March 5-7, 2019

2019 ATIS-PEG Conference
Northbrook, Il.

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"Solar Farm Inverter Harmonics Which Caused Interference in Telecommunications Copper Cable Facilities."

Presented by:
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CenturyLink Inc.

"Solar Farm Inverter Harmonics"

How it all began:

- New 20 MW Solar Farm, equipped with 8- DC to AC inverters, was placed in service April 2017.
- Customer reports of "noise on line" began soon after.
- Customer reports noise only on line during daylight hours.
- Local field techs worked on bonding/ grounding cable shields in affected area.
- Regional tech support brought in to help evaluate cause of noise metallic and high power influence.
- National ICEP tech support contacted April 23rd 2018.
- May 21st 2018, National ICEP tech support arrives to begin on site evaluation.

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Areas of exposure: Three phase distribution with 3 Phase "express" line from solar farm point of interconnect (PoI) to substation

The first area is approximately 6/10 of a mile long and includes a 3 phase "express" distribution line that runs between the solar farm PoI and the low voltage buss at a substation 2.7 miles NE of the solar farm. It also includes an under built 3 phase distribution line fed from the same substation. Both 3 phase lines share a neutral conductor.

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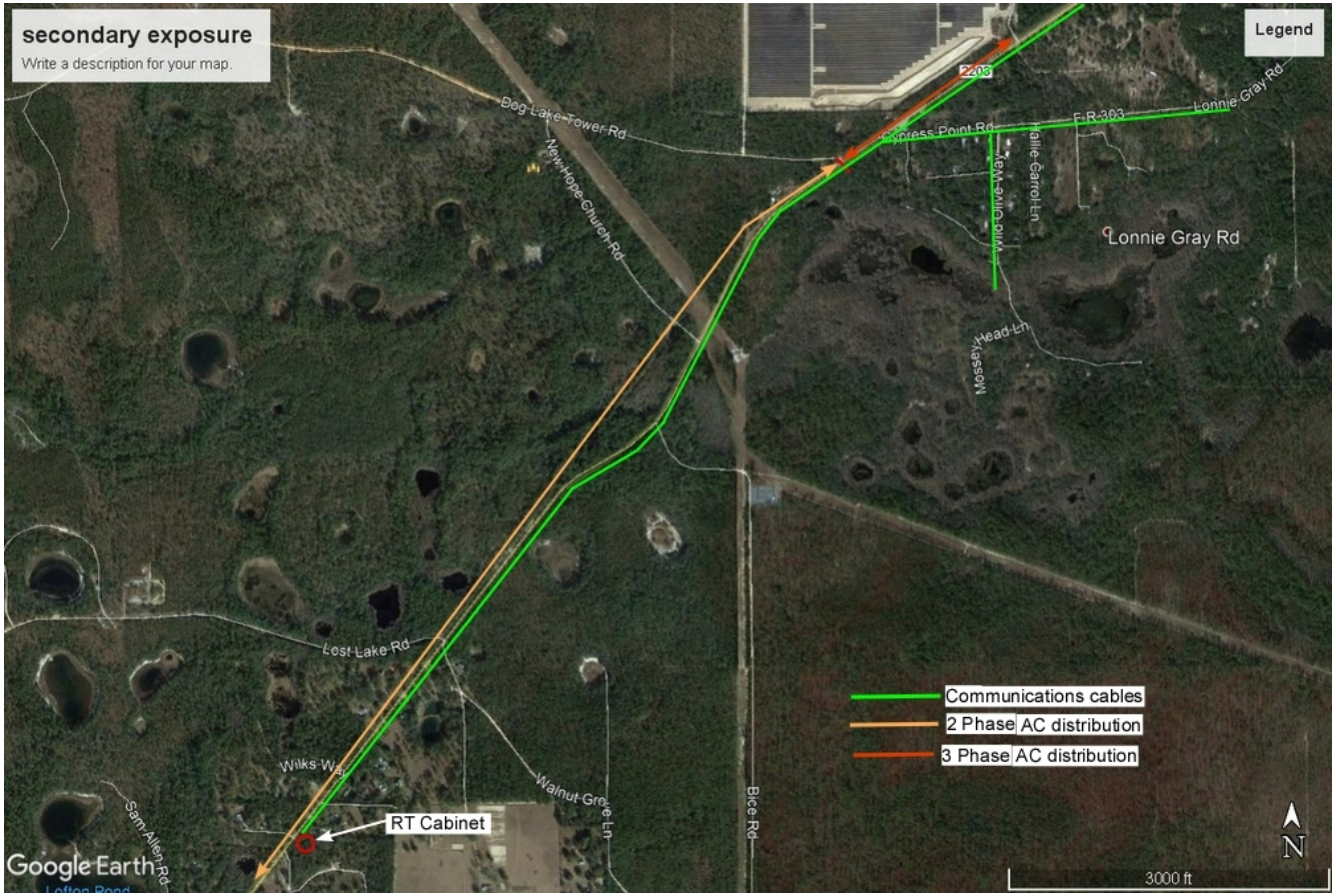
Areas of exposure: Communications cables between 3 Phase solar farm point of interconnect (PoI) and remote electronics cabinet (RT)



The second area of exposure is on the field side of the solar farm with a 3 phase MGN distribution line that continues for 4/10 of a mile before it transitions to 2 phase MGN. The remaining 5.6 miles of exposure are the 2 phase MGN line.

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Point of interconnect between solar farm invertors and the City of Tallahassee 3 phase "express" distribution line.

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Transition point between buried phase wires from solar farm PoI to aerial 3 phase "express" distribution line with 3 phase MGN distribution under build. Both 3 phase lines share the neutral conductor.

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Part I: Initial Evaluation

- Power Influence 92dBrnC*
- Noise Metallic 24dBrnC
- Balance 68dBrnC
- AC Voltage measured on cable pair = 5.7 volts
- Beginning shield current 0.02 to 5.5 amps AC. After additional cable shield bonding and grounding- shield current 0.6 to 5.5 amps AC depending on cable size and exposure.
- Additional shield current had no affect on power influence or noise metallic readings.

* dBrnC = Decibels, above reference noise, with C-message weighting.

