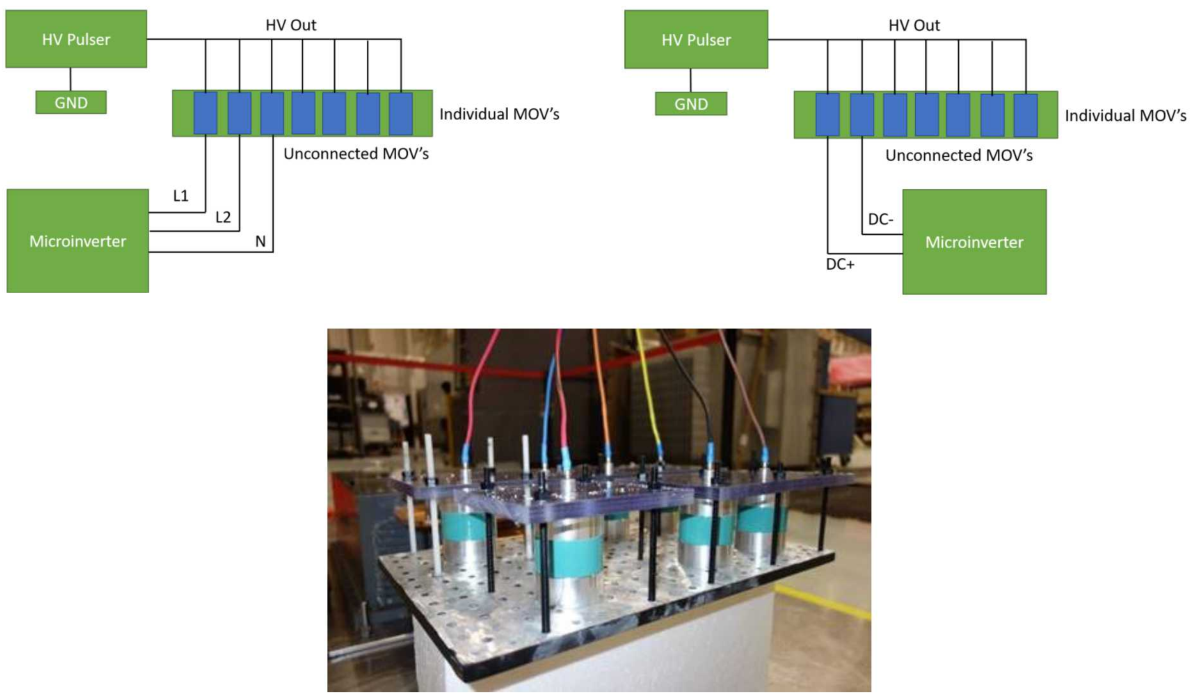


Figure 7: (top left) Schematic for including MOV between high voltage pulser and AC Terminals in common mode testing. (top right) Schematic for including MOV between high voltage pulser and DC terminals in common mode testing (bottom) MOV test fixture provided by Sandia National Laboratories.

The MOV fixture reduces the voltage observed at the desired insult location (for example, DC+ terminal). The charge voltage was not increased to compensate for this reduction and thus common mode test voltages which were measured at the output of the pulser itself are likely lower than the indicated voltages in the results. Figure 8 shows an instance of the voltage reduction observed in the DC common mode configuration before and after the MOV test fixture.

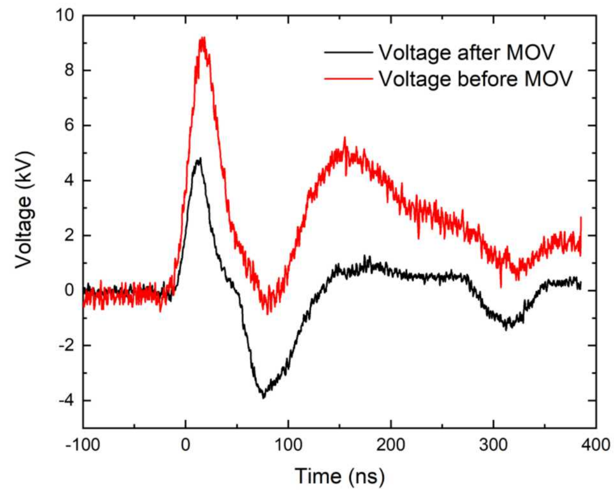


Figure 8: Voltage measured before (at the output of the pulser) and after the MOV test fixture under DC common mode configuration.

The experimental setup constructed is shown in Figure 9. A screen room housed the entire experiment to reduce the effects of the high voltage pulse on the diagnostic equipment. In this image, the current monitors and MOV test fixture are not shown. The system was built upon an insulating particle board material. Grounding of the microinverter, AC ground, and high voltage ground was done through a short wire to the ground plate of the high voltage pulser. Due to the very short distances in the test setup, a return ground plane was assumed not to be needed and only the short wire was used.

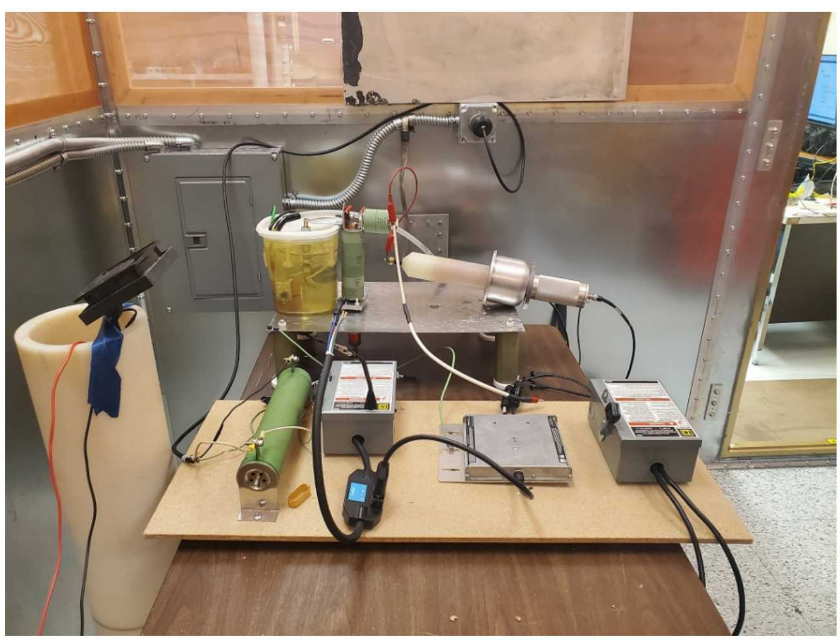


Figure 9: Experimental setup constructed at UNM housed in a screen room.

A Northstar PVM-6 1000:1 high voltage probe was used to measure the output directly from the high voltage pulser. One Pearson 6600 0.1 V/A current monitors was used on each DC lead to measure currents when the DC side was insulted with the high voltage pulser (Termination 1 MΩ).

2. TESTING PROCEDURE

The development of the test matrix (2) was accomplished with the intent of duplicating the actual environmental conditions that a microinverter would see during a HEMP event. The DC input for this microinverter is normally connected to the DC output of a 38 V_{OC}, 260 W PV panel. EMP radiated tests conducted on PV panels at Sandia [3] show that a 60 kV/m incident E-field pulse on the PV panel resulted in a common mode current output pulse of about 50 A. Duplication of this current pulse into the microinverter is the objective for testing the DC side of the microinverter as well as testing each DC terminal individually (differential testing). Therefore the pulser output voltage setting was adjusted to achieve this amount of current into the DC side of the microinverter, while the inverter was operating. Cabling from the microinverter to the PV panel, for this type of PV configuration, is short and has little potential for direct E1 coupling. The parasitic capacitance from the microinverter to ground was likely different than the PV panel output resistor to ground in [3], thus the common mode return currents are similar but not likely the same. A more accurate test would have been to perform testing of the PV module while it was connected to the microinverter, but this appropach was not possible at the time.

The AC side of microinverter was also pulse tested. The intent of this test was to simulate the effects of EMP E1 coupling onto the AC wires connecting the microinverter to the load. It was assumed that this wire could be long, with significant potential for EMP E1 coupling. A value of 60 kV was selected as a maximum likely coupled voltage to these wires. Pulse tests were initially conducted at lower voltages to identify the voltage that caused the failure, if a failure occurred. Applying this method over a large microinverter sample set allows the results to be used to constuct a conditional cumulative density function for the microinverter failure, providing a means to predict microinverter failure probabilities under different HEMP conditions. The AC-side tests were also conducted while the inverter was operating.

Although the DC side and AC side tests were conducted separately, a more realistic, but complex, test would be to simultaneously insult the AC side and DC side. This test, however, was outside the scope of this work and will be left to others. Radiated insults from an EMP E1 are of less concern on the microinverter. It is clad in metal and normally located underneath a PV panel, and is thus well shielded from direct radiation.

