MICROGRID RENEWABLE ENERGY INTEGRATION

by

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Dedicated to my father and mother

whose endless love and support carry me through difficult times.

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Abstract

The Microgrid is a small-scale electrical system that is designed to give Cal Poly students hands-on experience on power generation, system protection, distribution, and automation that would otherwise be very difficult to experiment in a large-scale model.

To closely replicate the modern electrical grid, a renewable energy source shall be added to the Microgrid in conjunction with the existing synchronous generators. Electrical engineering student, Virginia Yan initiated this effort, namely Grid-Tied Solar System project [1], by designing and constructing a set of solar panels and microinverter for future connection to the Microgrid. The scope of Virginia's project was, however, limited to designing and constructing the panels and microinverter.

This Microgrid Renewable Energy Integration project aims to integrate the designed solar panels and microinverter to the Microgrid by testing the microinverter when running on islanded mode that replicates the Microgrid and eventually running with the Microgrid. The project develops test methods and solutions to enhance integration capability from the test results. In addition, this project implements basic power protection elements such as over-current and under-voltage. Protection schemes and monitoring are configured using Schweitzer Engineering Laboratories (SEL) relays, such as SEL-751 Feeder Protection Relay and SEL-735 Power Quality Meter. The success of the Microgrid Renewable Energy Integration project guarantees a smooth synchronization and secured operation of the microinverter to the Microgrid.

Acknowledgement

Words cannot express how thankful I am to have Dr. Majid Poshtan as my senior advisor. Dr. Poshtan was always willing to spend time troubleshooting the problem and explaining technical concepts with great analogies. Dr. Poshtan's caring attitude always encouraged me to overcome difficulties. I will never forget these simple yet meaningful words of Dr. Poshtan, "Don't wait, just knock on my door."

I am very thankful to have Virginia Yan as a great partner who helped prepare test procedures for the Grid-Tied Solar System. Virginia's dedication and broad knowledge never stop inspiring me to become better. I cannot count how many weekends we spent together at the power lab room trying to fix the microinverter and the test setup. Virginia's persistence made integrating the renewable energy to the Microgrid possible.

I would also like to thank Dr. Ali Shaban, Dr. Taufik, and Dr. Ahmad Nafisi for offering advice on multiple test modifications so that I could design more efficient test setups. Dr. Taufik's knowledge in power electronics, especially in the field of DC-AC inverter, helped me understand the characteristics of the microinverter. Dr. Ali Shaban and Dr. Ahmad Nafisi's knowledge in rotating machines, power systems, and especially the Microgrid helped consolidate my understanding of the existing Microgrid system.

Thank you to Cal Poly Alumnus Eric Osborn, Matthew Guevara, Nicole Rexwinkel, Nathan Martinez, and Kenan Pretzer for designing various sections of the Microgrid and providing invaluable advice regarding SEL relays operation and protection schemes. Thank you to Grace Larson for proofreading this report and providing feedback.

Chapter 1. Background

1.1 Traditional Grid

The traditional grid typically contains generation units which are typically far away from the load, and a transformer to step up the voltage for transmission. The electricity is then stepped down via a transformer for distribution via a distribution network (Figure 1). The U.S. electric grid consists of three interties (Figure 2) with 300 electric utilities and over 300,000 miles of transmission and distribution lines. In the traditional grid, power flows unidirectionally from power plants to the load, typically referred to as non-distributed generation [2].
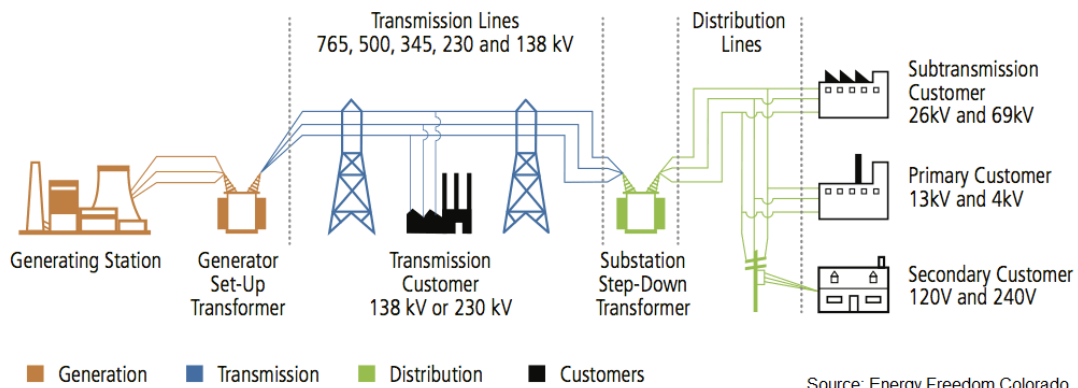
Figure 1. Electric Grid Infrastructure
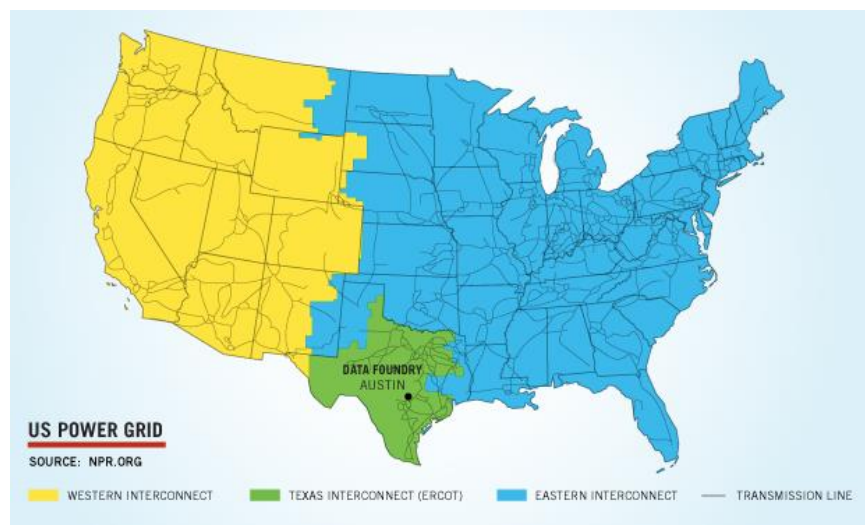
Figure 2. The United States Power Grid

1.2 Smart Grid

The smart grid shares similar distribution system infrastructure with the traditional grid. However, the smart grid better represents the modern-day grid which replaces the traditional grid by moving generating units closer to the load with sophisticated levels of automation and communication (Figure 3). In a smart grid system, renewable resources such as solar turn the power flow to a bidirectional flow. All grid-tied electrical equipment and protection relays communicate with each other to increase efficiency and reliability [2].