Audible Noise

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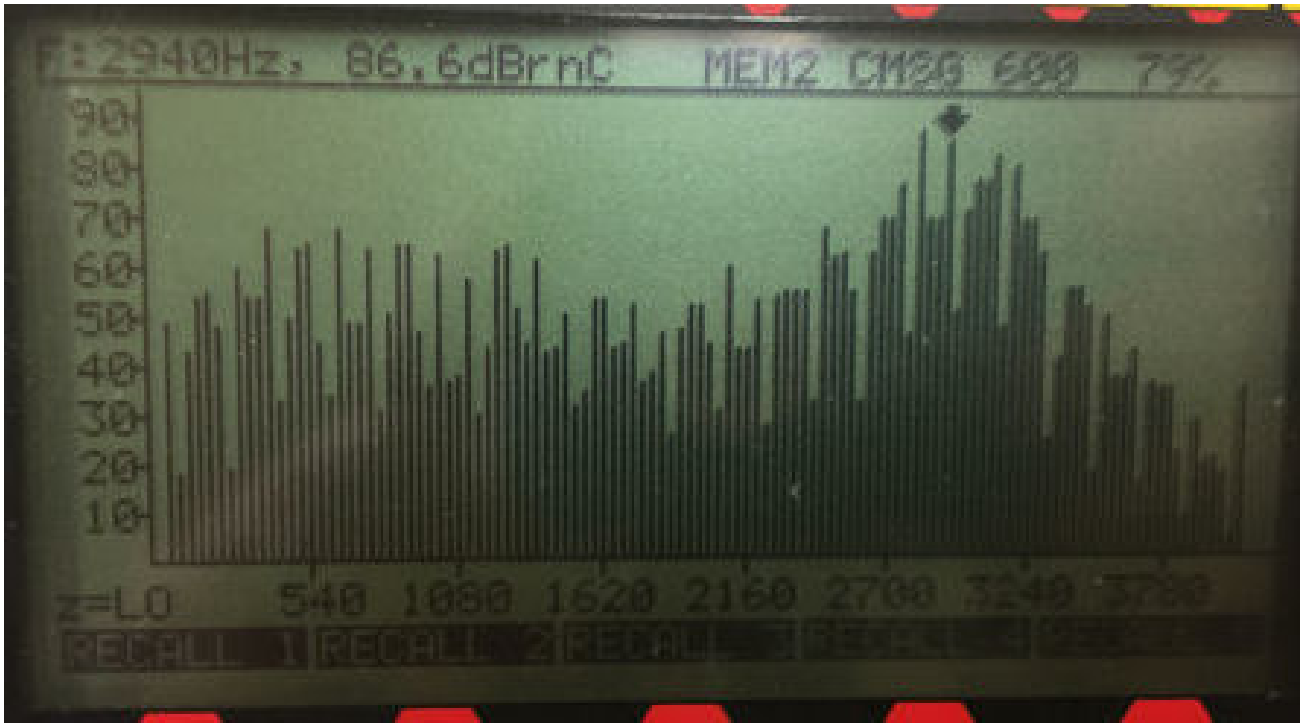

Harmonic graph readings taken from conductors in communications cable. 47th and 49th harmonic (2820/2940 Hz) identified as most offending.

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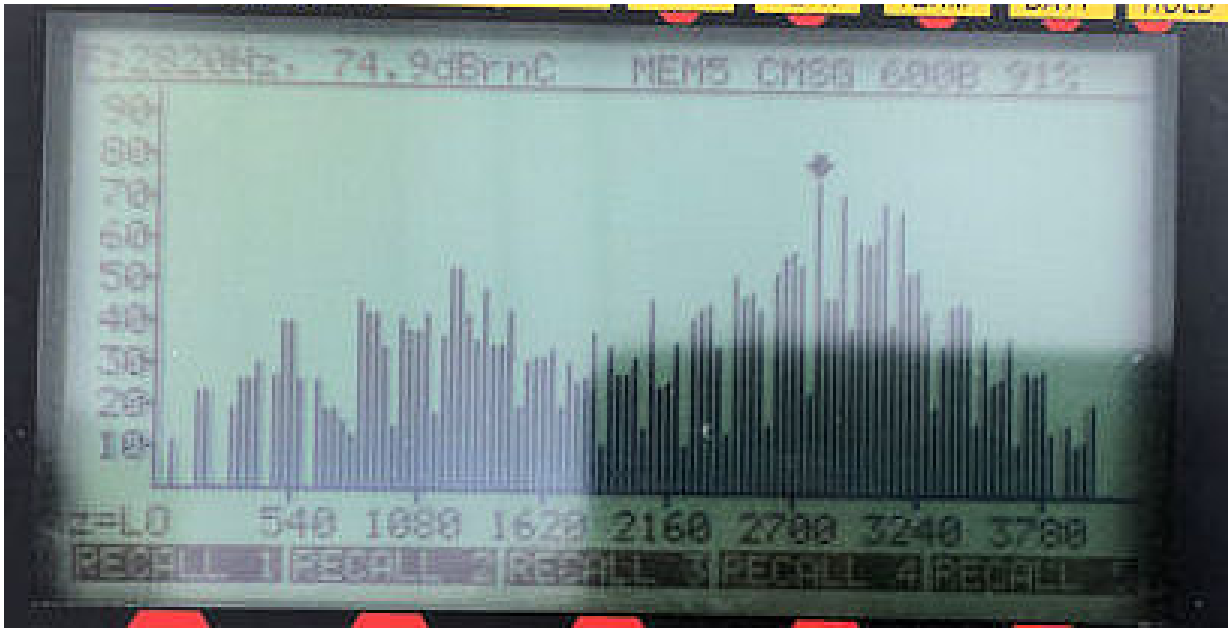

Harmonic graph readings taken from 100 foot probe wire placed under 3 phase solar farm express line conductors shows 47th and 49th harmonics to be the most offending.

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Harmonic graph reading using 100 foot probe wire under 3 phase distribution line beyond the solar farm point of interconnect.

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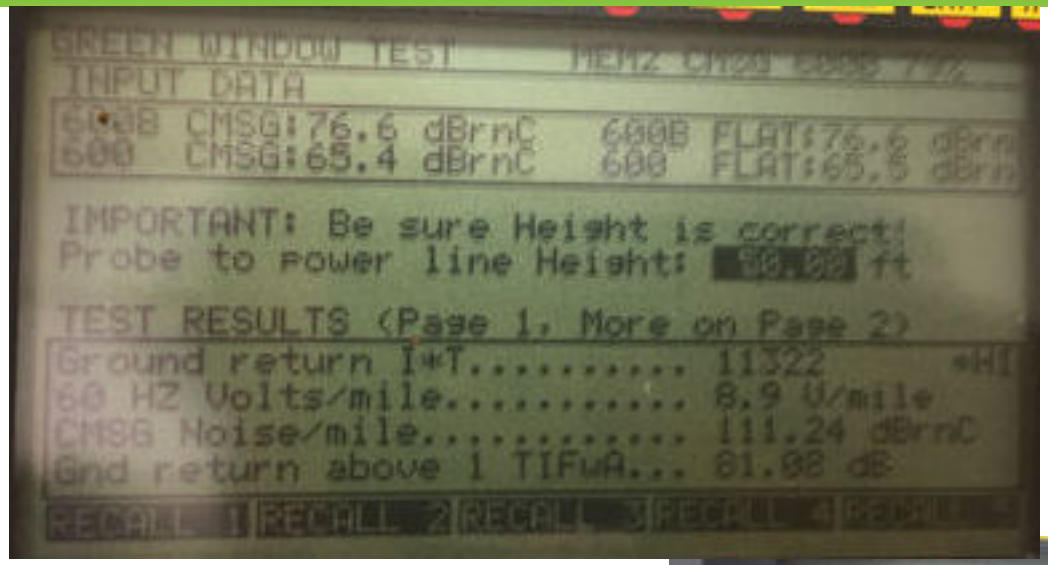
Green Window Test

This test, developed by Warren Green for Pacific NW Bell, uses 4 measurements using 3kHz terminated and bridged both flat and C- Message filters. This test is taken using a 100 foot probe wire, grounded at both ends, and the known distance to the nearest phase wire must be input into the test meter. (I used the Triplett Mitigator test set which preforms the necessary calculations)

Test results include:

- *Ground Return I*T* (A single number indicating the interfering potential of the section of power being evaluated)
- *60 Hz Volts per mile*
- *C-Message noise per mile*

"Solar Farm Inverter Harmonics"



Green Window Test- 3 phase "express" line from solar farm to substation.