2.1. State of Health Measurements

State-of-Health (SOH) measurements are a critical part of the test process. These measurments determine whether the test article was damaged or functially modified as a result of the test impulse. Any changes in the SOH meaurements from before an insult to after the same insult indicate the extent to which the device under test was damaged. Diagnostics for SOH measurements for the microinverter are obtained from DC/AC voltmeters and ammeters. Prior to the application of the high voltage pulse, the microinverter operation was checked and its DC and AC voltages were measured with a standard Fluke voltmeter. Additionally, the input and output currents were measured with a Fluke i30 DC/AC ammeter. The AC voltage was always measured across the 150 Ω load. The AC current was taken from the output of the microinverter on either L1 or L2 also using the Fluke ammeter. DC voltage was measured at the two-pole disconnect switch box. For DC current, the ammeter was connected to the positive lead of the battery supply.

2.2. Test Procedure

For each microinverter, the following procedure was executed. A single microinverter was tested according to the test matrix shown in Table 2 until failure or completion of the test matrix.

With both two-pole switches in the off position, the DC side switch was moved to the on position first, energizing the DC side of the microinverter from the battery. Immediately after, the AC side switch was moved to the on position, energizing the AC side of the microinverter from the wall outlet. After energizing, the microinverter status LED stays illuminated for 2 minutes, followed by 6 green blinks, indicating proper start-up. After the 6 green blinks, flashing red indicates that the normal start-up procedure was completed and no AC grid is detected. Flashing green indicates that the microinverter is in operation, producing power, and connected with the Enphase® Envoy communications gateway. Flashing orange indicates that the microinverter is in operation, producing power, but is not connected to the Enphase® Envoy communications gateway. Flashing orange was the typical status LED encountered during testing as the communications gateway was available, but was not connected or used for SOH testing.

With the microinverter operating (converting DC power to AC power), pre-insult SOH measurements were taken. Starting with Test ID #1, a high voltage pulse was applied then post-insult SOH measurements were taken before another voltage impulse was applied. The next impulse was then conducted (as specified in Table 2), with the post-insult SOH measurements being used as the next tests pre-insult measurements. SOH measurements were repeated in between each test. The microinverter was operational and producing power during all tests and SOH measurements.

All time-resolved waveforms shown in the data were smoothed with adjacent-averaging of 5 points to remove some digitizer noise.

2.3. Test Matrix

A total of 22 microinverters were tested in different test configurations, and all tested while operating. The first 5 microinverters were used to test bounds of the operating regime for the microinverters before they experienced failure and/or disruption (microinverters 1-4 and 21). These first 5 microinverters also allowed for the refinement of the test matrix since voltages above 20 kV on the DC side produced approximately 100 A, which was greater than the pulsed current magnitude desired for the test [3]. Thus, a total of 17 microinverters were used for full testing. For 9 microinverters, tests #1 – test #4 were conducted (see table below). For test identifiers #5 - #8, the other 8 were tested. For test identifier #9, 6 microinverters were tested using this configuration. Test #10, 6 different microinverters were tested in this configuration. Finally, test #11 resulted in the last 5 microinverters being tested in this configuration. Each microinverter was individually numbered from 1-22.

Table 2: Test matrix for the DC/AC microinverters.

Test Identifier	Pulser Hot lead	Pulser Ground	Charging Voltage	**M**icroinverter **Identifier**
1	L1 & L2	Case/Inverter	20 kV	5,6,7,8,9,10,11,12,13
2	L1 & L2	Case/Inverter	40 kV	5,6,7,8,9,10,11,12,13
3	L1 & L2	Case/Inverter	50 kV	5,6,7,8,9,10,11,12,13
4	L1 & L2	Case/Inverter	60 kV	5,6,7,8,9,10,11,12,13
5	L1 & L2 & Neutral	Case/Inverter	20 kV	14,15,16,17,18,19,20,22
6	L1 & L2 & Neutral	Case/Inverter	40 kV	14,15,16,17,18,19,20,22
7	L1 & L2 & Neutral	Case/Inverter	50 kV	14,15,16,17,18,19,20,22
8	L1 & L2 & Neutral	Case/Inverter	60 kV	14,15,16,17,18,19,20,22
9	DC+	Case/Inverter	20 kV	5,6,7,8,9,10
10	DC-	Case/Inverter	20 kV	11,12,13,14,15,16
11	DC+ & DC-	Case/Inverter	20 kV	17,18,19,20,22

The pulser developed at UNM, in its lowest voltage setting, generates an open-circuit voltage of 20 kV. With the microinverter connected, the transient peak current measured going into the DC terminals of the microinverter is approximately 100 A. As such, only the 20 kV voltage setting was tested in the DC configuration. This value exceeds the value of measured current coming out of a PV panel during a HEMP pulse test at 60 kV/m.

3. RESULTS

3.1. DC Differential Mode Tests

DC Differential mode tests are indicated in the test matrix (Table 2) by tests 9 and 10. High voltage was applied to either the DC+ or DC- terminal. A total of 5 microinverters were insulted by connecting the high voltage output to the DC+ terminal. Microinverter 9 reported correct operation but was found to be inoperable and as a result was not tested. Another 6 microinverters were insulted by connecting the high voltage output to the DC- terminal. Representative waveforms are shown in Figure 10 which show the high voltage pulse insult on both the DC+ and DC- terminal along with open-circuit (no device under test) voltages. Pulse voltage was limited to only testing a 20 kV pulse as this is the lowest pulse voltage for the pulser but still produced over 100 A of current into the microinverter.

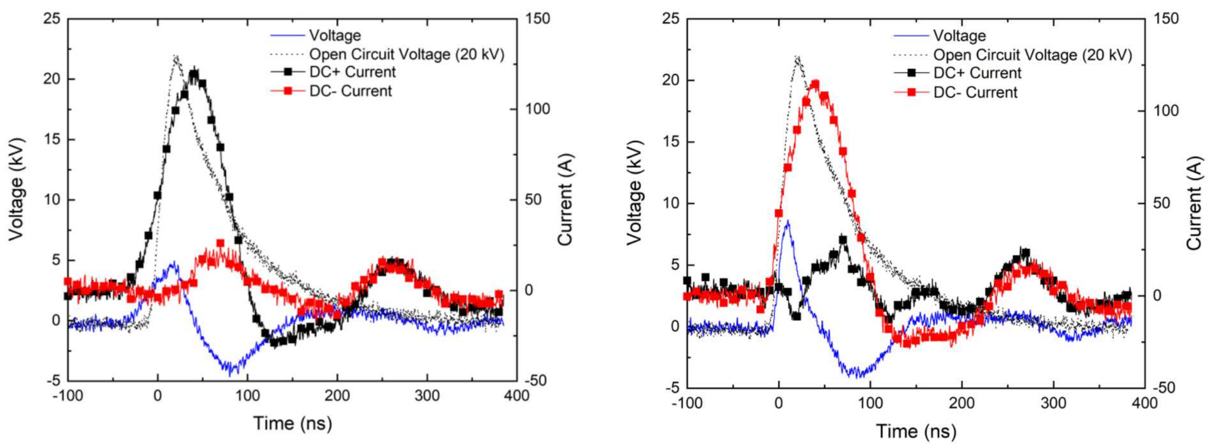


Figure 10: (left) Differential mode DC+ test for microinverter 5 showing voltage (blue), DC+ current (black squares), DC- current(red squares), and reference open-circuit voltage shot (dotted). (right) Differential mode DC- test for microinverter 11 showing voltage (blue), DC+ current (black squares), DC- current (red squares), and reference open-circuit voltage shot (dotted).

From the waveforms (Figure 10), the open circuit voltage waveform reduces in amplitude from a peak of +20 kV without the microinverter (dotted line) to a peak of approximately +10 kV (blue line). In both measurements, the current peak into either the DC+ (left Figure) or DC- side (right Figure) is approximately 125 A and occurs after the voltage peaks. There is a small amount of current measured into the non-insulted DC lead; however, this is likely noise from the high voltage pulser. Further testing would be required to verify this claim.