Figure 3. Smart Grid Elements

1.3 The Microgrid

The microgrid shares many characteristics with the smart grid such as automation, communication, and smart protection systems. The key differences between a microgrid and a smart grid are the small-scale and self-sustainability of the microgrid. The microgrid can be islanded (isolated from the utility grid) and self-sustain for a designed period. In a microgrid system, the loads are much closer to the generating units [3].

The Cal Poly Microgrid (referred to as "the Microgrid" throughout this report) was developed based on the idea of a self-sustainable smart grid. The Microgrid consists of two synchronous generators as the main generating units, one-to-one transformers, modelled transmission lines, static loads, induction motors, and capacitor banks (Figure 4).
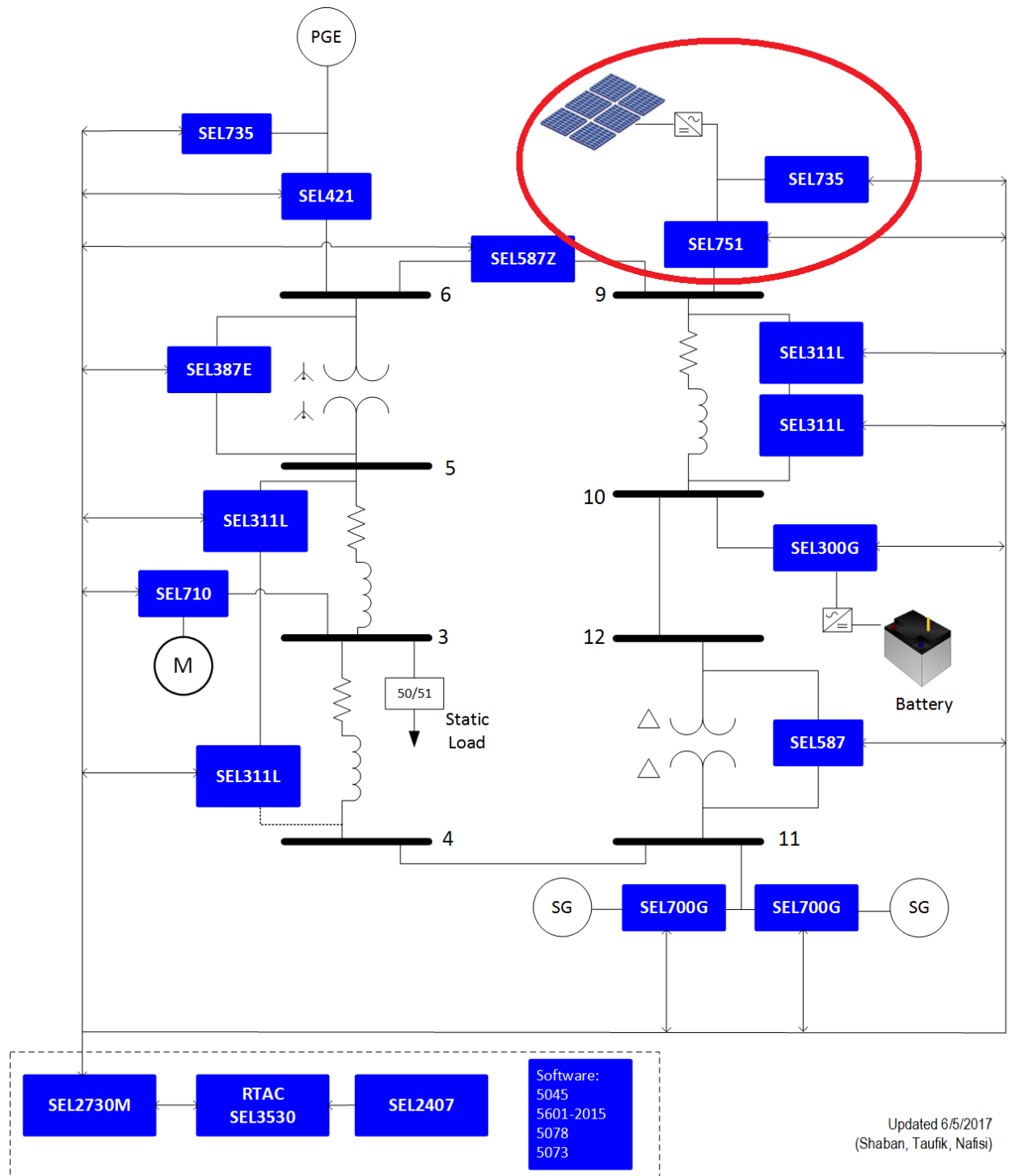
Figure 4. Microgrid System Diagram (Future Grid-Tied Solar System circled in red)