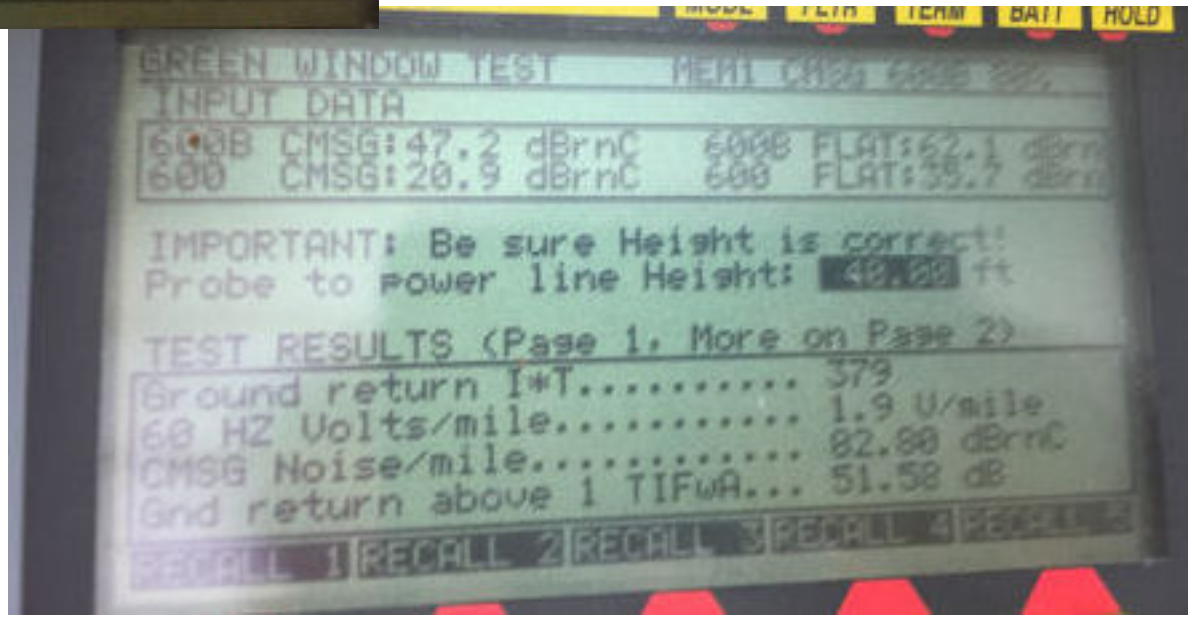
- Ground Return I*T = 11322.
- 60HZ V per mile 8.9 V.

Measured AC voltage in 6/10 mile exposure of 5.7 V very close to calculated 5.34 V in 6/10 mile.

Green Window Test- 3 phase distribution line south of solar farm.

- Ground Return I*T = 379.
- CMSG Noise/mile and Grd return above 1 TIFwA* both dropped about 29 dB.
- 60 HZ V per mile 1.9 Volts.

*TIFwA = Telephone Influence Factor weighted Amp



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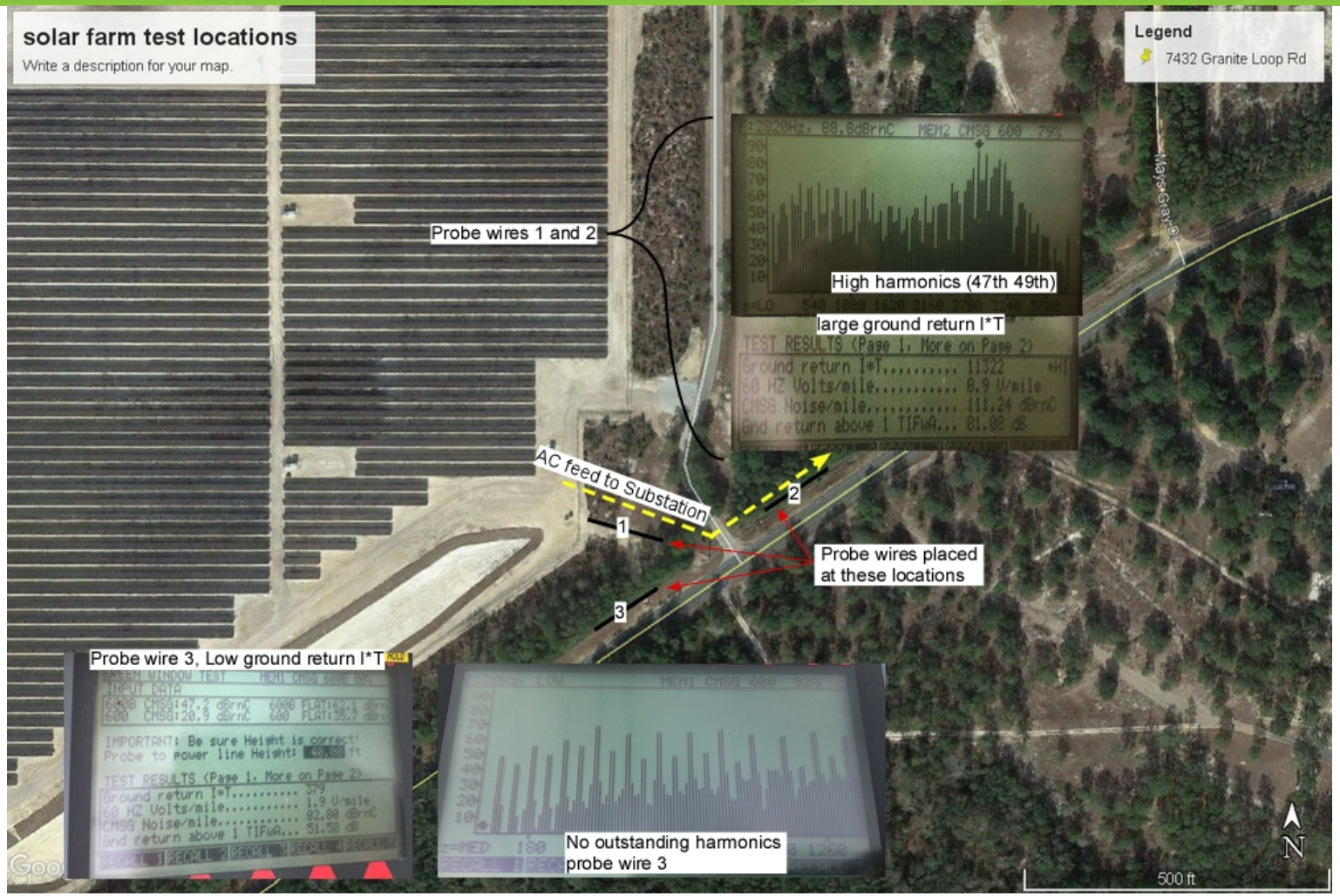

Preliminary investigation, through the use of specific probe wire placements, showed the source of the offending harmonics to be the solar farm.

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Commonly used noise mitigation devices are designed for lower harmonic frequencies and, even though PI levels where reduced, had no affect on reducing Nm in this case.

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Now what do we do???

- Opened dialog with solar farm owner (City of Tallahassee, FL), builder (Origis Energy) and Inverter manufacturer (SMA Solar Technology).

Note: *Per the City of Tallahassee and Origis Energy, the total harmonic distortion measured on the low voltage buss at the substation was within IEEE standards.*

- Schedule second site visit to test theoretical mitigation of invertor produced harmonics.
- Requested information from invertor manufacturer concerning pulse rate i.e. 6 pulse, 12 pulse …48 pulse etc.
- Initial research of harmonics made a 48 pulse inverter suspect due to a lack of cancelling at the 47^{th} harmonic.
- SMA feedback was that the site is equipped with 6 pulse inverters.