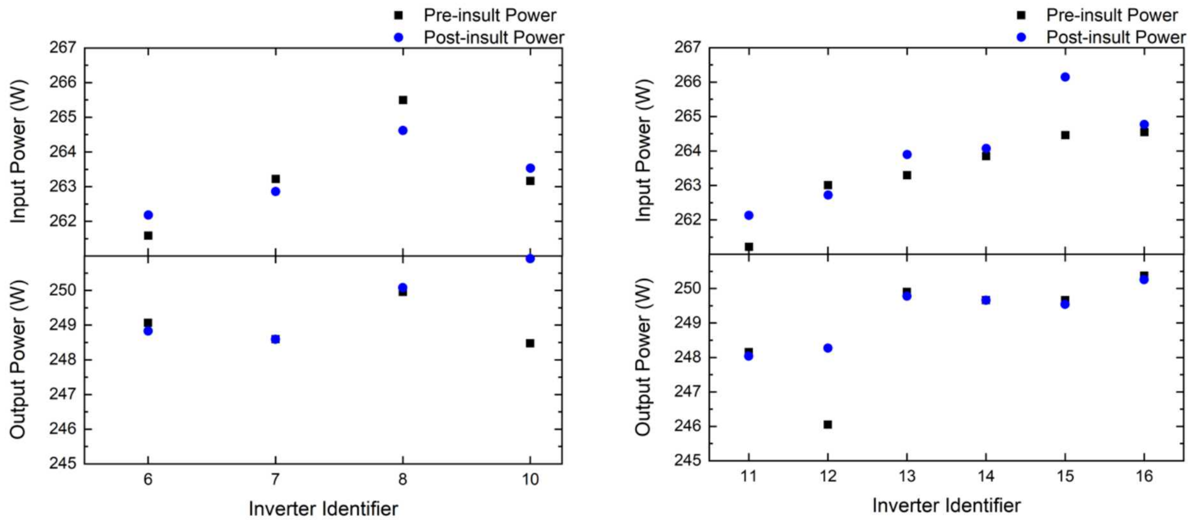


Figure 11: Input and output powers pre- and post-insult for insulting the DC+ terminal (left) and DC- terminal (right) with a 20 kV high voltage pulse.

Figure 11 shows the input and output powers for the differential mode DC tests. For DC+ differential testing, microinverter 5 data is not reported as the post-insult output voltage and currents were not recorded. Microinverter 9 was found to be inoperable and was also not reported. Regardless, no disruption or failures of the microinverters were observed in the DC+ insult test. Output powers stayed nominally around 250 W pre- and post-insult. The results are relatively the same for the DC- tests as no degradation in operation was found. Note that the scaling of the graphs in Figure 11 has been set to highlight differences, however there is little difference between the pre- and post-insult power levels. Differences can be attributed to normal variances in the microinverters' connected AC power supply (wall outlet) and DC power supply (battery voltage). All microinverters reported normal operation (via their status LED and SOH) after every test.

At insult voltages of 40 kV, the few microinverters subjected to this voltage level experienced disruption and faults. In this case, the microinverter was reset with the communications gateway to resume normal operation. If the voltage was increased further to 60 kV, the microinverter would cease to operate regardless of whether a reset was performed. In this case, the microinverter ceased operating and stopped producing output power.

3.2. DC Common Mode Tests

Test identifier 11 indicates the DC common mode tests. The high voltage in this configuration is connected to both the DC+ and DC- terminals (see Figure 7). A total of 5 microinverters were tested in this configuration. The MOV test fixture is used to prevent shorting of the DC+ and DC- terminals until a high voltage is applied from the pulser.

The left panel of Figure 12 shows the representative waveforms for microinverter 17 when it is insulted in common mode configuration. Once again, the voltage of the pulse directly from the output terminal is reduced to a peak of approximately 8-9 kV after the MOV. The peak current observed is approximately 60-70 A and half of the peak current observed in differential mode testing. As noted previously, the measured voltage was taken before the MOV test fixture and thus likely reports a voltage value that is about 5 kV higher than incident on the microinverters. The current, however, was measured at the input terminals of the microinverter and is expected to be accurate.

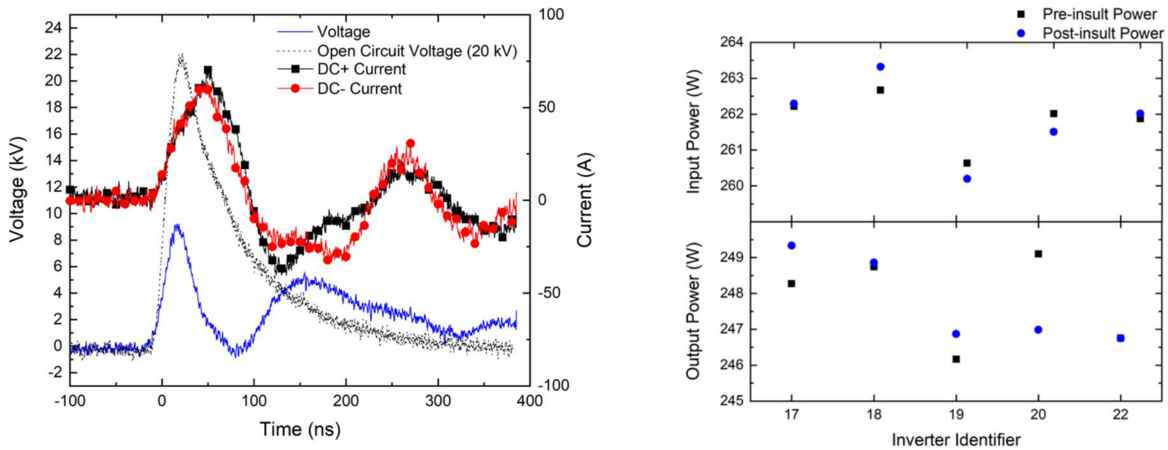


Figure 12: (left) DC common mode test for microinverter 17 showing voltage (blue), DC+ current (black squares), DC- current (red squares), and reference open-circuit voltage shot (dotted). (right) Input and output powers for common mode DC test.

The right panel of Figure 12 shows the pre- and post-insult input and output powers for the L1 and L2 common mode test. Again, there appears to be no degradation of input or output power of the microinverters. All microinverters reported normal operation (via their status LED) after every test.

3.3. AC Common Mode Tests

Two common mode configurations were tested. Test identifiers 1-4 were conducted with the high voltage output connected to L1 and L2 of the microinverter and wall outlet. Test identifiers 5-8 connected the high voltage output to L1, L2, and neutral of the microinverter and wall outlet. Furthermore, the voltage was increased from 20 kV up to 60 kV over the 4 different common mode AC tests. The measured voltages before the MOV test fixture are shown in Figure 11 for the different voltages tested in both test configurations.

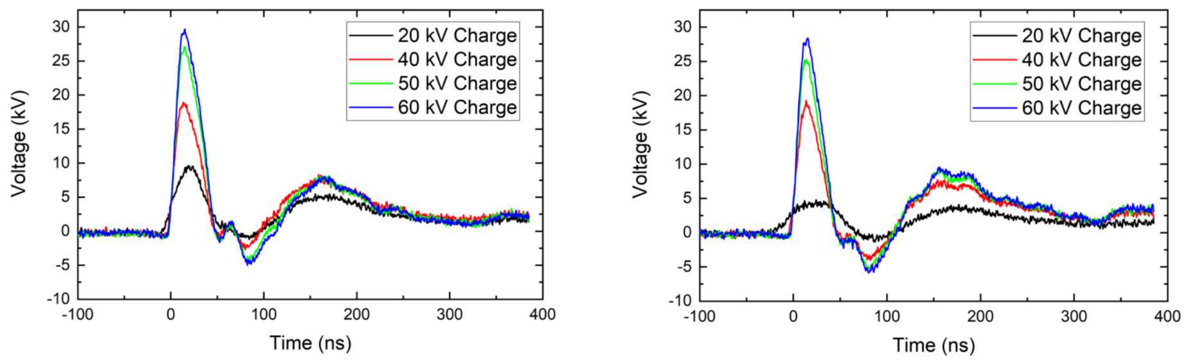


Figure 13: (left) Insult voltages for the L1,L2 common mode tests measured for microinverter 6. (right) Insult voltages for the L1,L2, and N common mode tests measured for microinverter 14.

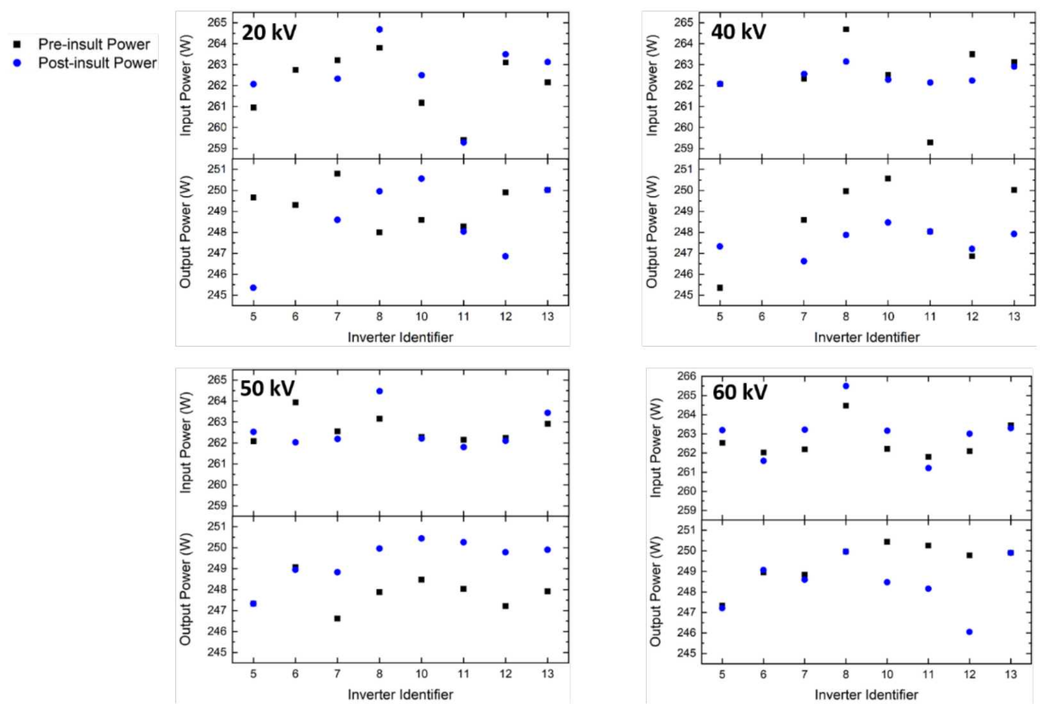


Figure 14: Comparison of pre-insult and post-insult input and output powers for the common mode L1 and L2 tests.