1.4 Grid-Tied Solar System [1]

The Grid-Tied Solar System is referred throughout this report as a completed hardware system designed by electrical engineering student Virginia Yan. The system consists of four solar panels, a three-phase microinverter, DC disconnect switch, and an AC circuit breaker. Two panels are connected in series and mounted on a movable cart with solar tracking capability. The photovoltaic panels absorb the solar energy and generate direct current (DC) electricity. The DC electricity is converted to AC electricity using a microinverter. For the Microgrid application, this AC electricity is a three-phase Y-connected 120/208V system. The DC disconnect switch isolates the solar panels from the other parts of the circuit when power outages or natural disturbances occur. The AC disconnect switch (circuit breaker) disconnects the solar panels and microinverter from the rest of the circuit when a fault is detected. The AC circuit breaker can be operated manually or by SEL relays (Figure 5).
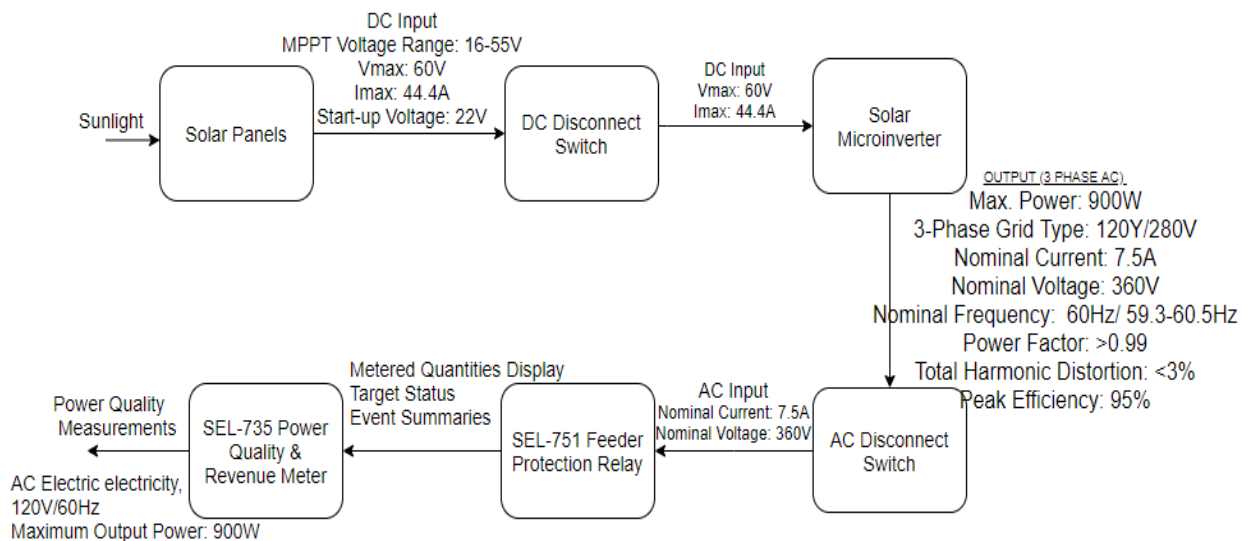
Figure 5. Level 1 Grid-Tied Solar System Design Functionality (By Virginia Yan)
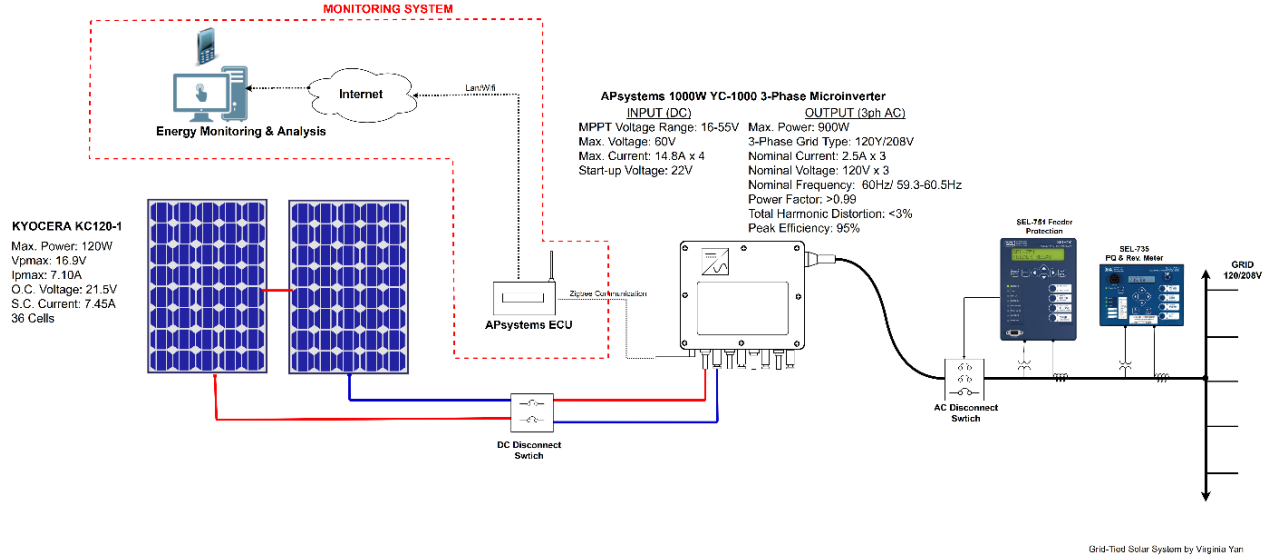
Figure 6. Overall Grid-Tied Solar System (By Virginia Yan)

1.5 Variable Three-Phase Load

Various tests described in this report use a variable three-phase load. This variable three-phase load consists of a three-phase variac (Figure 8) in series with a Y-connected three-phase load. The main difference between a variac and a transformer is the absence of the secondary coil in which the variac's secondary voltage is varied by varying the tapping point along the coil. As a result, the arbitrary number of turns on the secondary is always less than the number of turns on the primary. The variable three-phase load works based on the principles of an ideal transformer (Figure 7). It is convenient to describe the variac using an ideal transformer model.