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6 pulse inverters

- 6 pulse inverters may produce harmonics in the AC power distribution system. Having multiple inverters may produce a greater magnitude of harmonics depending on how many inverters are wired in parallel.
- "The characteristic harmonics are based on the number of rectifier [inverter] (pulse number) used in a circuit and can be determined by the following equation" *(1)*

$$h = (n \times p) \pm 1$$

Where: n = an integer (1,2,3…)

p = number of pulses or rectifiers

Using a 6 pulse rectifier the characteristic harmonics will be:

$h = (1 \times 6) \pm 1 \rightarrow 5^{th}$ & 7^{th} harmonics

$h = (2 \times 6) \pm 1 \rightarrow 11^{th}$ & 13^{th} harmonics

For the solar farm I confirmed the offending harmonics with the following equation:

$h = (8 \times 6) \pm 1 \rightarrow 47^{th}$ & 49^{th} harmonics

(1) Square D Product Data Bulletin 8803PD9402

Power System Harmonics Causes and Effects of Variable Frequency Drives Relative to the IEEE 519-1992 Standard

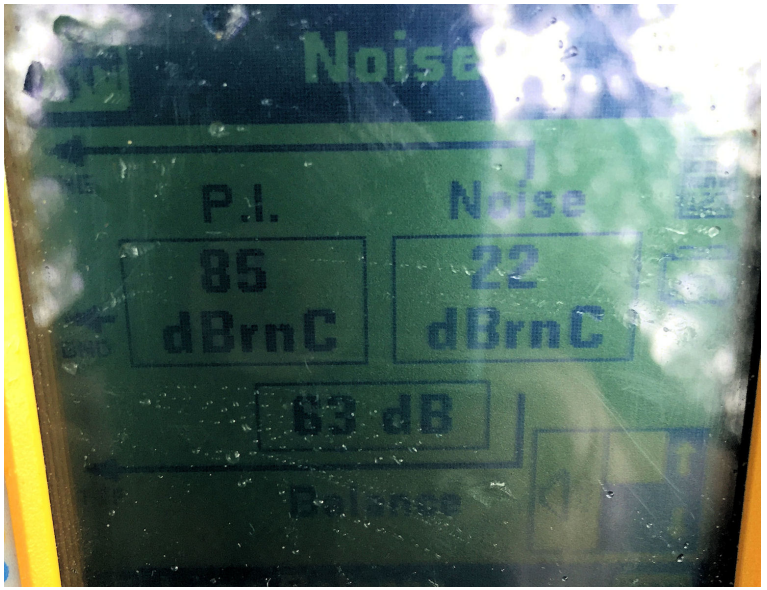
"Solar Farm Inverter Harmonics"

Second site visit

(August 29th and 30th 2018)

Initial Evaluation

- Power Influence 85dB
- Noise Metallic 22dB
- Balance 63dB
- AC Voltage measured on cable pair = 3.1v
- Shield current 0.6 to 5.5 Amps AC depending on cable size and exposure.



Initial retesting of PI, Nm and Bal and AC voltages indicated a reduction in the overall affect from the solar farm.

While discussing this data with the City of Tallahassee solar farm technicians, it was learned that one of the eight inverters was off-line due to lightning damage.

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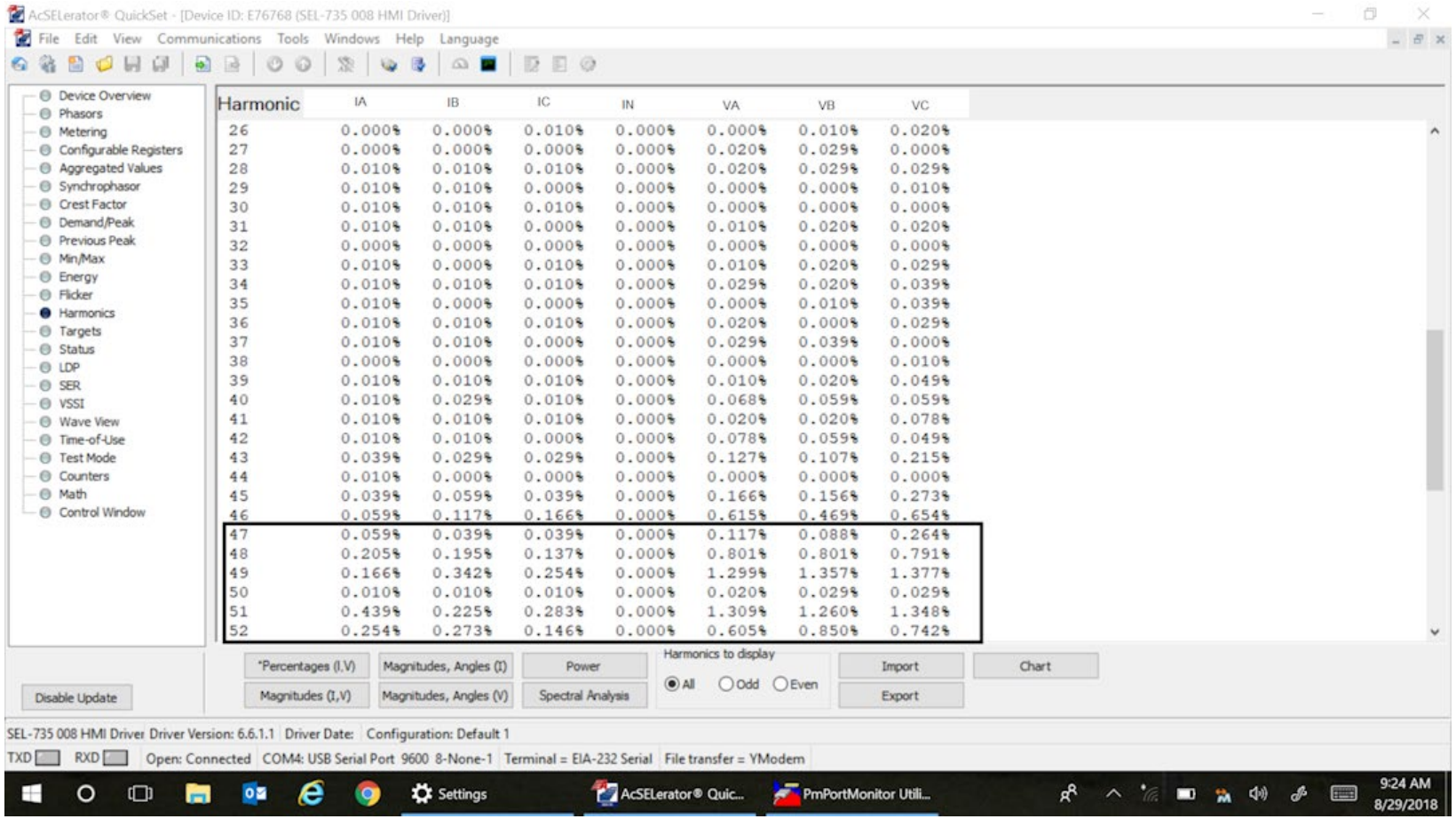

Harmonic data provided by the City of Tallahassee taken at the point of interconnect for inverters 1 to 4. Data includes harmonics in the phase current (IA,B,C and N) and harmonics in the phase voltage (VA,B and C).