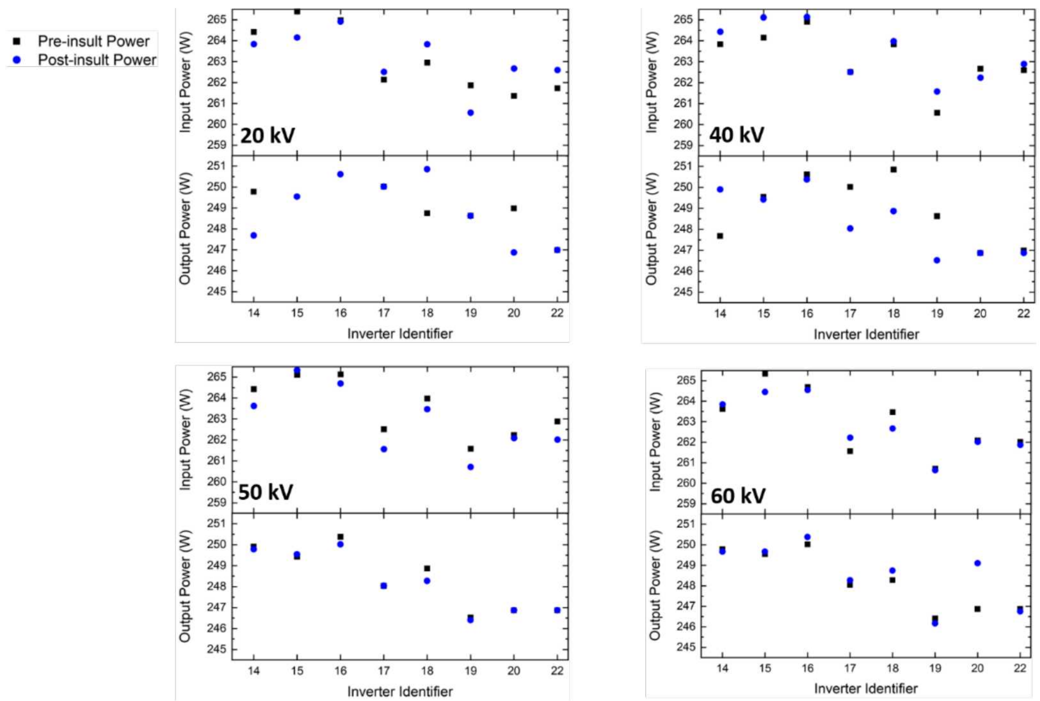


Figure 15: Comparison of pre-insult and post-insult input and output powers for common mode L1, L2, and Neutral tests.

Figures 12 and 13 show the individual microinverter data for comparisons of input power and output power before and after high voltage was applied. Specifically, Figure 12 shows the common tests for connection of high voltage to L1 and L2 only. Figure 13 shows the common mode tests for connection of high voltage to L1, L2, and the neutral component. The different charge voltages are indicated in the figure. In general, there is usually less than 2 W of difference between input and output powers for every microinverter. All microinverters reported normal operation (via their status LED and SOH) after every test.

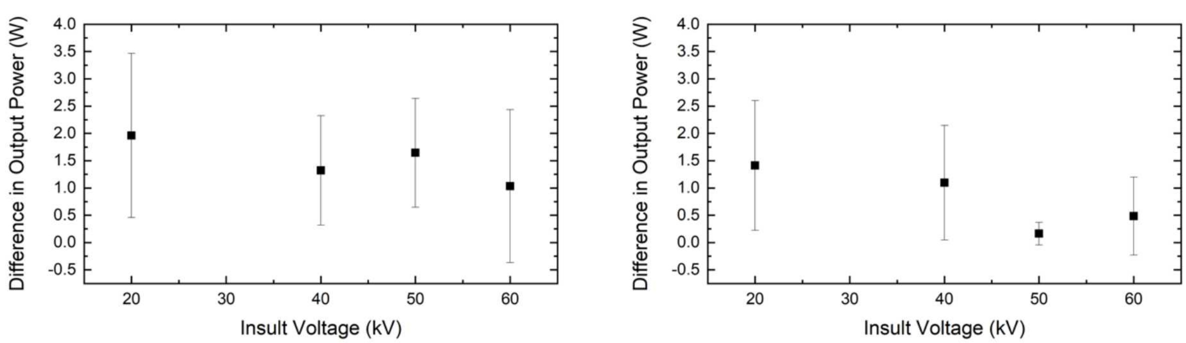


Figure 16: (left) Difference in output power for common mode L1 and L2 tests. (right) Difference in output power for common mode L1, L2, and neutral tests.

Figure 16 attempts to summarize the output power results shown in Figures 14 and 15. Here, the different in output power pre- and post-insult are calculated for both common mode configurations. At each voltage, the average of output power differences were taken (absolute value) along with the standard deviation.

4. CONCLUSION

As EMP effects on components is not fully quantified, investigating potential hazards on critical power grid components is necessary. As a result, the potential impact of EMP coupling on residential DC to AC microinverters was determined via test. The impact was determined by applying a high voltage conducted impulse to the micronverter AC then DC leads. State-of-health measurements were taken before and after each high voltage impulse to determine if there was any detrimental effects to the operation of the microinverter. SOH measurements included operational input and output voltages and currents.

A total of 22 residential microinverters were subjected to conducted pulse tests simulating EMP insults. Tested voltages ranged from 20 kV to 60 kV on the AC side and 20 kV on the DC side. In testing, and as shown in Table 2, no microinverters failed or were disrupted by insulting either AC or DC side in common mode or differential mode, when tested within their maximum expected insult values. Input and output power variations on the order of 2 W or less were observed in SOH measurements. However, these variances were likely due to normal variations in AC line-to-line voltage and DC input voltage.

The microinverters AC and DC sides were tested individually. That is, high voltage impulses were isolated to a single side. Realistically, an EMP event would affect both AC and DC sides simultaneously. Future testing should involve insulting both AC and DC sides simultaneously to determine if failures of the microinverter are more prevalent under these circumstances.

REFERENCES

[1] D. Sanabria, "Early Time (E1) Electromagnetic Pulse Effects on Lightning Surge Arresters and Trip Coils," University of New Mexico, 2020.

[2] Enphase Energy, "Enphase M250 and M215 Microinverters," Enphase Energy, 2016.

[3] T. Bowman, J. Flicker, R. Guttromson, M. Halligan, R. Llanes and M. Ropp, "High Altitude Electromagnetic Pulse Testing of Photovoltaic Modules," Sandia Report SAND2020-3824, 2020.

APPENDIX A. RAW DATA FOR EACH MICROINVERTER

Raw data for each microinverter is compiled here. High voltages from the pulser were measured with a Northstar PVM-6. Fast currents generated by the high voltage pulser into the DC terminals of the microinverter were measured with a Pearson 6600 fast current transformer. AC and DC voltages were measured with a standard Fluke 87-V voltmeter. AC and DC current was measured with a Fluke i30 DC/AC ammeter. Figure 17 shows the locations of each probe on the microinverter. The high voltage from the output pulser was always measured directly at the output and always before the MOV's if they were used.