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1} \rightarrow \frac{R_1}{R_2} = \frac{\frac{V_1}{I_1}}{\frac{V_2}{I_2}} = \frac{V_1}{V_2} \times \frac{I_2}{I_1} = \frac{N_1}{N_2} \times \frac{N_1}{N_2} = (\frac{N_1}{N_2})^2$$

Therefore, the secondary resistance as seen on the primary side $R_1 = R_2(\frac{N_1}{N_2})^2$
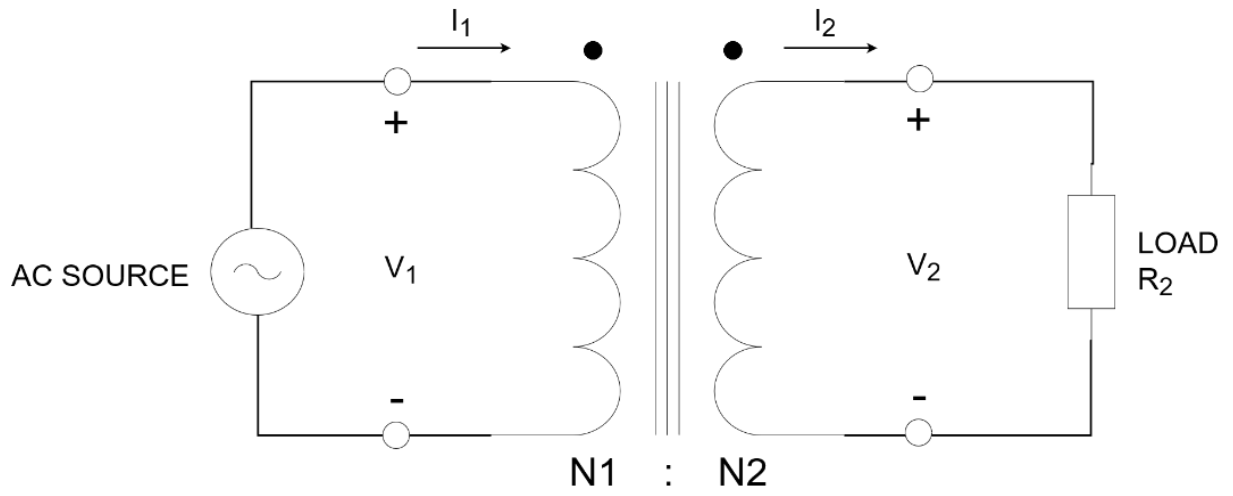
Figure 7. Transformer Principle
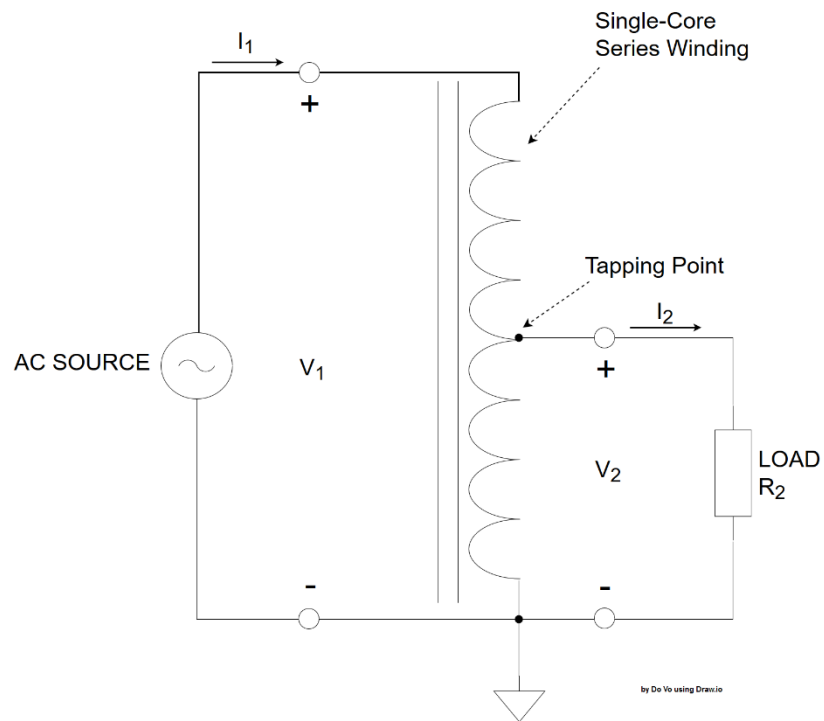
Figure 8. Single-Phase Variac

Table 1. Varying Resistance by the Variac Positions

Variac Position	V_1 (V)	I_1 (mA)	P (W)	R_1 (Ω)	R_2 (Ω)
1	206.60	84.6	28	1304	216
2	206.60	113.2	38.8	1009	216
3	206.60	158.3	55.2	734	216
4	206.60	211.7	34.6	257	216
5	206.60	278.9	98.3	421	216
6	206.60	350.7	124.5	337	216
7	206.60	429	152.4	276	216
8	206.60	513.6	183	231	216
9	206.60	581	207	204	216

Example calculation assuming ideal variac: $R_1 = \frac{P}{3(I_1 \times 10^{-3})^2} = \frac{28}{3(84.6 \times 10^{-3})^2} = 1304$ (Ω)

From Table 1, as the variac position increases, N_2 will also increase from 0 to 1, thus, $\left(\frac{N_1}{N_2}\right)$ will decrease to 1. Therefore, when the variac position reaches "9", the ratio $\left(\frac{N_1}{N_2}\right)$ also approaches 1 causing the magnitude of the secondary resistance to approach the primary resistance.

1.6 acSELerator QuickSet SEL-5030 Software

The acSELerator QuickSet SEL-5030 Software is a tool for technicians and engineers to conveniently and quickly program, configure, and manage power system protection, metering, and monitoring SEL device. The software is used extensively for this project to program the SEL-751 Feeder Protection Relay and monitor the SEL-735 Power Quality Meter using the Human Machine Interface (HMI) feature [7].

Chapter 2. Project Description

The Microgrid Renewable Energy Integration project's first objective is to integrate the solar panels and microinverter to the Microgrid. A successful integration requires that the microinverter does disconnect itself or cause the synchronous generators to trip when isolated from the utility grid. This project develops a series of tests to evaluate the microinverter's capability to work with the Microgrid in an isolated environment. The test results are analyzed to develop a solution to fix potential problems.

The second objective of this project is to install protective relays to protect the Microgrid and the microinverter from grid disturbances and faults. The AC current and voltage signals are monitored by both the SEL-751 Feeder Protection Relay and SEL-735 Power Quality Meter. The SEL-735 provides high-accuracy revenue metering, displays real-time current and voltage signals, and captures power quality disturbances. The SEL-751 sends trip signals to open the AC circuit breaker if a fault or grid disturbance such as overcurrent, overvoltage, or under-frequency conditions are detected. The circuit breaker is used a relay-controlled circuit breaker and a switch to isolate the inverter from the grid.