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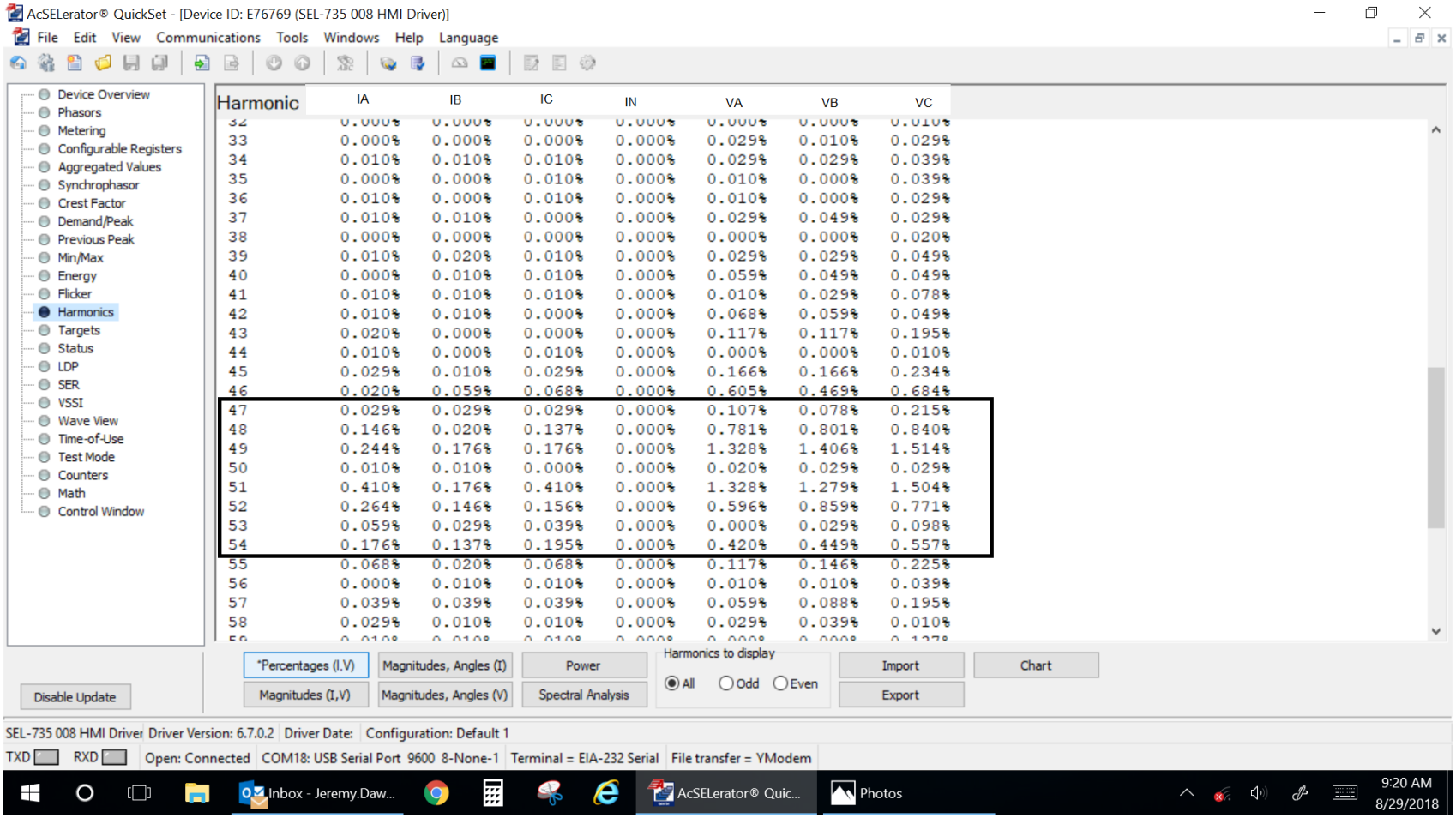

Harmonic data provided by the City of Tallahassee taken at the point of interconnect for inverters 5 to 8.

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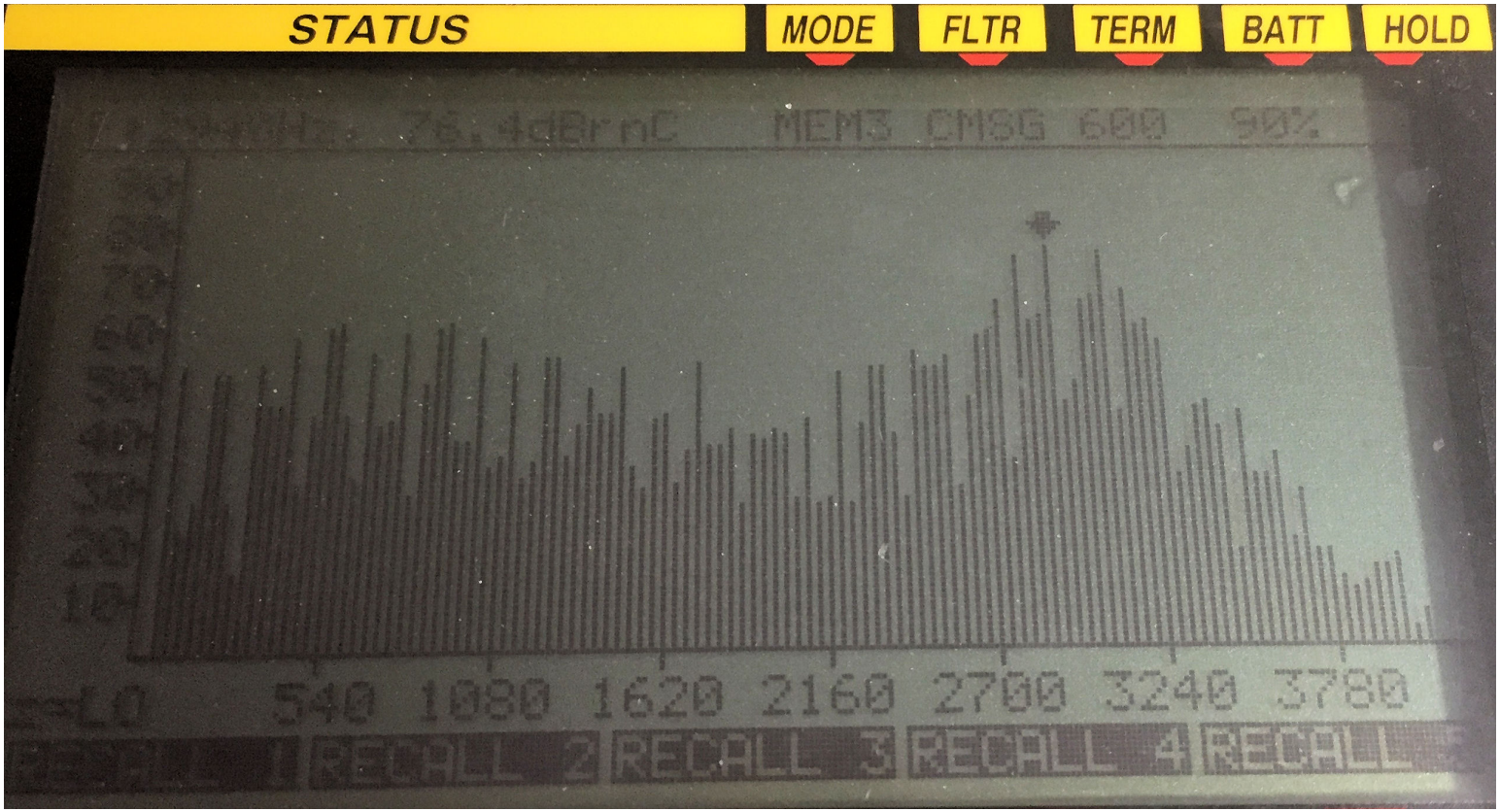

Harmonic graph readings taken from 100 foot probe wire placed under 3 phase solar farm "express" conductors. Reduced magnitude of harmonics due to 1 inverter taken off line.