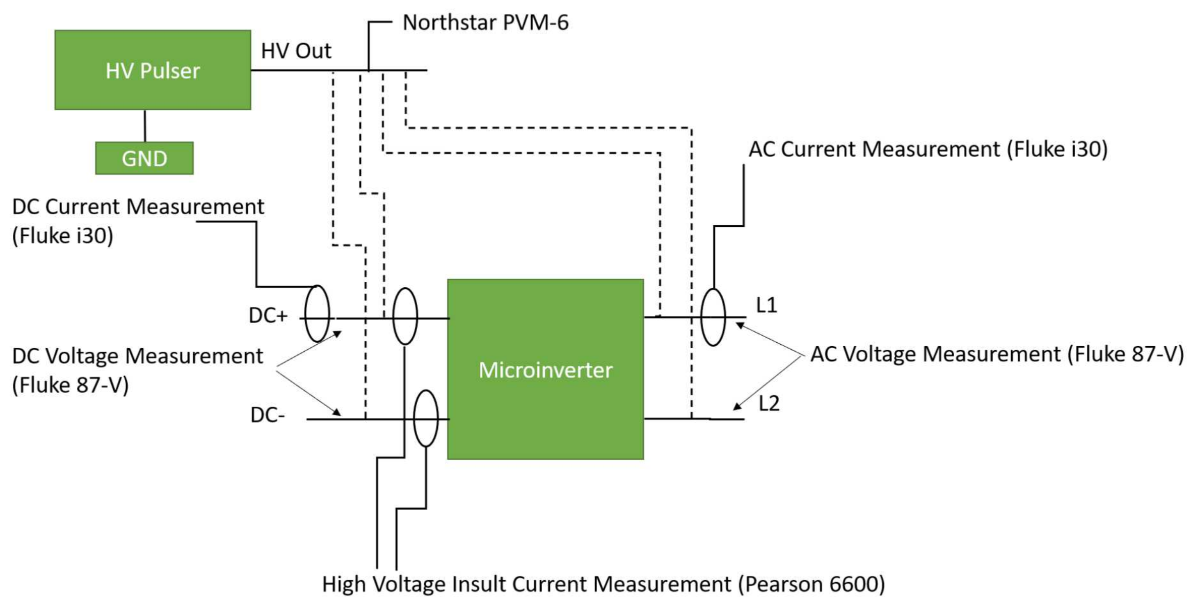


Figure 17: Location of AC, DC, and transient diagnostics.

A.1. Microinverter 5

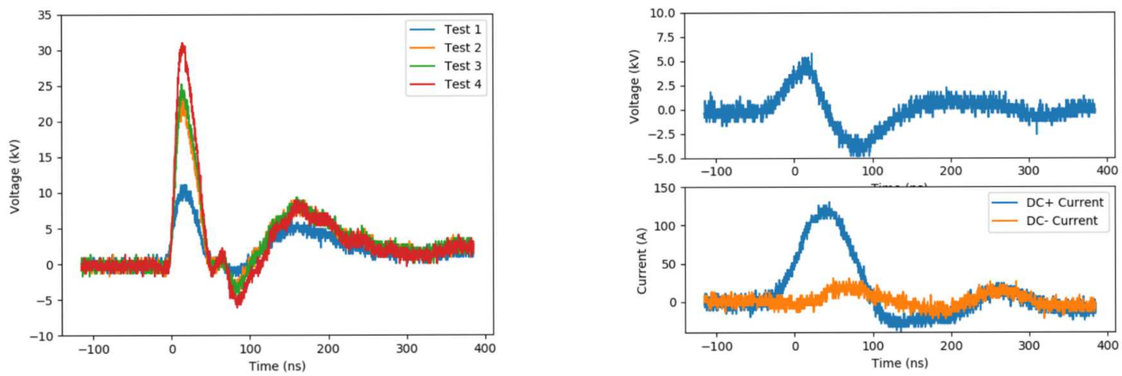


Figure 18: (left) AC Test voltage waveforms – Tests 1,2,3,4 (right) DC test voltage (top) and current (bottom) waveforms – Test 9.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	7.07	36.91	1.19	209.8
2	7.11	36.86	1.17	209.7
3	7.12	36.81	1.18	209.6
4	7.13	36.82	1.18	209.6

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	7.11	36.86	1.17	209.7
2	7.12	36.81	1.18	209.6
3	7.13	36.82	1.18	209.6
4	7.15	36.81	1.18	209.5

DC Data

DC Test 9	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.15	36.81	1.18	209.5
Post-insult	Not recorded	Not recorded	Not recorded	Not recorded

A.2. Microinverter 6

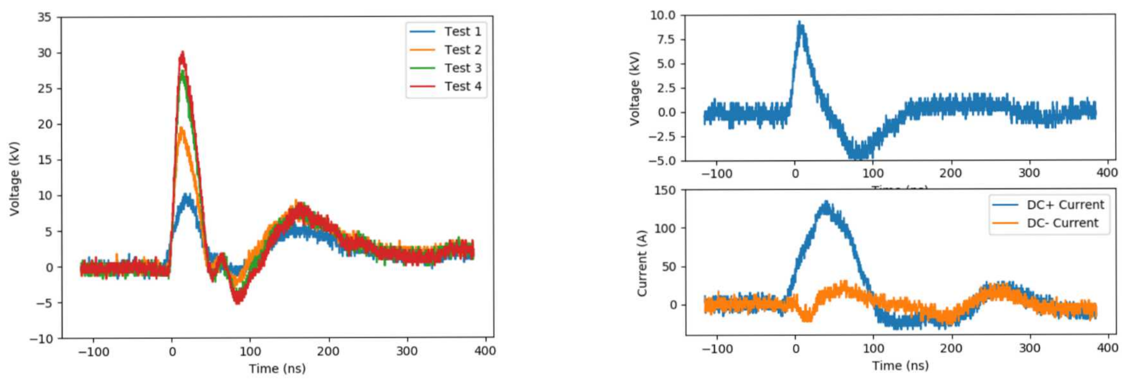


Figure 19: (left) AC Test voltage waveforms – Tests 1,2,3,4 (right) DC test voltage (top) and current (bottom) waveforms – Test 9.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	7.14	36.8	1.19	209.5
2	Not recorded	Not recorded	Not recorded	Not recorded
3	7.18	36.76	1.19	209.3
4	7.13	36.75	1.19	209.2

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	Not recorded	Not recorded	Not recorded	Not recorded
2	7.18	36.76	1.19	209.3
3	7.13	36.75	1.19	209.2
4	7.12	36.74	1.19	209.3

DC Data

DC Test 9	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.12	36.74	1.19	209.3
Post-insult	7.14	36.72	1.19	209.1

A.3. Microinverter 7

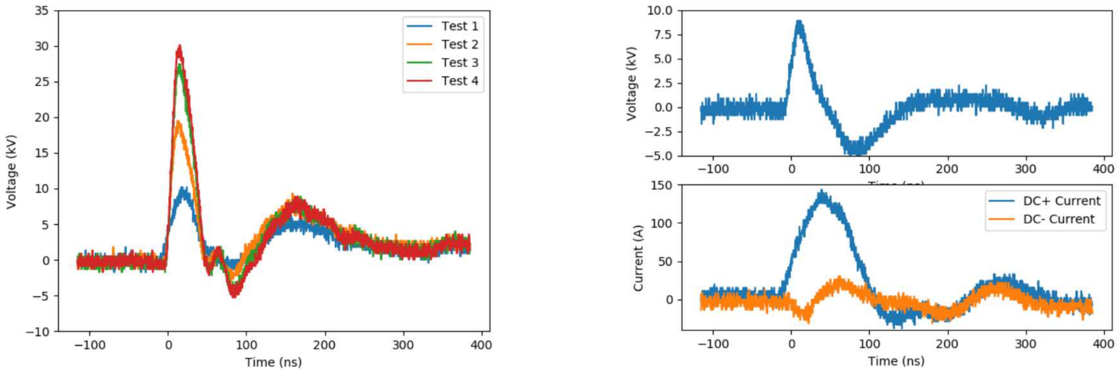


Figure 20: (left) AC Test voltage waveforms – Tests 1,2,3,4 (right) DC test voltage (top) and current (bottom) waveforms – Test 9.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	7.17	36.71	1.2	209
2	7.15	36.69	1.19	208.9
3	7.16	36.67	1.18	209
4	7.15	36.67	1.19	209.1

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	7.15	36.69	1.19	208.9
2	7.16	36.67	1.18	209
3	7.15	36.67	1.19	209.1
4	7.18	36.66	1.19	208.9

DC Data

DC Test 9	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.18	36.66	1.19	208.9
Post-insult	7.18	36.61	1.19	208.9