2.1 Islanded Mode Test

The Islanded Mode Test replicates a small portion of the microgrid that represents the self-sustainability characteristic. The test is designed to observe the behavior of the microinverter and the reaction of the synchronous generator during the isolation process from the utility grid.

The setup consists of a synchronous generator and a coupled DC motor to form a generator, a three-phase load, a Yokogawa WT130 three-phase power meter, an APsystem microinverter, and two solar panels (Figure 9). Detailed Islanded Mode Test Program is attached at Appendix A.
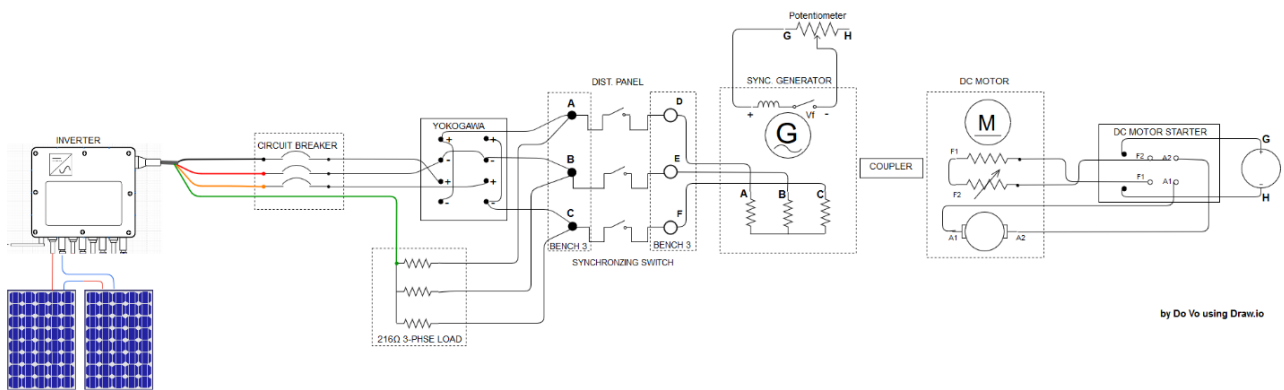
Figure 9. Islanded Mode Test Wiring Diagram

Figure 10 and Figure 11 show the actual setup of the Islanded Mode Test. The test takes

place in the power lab room 20-102 and the solar panels are installed at the hallway between

building 20A and room 20-102.

Figure 10. Islanded Mode Testbench Setup
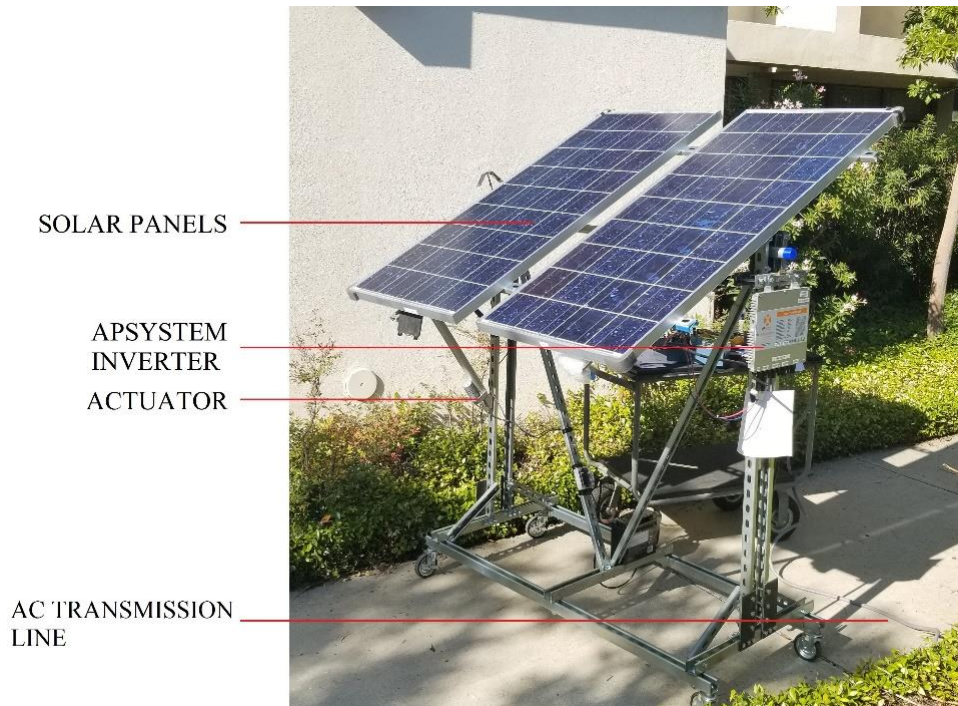
Figure 11. Solar Panel Setup of the Islanded Mode Test

The microinverter outputted approximately 141W after synchronizing with the utility grid (Figure 12) and the generator outputted 0.09A current per phase (32.4W). The three-phase load drew about 0.57A current per phase (205.2 W) (Figure 13). The utility grid supplied approximately 31.8W.

Figure 12. Microinverter's Output Power Display on the ECU

GENERATOR PHASE CURRENT OUTPUT   LOAD PHASE CURRENT

Figure 13. Generator and Load Phase Currents

<u>Test Result</u>

The microinverter disconnected after isolation.

<u>Investigation</u>

With the microinverter delivering power, the system received approximately 32W from the utility grid. Upon isolating the system from the utility grid (islanded mode), the synchronous generator made noise and instantly dropped its speed below 1780 RPM (59.3 Hz) and returned to 1795 RPM (59.8 Hz). The microinverter sensed the decrease of frequency and disconnected itself from the system. It was believed that when isolation occurred the 32W load transferred to the synchronous generator causing it to decrease in speed and voltage, causing the microinverter's internal protection to disconnect itself.