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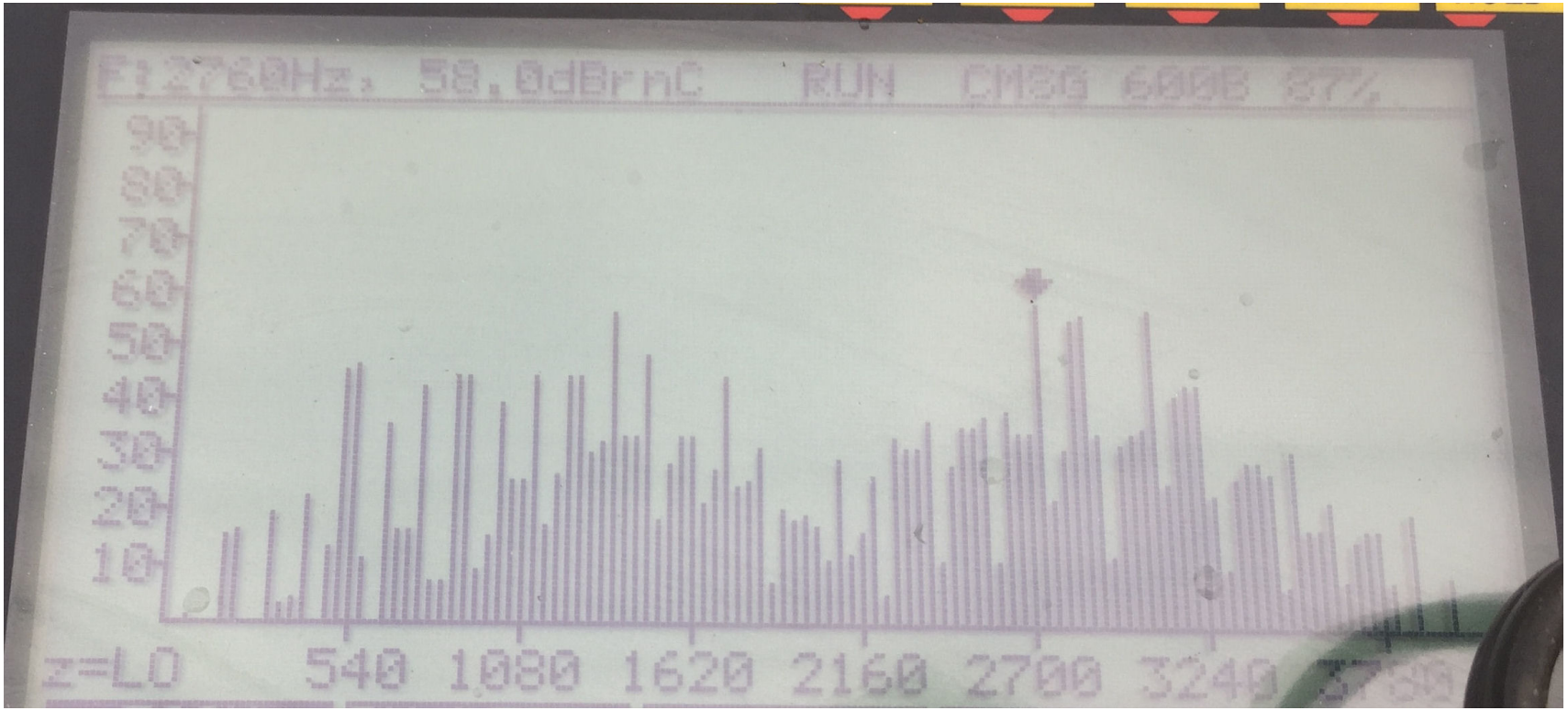

Harmonic graph with 4 invertors off line shows a significant reduction of harmonics.

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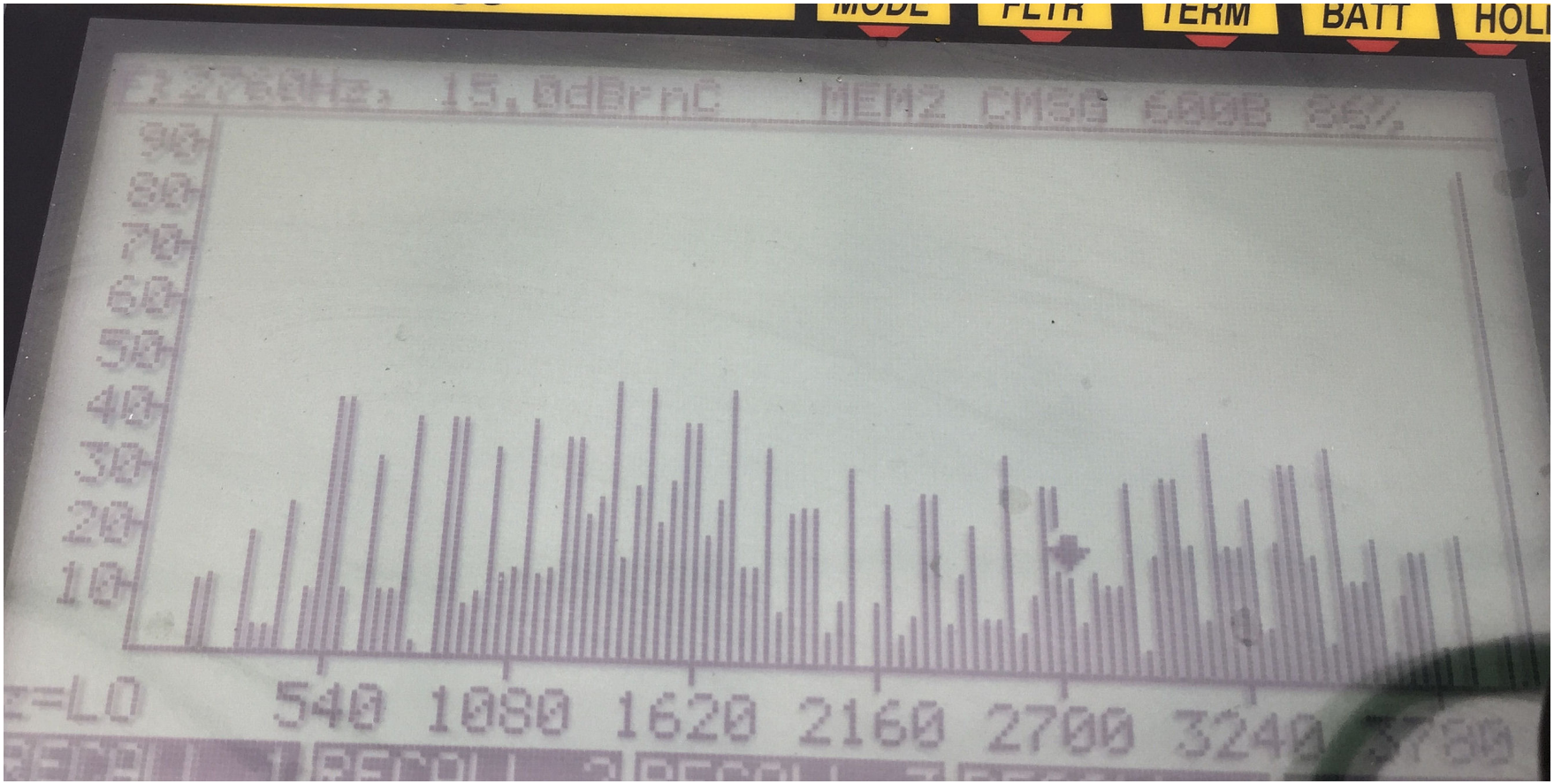

Harmonic graph with all invertors off line. Offending harmonics removed from system.