A.4. Microinverter 8

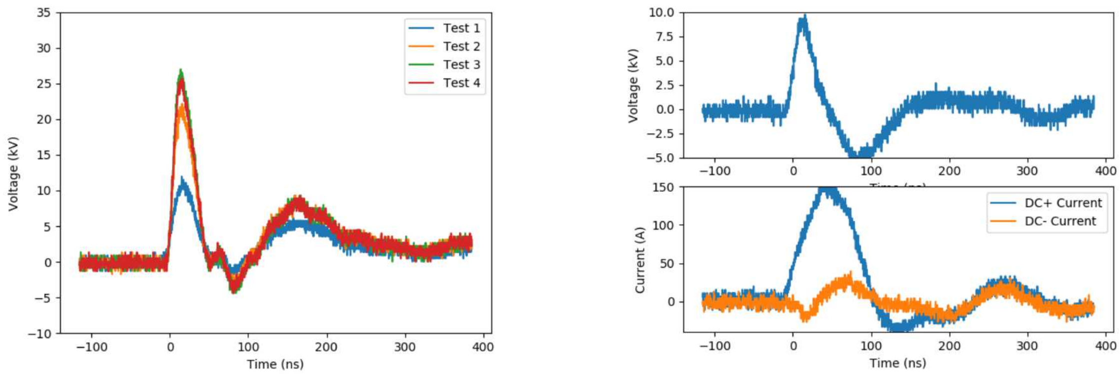


Figure 21: (left) AC Test voltage waveforms – Tests 1,2,3,4 (right) DC test voltage (top) and current (bottom) waveforms – Test 9.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	7.2	36.64	1.19	208.4
2	7.23	36.61	1.2	208.3
3	7.19	36.6	1.19	208.3
4	7.23	36.58	1.2	208.3

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	7.23	36.61	1.2	208.3
2	7.19	36.6	1.19	208.3
3	7.23	36.58	1.2	208.3
4	7.26	36.57	1.2	208.3

DC Data

DC Test 9	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.26	36.57	1.2	208.3
Post-insult	7.24	36.55	1.2	208.4

A.5. Microinverter 10

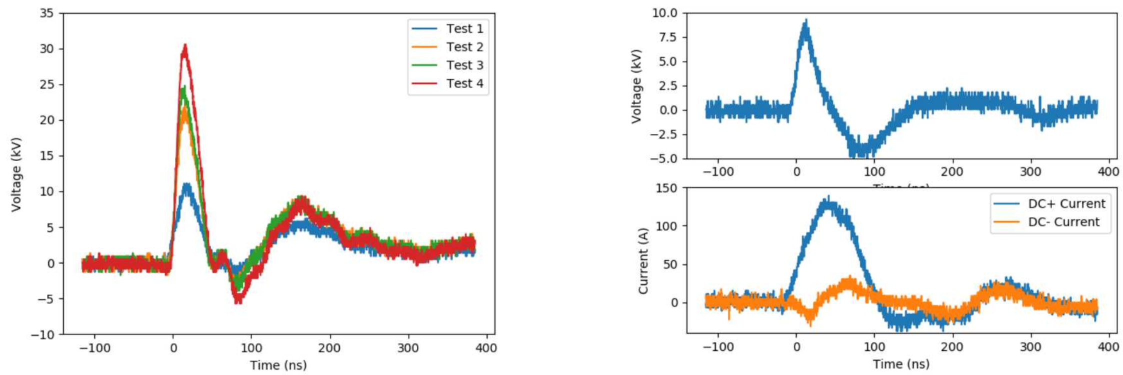


Figure 22: (left) AC Test voltage waveforms – Tests 1,2,3,4 (right) DC test voltage (top) and current (bottom) waveforms – Test 9.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	7.14	36.58	1.19	208.9
2	7.18	36.56	1.2	208.8
3	7.18	36.53	1.19	208.8
4	7.18	36.52	1.2	208.7

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	7.18	36.56	1.2	208.8
2	7.18	36.53	1.19	208.8
3	7.18	36.52	1.2	208.7
4	7.21	36.5	1.19	208.8

DC Data

DC Test 9	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.21	36.5	1.19	208.8
Post-insult	7.22	36.5	1.2	209.1

A.6. Microinverter 11

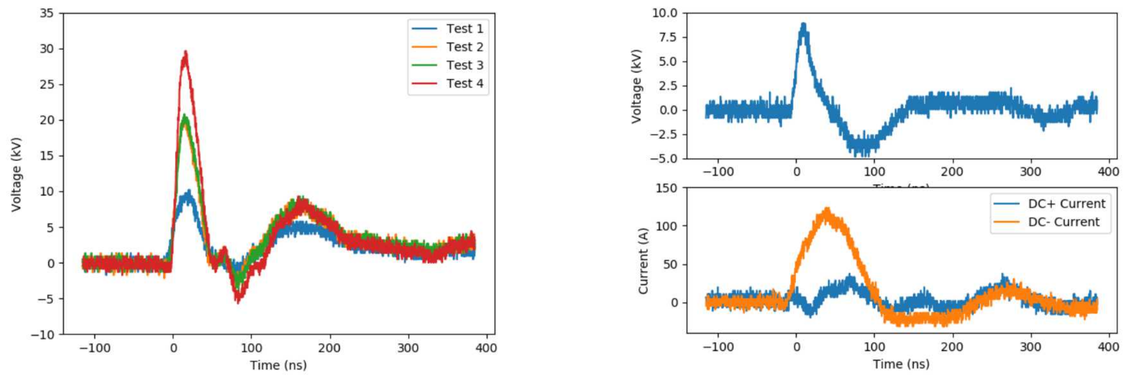


Figure 23: (left) AC Test voltage waveforms – Tests 1,2,3,4 (right) DC test voltage (top) and current (bottom) waveforms – Test 10.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	6.91	37.54	1.18	210.4
2	6.92	37.47	1.18	210.2
3	7	37.45	1.18	210.2
4	7	37.4	1.19	210.3

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	6.92	37.47	1.18	210.2
2	7	37.45	1.18	210.2
3	7	37.4	1.19	210.3
4	6.99	37.37	1.18	210.3

DC Data

DC Test 10	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	6.99	37.37	1.18	210.3
Post-insult	7.02	37.34	1.18	210.2

A.7. Microinverter 12

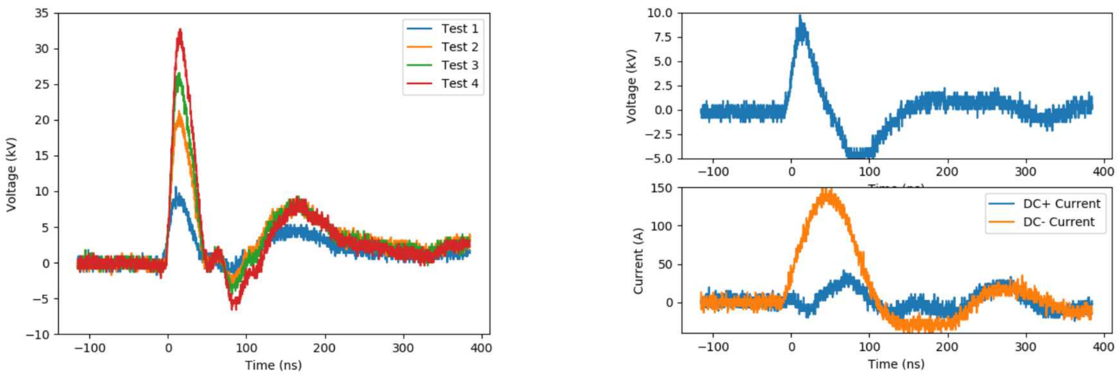


Figure 24: (left) AC Test voltage waveforms – Tests 1,2,3,4 (right) DC test voltage (top) and current (bottom) waveforms – Test 10.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	7.05	37.32	1.19	210
2	7.07	37.27	1.18	209.2
3	7.04	37.25	1.18	209.5
4	7.04	37.23	1.19	209.9

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	7.07	37.27	1.18	209.2
2	7.04	37.25	1.18	209.5
3	7.04	37.23	1.19	209.9
4	7.07	37.2	1.17	210.3

DC Data

DC Test 10	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.07	37.2	1.17	210.3
Post-insult	7.07	37.16	1.18	210.4

A.8. Microinverter 13

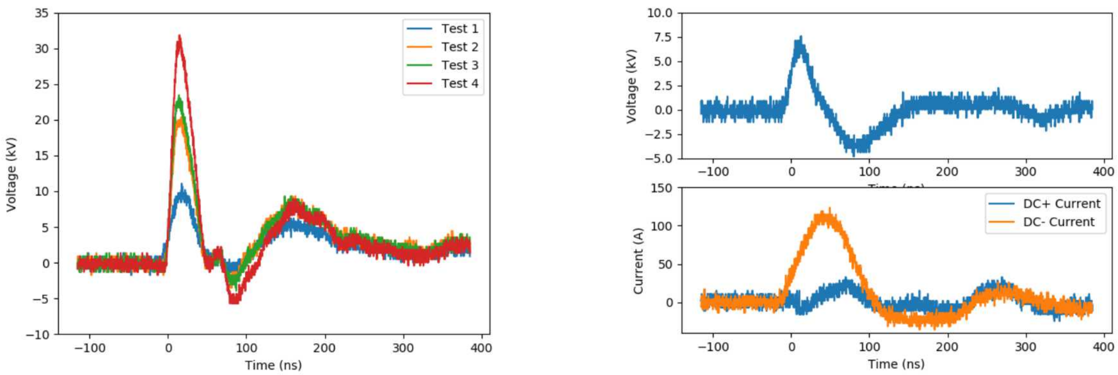


Figure 25: (left) AC Test voltage waveforms – Tests 1,2,3,4 (right) DC test voltage (top) and current (bottom) waveforms – Test 10.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	7.07	37.08	1.19	210.1
2	7.1	37.06	1.19	210.1
3	7.1	37.03	1.18	210.1
4	7.12	37	1.19	210