2.2 Modified Islanded Mode Test

The Modified Islanded Mode Test attempts to solve the problem with speed fluctuation of the synchronous generator after isolation from the grid presented in Chapter 2.1. The idea is to minimize the reliance on the utility grid except for grid frequency and voltage support. To achieve this independence the system must draw as little power from the infinite bus as possible. This ensures that no load will transfer to the synchronous generator and cause the speed and voltage to drop during the isolation process.

This test proposed the addition of a variable three-phase load. The load shall be tuned to draw 0W from the infinite bus. The 0W requirement from the infinite bus can be interpreted as both the microinverter and the synchronous generator provided enough power to self-sustain, and only needed the utility grid for initial synchronization. The setup consists of a synchronous generator and a coupled DC motor to form a generator, a fixed three-phase load, a variable three-phase load, a Yokogawa WT130 three-phase power meter, microinverter, and solar panels (Figure 14). The test also moved the microinverter from the solar panel cart to the power lab room 20-102 and replaced the AC transmission line with a DC transmission line for convenience. The test setup is shown in Figure 15 through Figure 18.

It is important to be aware that the proposed load adjustment method is chosen to reduce the reliance on the utility grid because neither the inverter nor the solar panels has the capability to change the output power. Varying the output power by changing the tilt angle of the solar panels is possible but difficult to implement and control. In reality, the loads are controlled by the customer and it is therefore impractical to vary the load unnecessarily. Detailed Islanded Mode Test Program is attached at Appendix B.
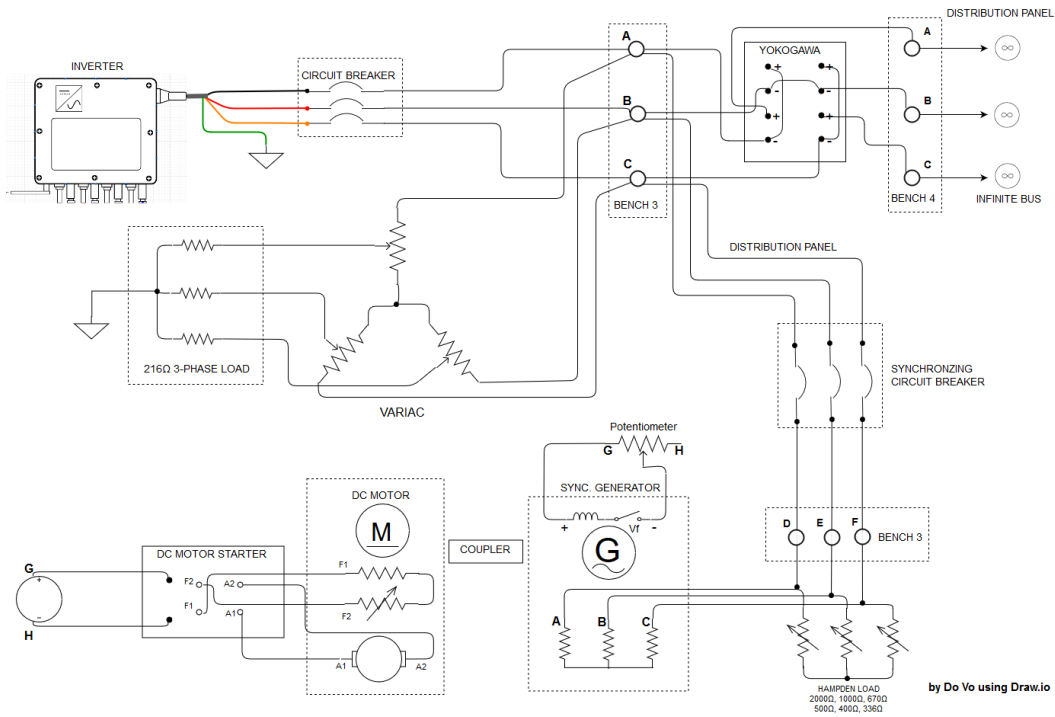
Figure 14. Modified Islanded Mode Test Wiring Diagram

Figure 15 and Figure 16 detail the physical test setup on bench 3. Figure 17 shows the physical test setup on bench 4 with the ABC terminals wired to the Yokogawa WT130 and to the ABC terminals of bench 3.
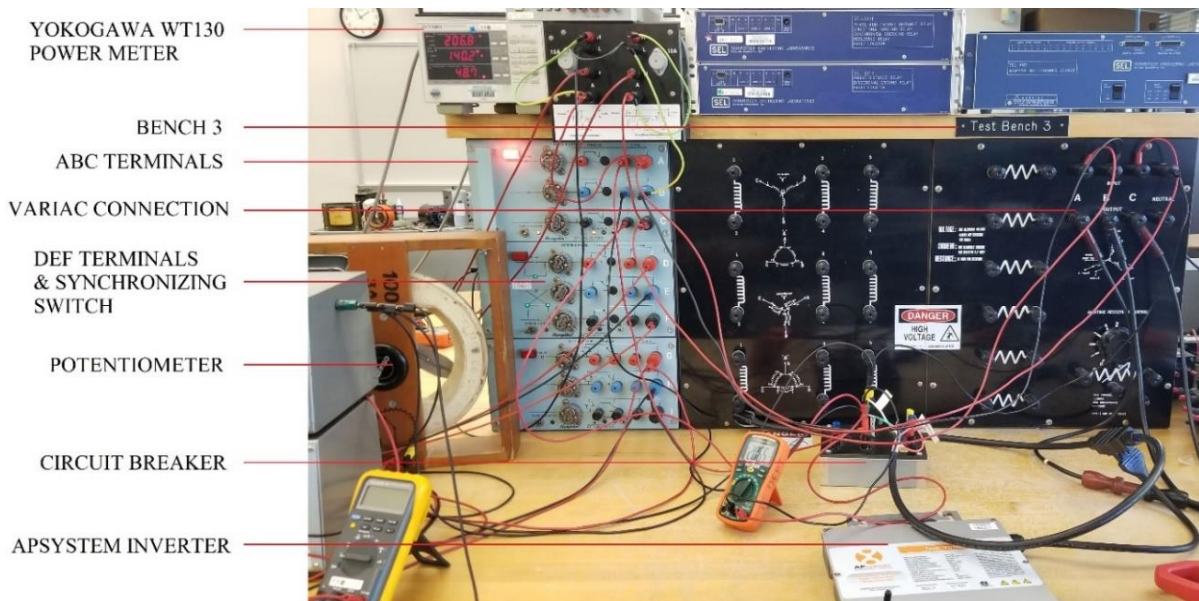
Figure 15. Modified Islanded Mode Test Setup (Part 1)