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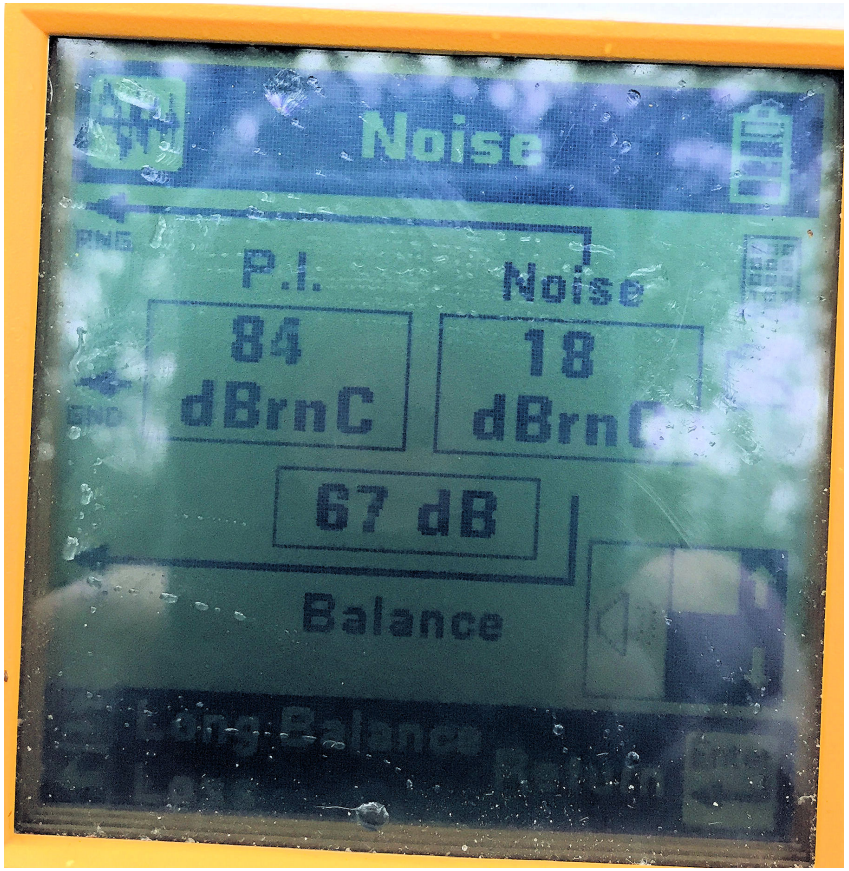
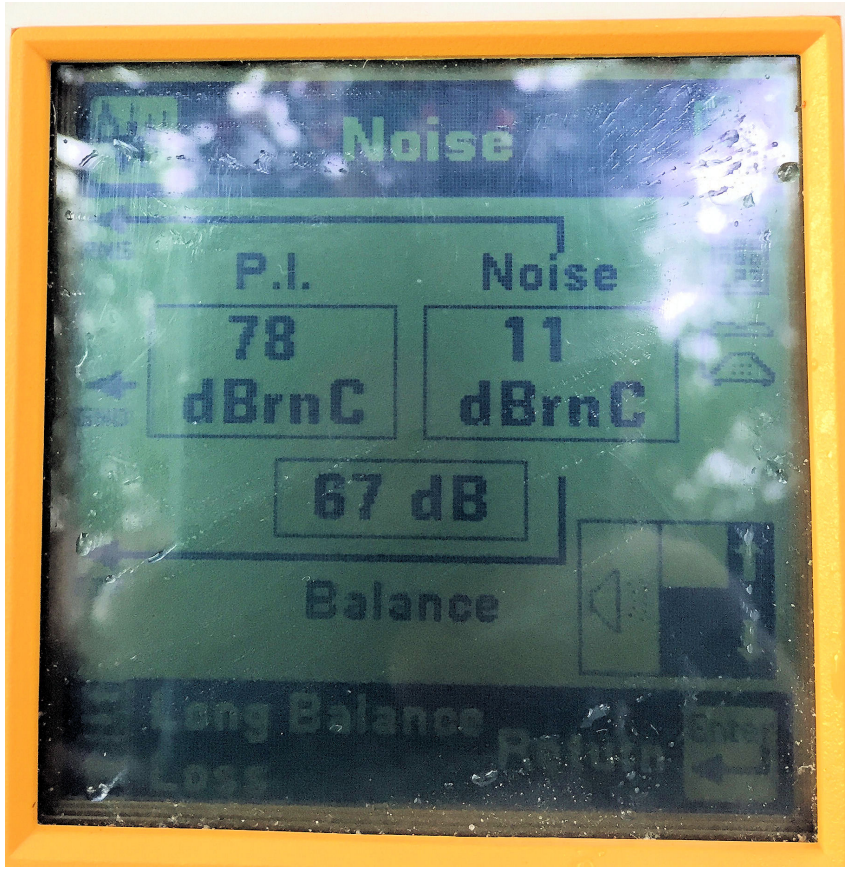
Noise measurements taken at Pedestal 90769 Springhill Rd (across from Pol of solar farm)



Noise and PI levels with 4 Invertors off line. Noise dropped 4 dBrnC from previous measurement.



Noise and PI levels with all Invertors off line.
Noise dropped an additional 7 dBrnC