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
1	7.1	37.06	1.19	210.1
2	7.1	37.03	1.18	210.1
3	7.12	37	1.19	210
4	7.12	36.98	1.19	210

DC Data

DC Test 10	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.12	36.98	1.19	210
Post-insult	7.14	36.96	1.19	209.9

A.9. Microinverter 14

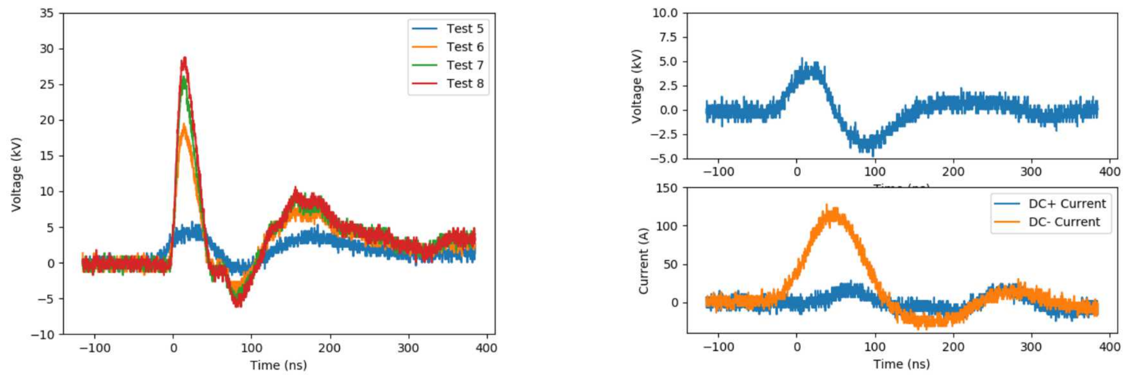


Figure 26: (left) AC Test voltage waveforms – Tests 5,6,7,8 (right) DC test voltage (top) and current (bottom) waveforms – Test 10.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.16	36.93	1.19	209.9
6	7.15	36.9	1.18	209.9
7	7.17	36.88	1.19	210
8	7.15	36.87	1.19	209.9

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.15	36.9	1.18	209.9
6	7.17	36.88	1.19	210
7	7.15	36.87	1.19	209.9
8	7.16	36.85	1.19	209.8

DC Data

DC Test 10	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.16	36.85	1.19	209.8
Post-insult	7.17	36.83	1.19	209.8

A.10. Microinverter 15

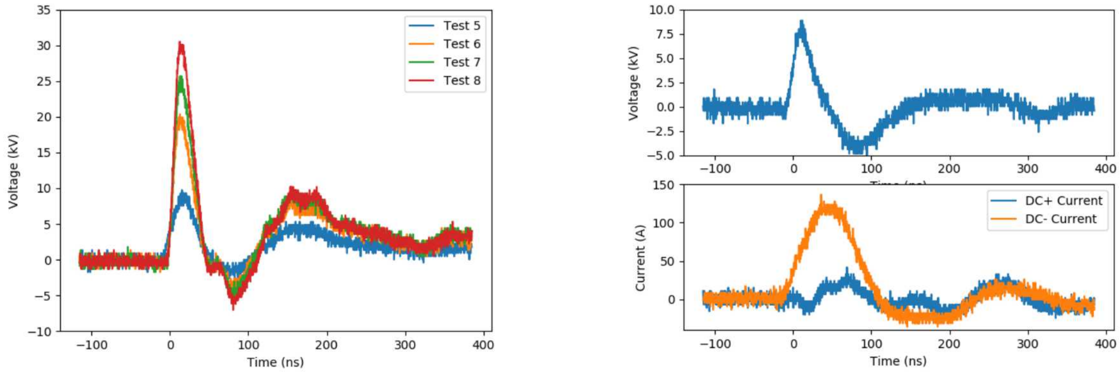


Figure 27: (left) AC Test voltage waveforms – Tests 5,6,7,8 (right) DC test voltage (top) and current (bottom) waveforms – Test 10.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.2	36.86	1.2	209.8
6	7.18	36.79	1.19	209.7
7	7.21	36.77	1.19	209.6
8	7.22	36.75	1.19	209.7

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.18	36.79	1.19	209.7
6	7.21	36.77	1.19	209.6
7	7.22	36.75	1.19	209.7
8	7.2	36.73	1.19	209.8

DC Data

DC Test 10	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.2	36.73	1.19	209.8
Post-insult	7.25	36.71	1.19	209.7

A.11. Microinverter 16

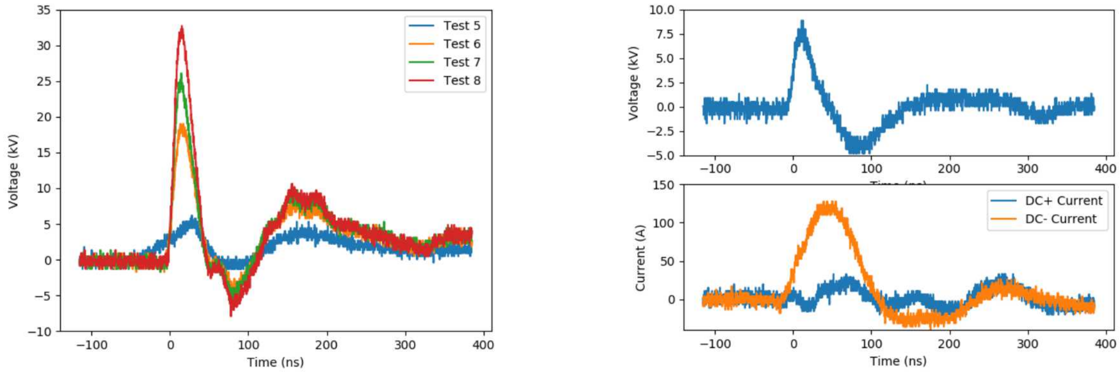


Figure 28: (left) AC Test voltage waveforms – Tests 5,6,7,8 (right) DC test voltage (top) and current (bottom) waveforms – Test 10.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.23	36.65	1.21	209.4
6	7.24	36.59	1.19	210.6
7	7.25	36.57	1.19	210.4
8	7.24	36.56	1.19	210.1

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.24	36.59	1.19	210.6
6	7.25	36.57	1.19	210.4
7	7.24	36.56	1.19	210.1
8	7.24	36.54	1.19	210.4

DC Data

DC Test 10	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.24	36.54	1.19	210.4
Post-insult	7.25	36.52	1.19	210.3

A.12. Microinverter 17

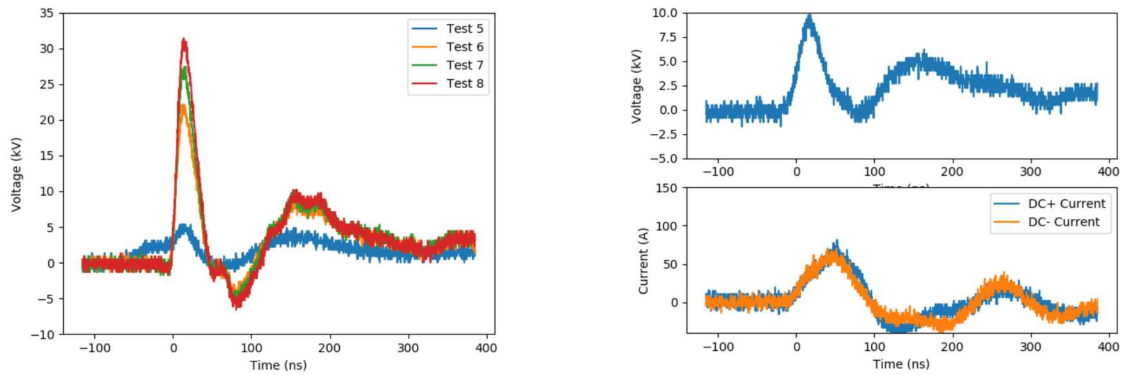


Figure 29: (left) AC Test voltage waveforms – Tests 5,6,7,8 (right) DC test voltage (top) and current (bottom) waveforms – Test 11.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.17	36.56	1.19	210.1
6	7.19	36.51	1.19	210.1
7	7.19	36.51	1.18	210.2
8	7.17	36.48	1.17	212

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.19	36.51	1.19	210.1
6	7.19	36.51	1.18	210.2
7	7.17	36.48	1.17	212
8	7.19	36.47	1.17	212.2

DC Data

DC Test 11	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.19	36.47	1.17	212.2
Post-insult	7.2	36.43	1.18	211.3