20
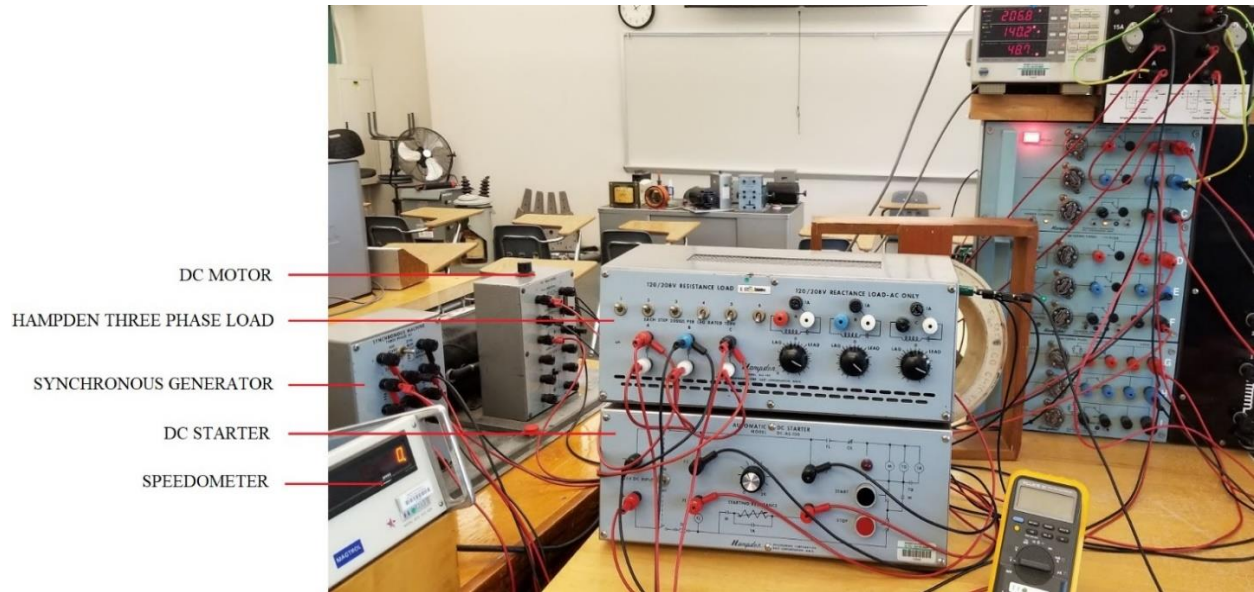
Figure 16. Modified Islanded Mode Test Setup (Part 2)
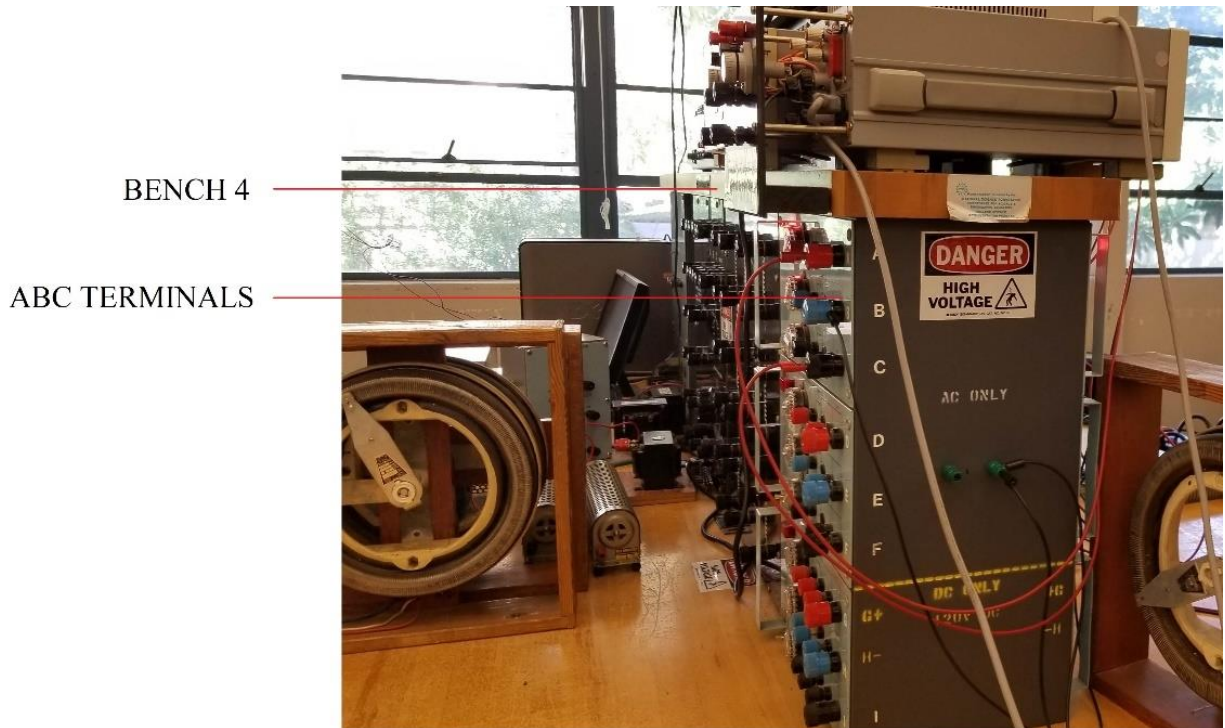
Figure 17. Modified Islanded Mode Test Setup (Part 3)
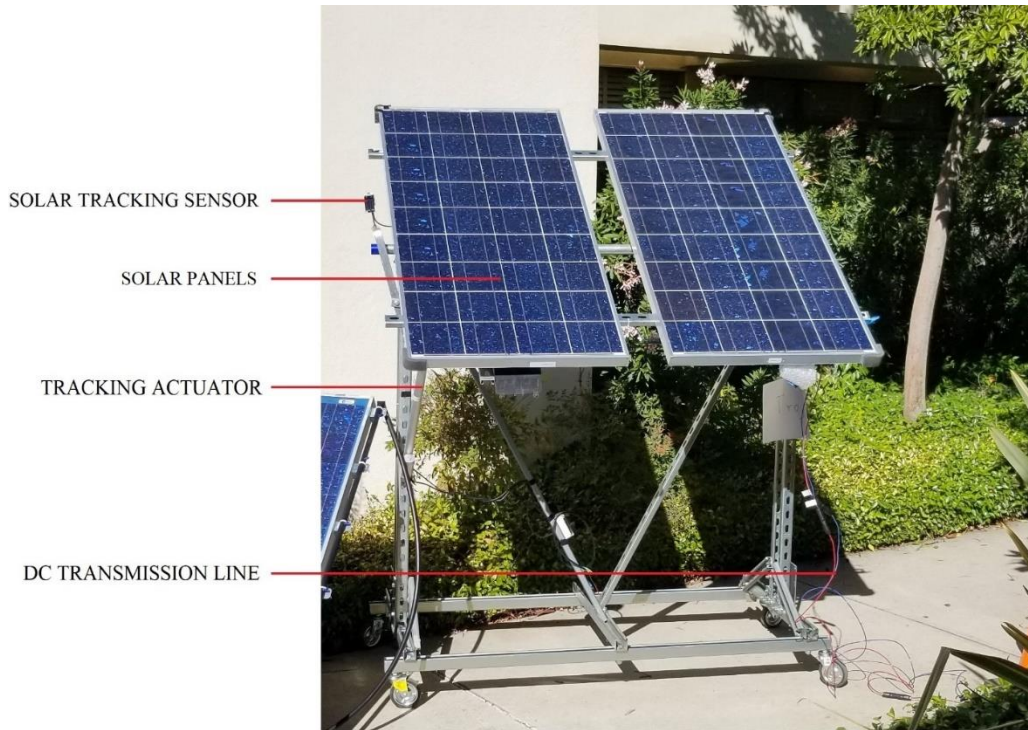
Figure 18. Modified Islanded Mode Solar Panel Setup