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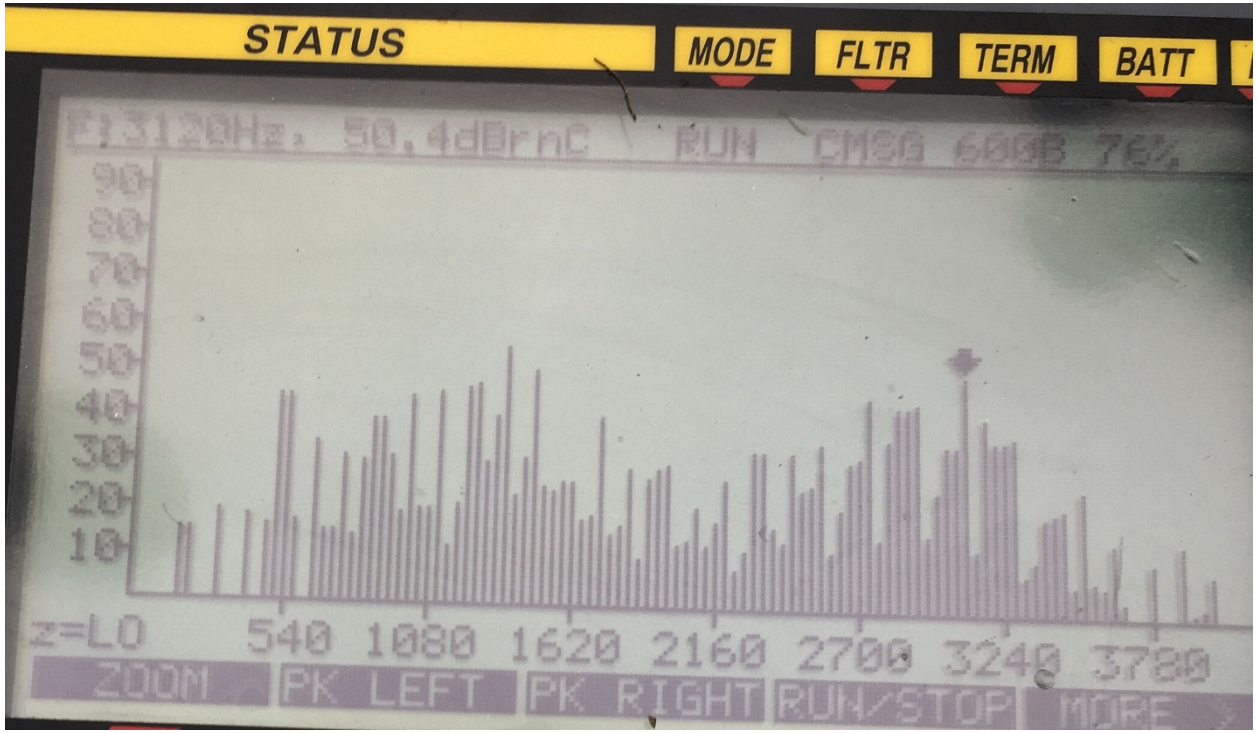
After the initial testing, SMA engineers working remotely-

> "Set parameters to have the inverters sync a specific way and then phase shifted the pulses of half of the inverters. This allows certain harmonics caused from the inverters to cancel out at the point of interconnection."

This change in the invertors reduced the overall harmonic levels as shown in the graph below.



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Harmonic	IA	IB	IC	IN	VA	VB	VC
33	0.039%	0.000%	0.039%	0.000%	0.000%	0.000%	0.000%
34	0.039%	0.039%	0.039%	0.000%	0.000%	0.000%	0.000%
35	0.039%	0.039%	0.039%	0.000%	0.000%	0.000%	0.000%
36	0.039%	0.039%	0.039%	0.000%	0.000%	0.000%	0.000%
37	0.078%	0.039%	0.078%	0.000%	0.010%	0.000%	0.000%
38	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.010%
39	0.039%	0.039%	0.039%	0.000%	0.000%	0.000%	0.000%
40	0.078%	0.078%	0.039%	0.000%	0.000%	0.000%	0.000%
41	0.039%	0.039%	0.039%	0.000%	0.000%	0.000%	0.000%
42	0.078%	0.039%	0.078%	0.000%	0.000%	0.000%	0.000%
43	0.078%	0.078%	0.127%	0.000%	0.010%	0.000%	0.029%
44	0.000%	0.000%	0.000%	0.000%	0.010%	0.000%	0.000%
45	0.127%	0.078%	0.127%	0.000%	0.010%	0.020%	0.039%
46	0.430%	0.391%	0.430%	0.000%	0.059%	0.059%	0.059%
47	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%	0.029%
48	0.557%	0.518%	0.479%	0.000%	0.088%	0.098%	0.078%
49	0.781%	0.732%	0.742%	0.000%	0.137%	0.166%	0.137%
50	0.039%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
51	0.732%	0.605%	0.654%	0.000%	0.146%	0.166%	0.117%
52	0.342%	0.391%	0.391%	0.000%	0.059%	0.098%	0.078%
53	0.039%	0.039%	0.000%	0.000%	0.000%	0.000%	0.020%
54	0.254%	0.215%	0.254%	0.000%	0.029%	0.059%	0.039%
55	0.078%	0.039%	0.039%	0.000%	0.000%	0.029%	0.029%
56	0.039%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
57	0.039%	0.039%	0.039%	0.000%	0.000%	0.010%	0.010%
58	0.039%	0.000%	0.000%	0.000%	0.000%	0.000%	0.000%
59	0.039%	0.000%	0.000%	0.000%	0.000%	0.010%	0.020%

Harmonic data provided by the City of Tallahassee taken at the point of interconnect for inverters 1 to 4 after changes where made to invertors. This shows a significant reduction in harmonics in the output voltages.

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Harmonic	IA	IB	IC	IN	VA	VB	VC
34	0.020%	0.020%	0.020%	0.000%	0.000%	0.000%	0.000%
35	0.049%	0.020%	0.020%	0.000%	0.000%	0.010%	0.010%
36	0.020%	0.020%	0.020%	0.000%	0.000%	0.000%	0.000%
37	0.020%	0.049%	0.020%	0.000%	0.000%	0.000%	0.010%
38	0.000%	0.000%	0.020%	0.000%	0.000%	0.000%	0.000%
39	0.020%	0.020%	0.000%	0.000%	0.000%	0.000%	0.000%
40	0.049%	0.020%	0.020%	0.000%	0.000%	0.000%	0.000%
41	0.020%	0.020%	0.020%	0.000%	0.000%	0.000%	0.000%
42	0.020%	0.020%	0.049%	0.000%	0.000%	0.010%	0.000%
43	0.049%	0.020%	0.049%	0.000%	0.010%	0.000%	0.020%
44	0.020%	0.020%	0.000%	0.000%	0.000%	0.000%	0.000%
45	0.068%	0.049%	0.068%	0.000%	0.010%	0.010%	0.029%
46	0.244%	0.215%	0.244%	0.000%	0.068%	0.059%	0.068%
47	0.020%	0.020%	0.020%	0.000%	0.000%	0.010%	0.039%
48	0.293%	0.244%	0.322%	0.000%	0.088%	0.098%	0.059%
49	0.508%	0.410%	0.518%	0.000%	0.156%	0.195%	0.166%
50	0.000%	0.020%	0.020%	0.000%	0.000%	0.000%	0.000%
51	0.459%	0.391%	0.439%	0.000%	0.156%	0.195%	0.156%
52	0.244%	0.166%	0.215%	0.000%	0.059%	0.098%	0.078%
53	0.020%	0.020%	0.020%	0.000%	0.000%	0.010%	0.000%
54	0.146%	0.117%	0.098%	0.000%	0.039%	0.059%	0.029%
55	0.049%	0.049%	0.049%	0.000%	0.000%	0.029%	0.029%
56	0.020%	0.020%	0.020%	0.000%	0.000%	0.000%	0.000%
57	0.020%	0.020%	0.020%	0.000%	0.000%	0.000%	0.000%
58	0.020%	0.020%	0.020%	0.000%	0.000%	0.000%	0.000%
59	0.020%	0.020%	0.020%	0.000%	0.000%	0.000%	0.000%
60	0.020%	0.020%	0.000%	0.000%	0.000%	0.000%	0.000%

Harmonic data provided by the City of Tallahassee taken at the point of interconnect for inverters 5 to 8 after changes where made to invertors. This shows a significant reduction in harmonics in the output voltages.

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Noise measurements taken at Pedestal 90769 Springhill Rd (across from PoI of solar farm) after changes made to inverters by SMA.

Power influence	76 dBrnC
Noise metallic	9 dBrnC
Balance	67 dBrnC

Additional testing throughout the area reflected the same reductions in power influence and noise readings shown above.

Conclusion:

The adjustments made by SMA successfully mitigated the harmonics and noise on CenturyLink customers POTS lines.

Questions

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