A.13. Microinverter 18

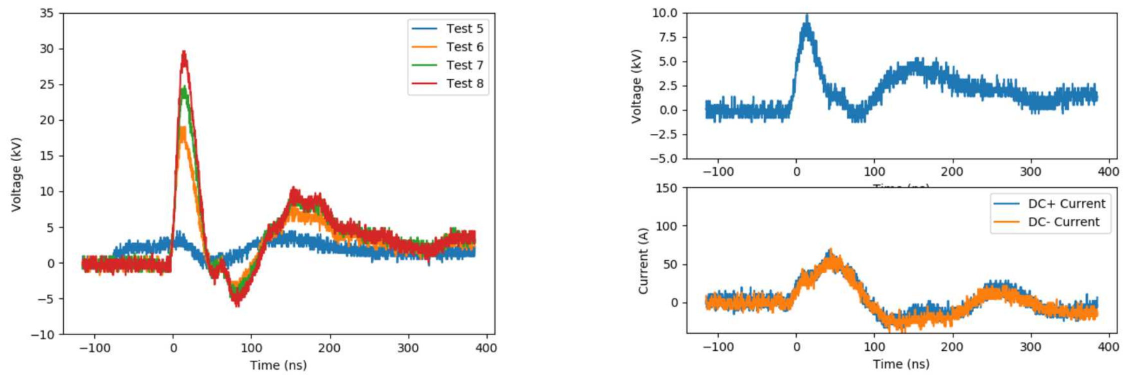


Figure 30: (left) AC Test voltage waveforms – Tests 5,6,7,8 (right) DC test voltage (top) and current (bottom) waveforms – Test 11.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.21	36.47	1.18	210.8
6	7.25	36.39	1.19	210.8
7	7.26	36.36	1.18	210.9
8	7.25	36.34	1.18	210.4

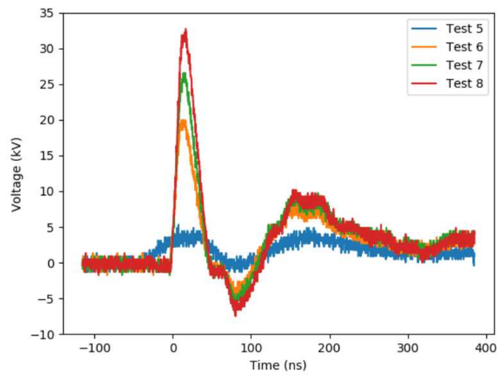
Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.25	36.39	1.19	210.8
6	7.26	36.36	1.18	210.9
7	7.25	36.34	1.18	210.4
8	7.23	36.33	1.18	210.8

DC Data

DC Test 11	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.23	36.33	1.18	210.8
Post-insult	7.25	36.32	1.18	210.9

A.14. Microinverter 19



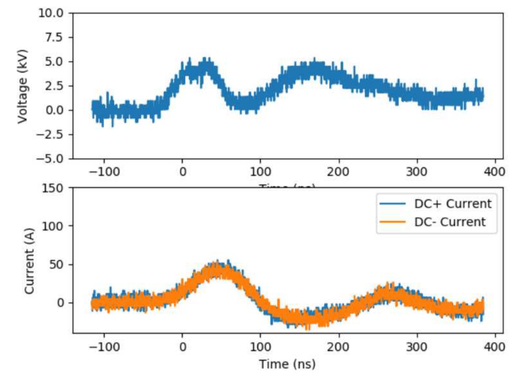


Figure 31: (left) AC Test voltage waveforms – Tests 5,6,7,8 (right) DC test voltage (top) and current (bottom) waveforms – Test 11.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.2	36.37	1.18	210.7
6	7.17	36.34	1.18	210.7
7	7.2	36.33	1.17	210.7
8	7.18	36.31	1.17	210.6

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.17	36.34	1.18	210.7
6	7.2	36.33	1.17	210.7
7	7.18	36.31	1.17	210.6
8	7.18	36.3	1.17	210.4

DC Data

DC Test 11	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.18	36.3	1.17	210.4
Post-insult	7.17	36.29	1.17	211

A.15. Microinverter 20

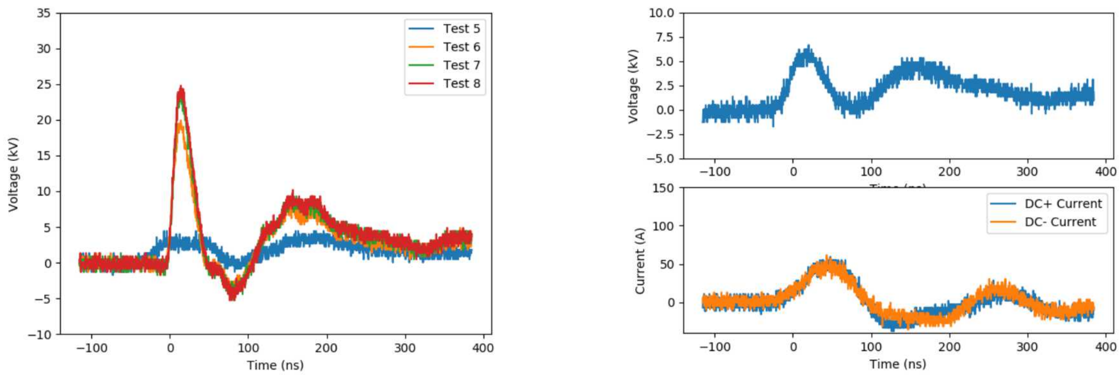


Figure 32: (left) AC Test voltage waveforms – Tests 5,6,7,8 (right) DC test voltage (top) and current (bottom) waveforms – Test 11.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.2	36.3	1.18	211
6	7.24	36.28	1.17	211
7	7.23	36.27	1.17	211
8	7.23	36.25	1.17	211

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.24	36.28	1.17	211
6	7.23	36.27	1.17	211
7	7.23	36.25	1.17	211
8	7.23	36.24	1.18	211.1

DC Data

DC Test 11	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.23	36.24	1.18	211.1
Post-insult	7.22	36.22	1.17	211.1

A.16. Microinverter 22

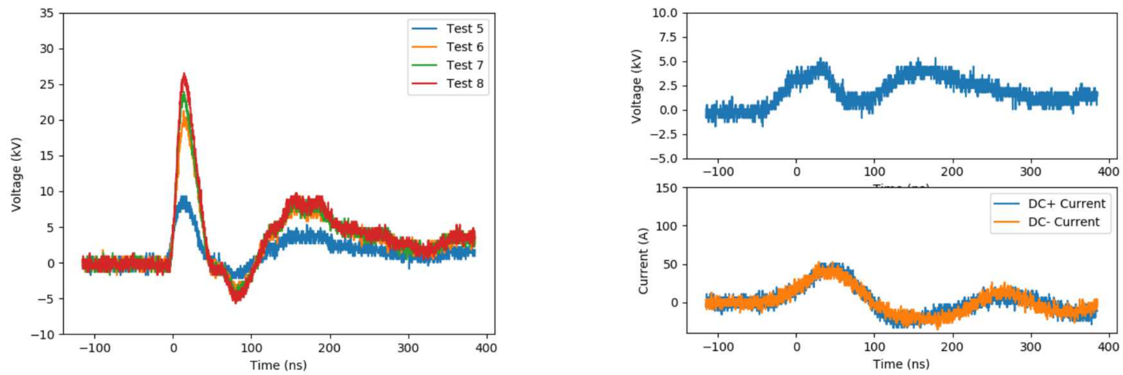


Figure 33: (left) AC Test voltage waveforms – Tests 5,6,7,8 (right) DC test voltage (top) and current (bottom) waveforms – Test 11.

Pre-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.21	36.3	1.17	211.1
6	7.25	36.22	1.17	211.1
7	7.26	36.21	1.17	211
8	7.24	36.19	1.17	211

Post-insult data

AC Test	DC Current	DC Voltage	AC Current	AC Voltage
5	7.25	36.22	1.17	211.1
6	7.26	36.21	1.17	211
7	7.24	36.19	1.17	211
8	7.24	36.17	1.17	210.9

DC Data

DC Test 11	DC Current	DC Voltage	AC Current	AC Voltage
Pre-insult	7.24	36.17	1.17	210.9
Post-insult	7.25	36.14	1.17	210.9

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Name	Org.	Sandia Email Address
Ross Guttromson	08812	rguttro@sandia.gov
Matt Halligan	01353	mhallig@sandia.gov
Technical Library	01977	sanddocs@sandia.gov

Email—External [redacted]

Name	Company Email Address	Company Name
Andrew Fierro	asfierro@unm.edu	The Univeristy of New Mexico
David E Sanabria	desanabriad@unm.edu	The University of New Mexico
Jane Lehr	jmlehr@unm.edu	The University of New Mexico
Ken Le	kle@unm.edu	The University of New Mexico

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