Test Data

Table 2 shows the voltage, current, and power measurement from the Yokogawa power

meter before and after the microinverter started to deliver power.

Table 2. Yokogawa Measurements Before and After the Microinverter's Synchronization

Microinverter Synchronization	Grid Voltage (V)	Grid Current (mA)	Grid Power (W)	Variac Position
Before	206.8	140.2	48.7	2.5
After	207.1	116.7	-35.5	2.5

The positive power reading of the Yokogawa means the grid was delivering power to the

variable three phase load. Once the microinverter started delivering power to the system, the

power reading became negative. The microinverter generated more power to feed the variable

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three-phase load (48.7W) and the remaining power (35.5W) transferred to the grid. Figure 19 shows the output power of the microinverter recorded and uploaded by the ECU to the APsystem EMA server at the time of this test.
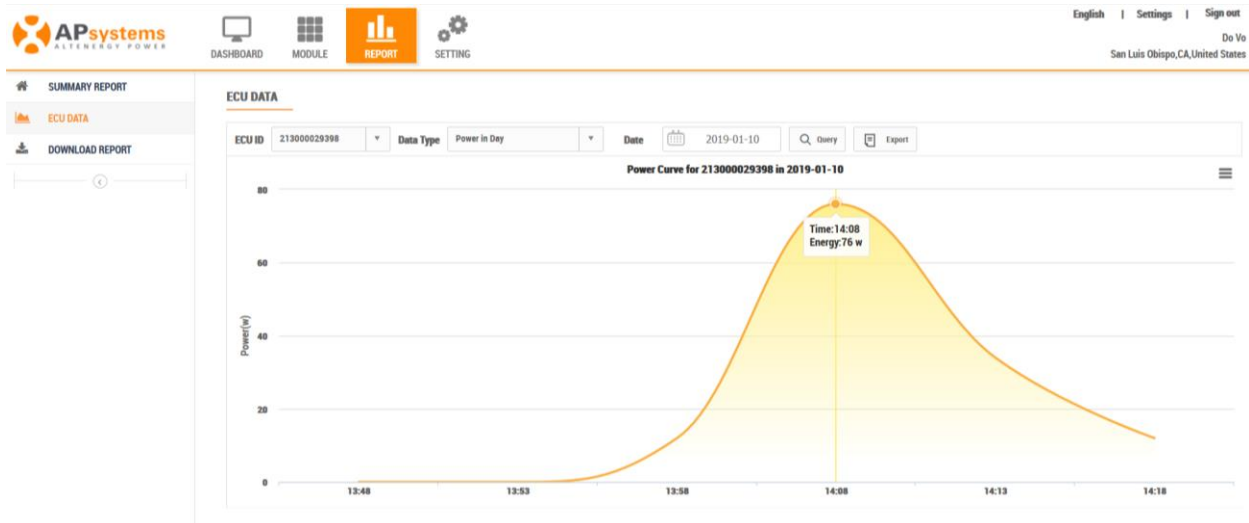
Figure 19. Output Power of the Microinverter using Energy Monitoring & Analysis (EMA)

The variac knob was turned to position 4 to increase the three-phase load and reduce power delivered to the utility grid. The resultant power flow was 5W being received from the utility grid. At this point the utility switch was turned off. The speed of the generator increased to 1805 RPM (60.16 Hz) while the terminal voltage dropped to ~114V L-N. Field current injection into the synchronous machine increased the terminal voltage to 120V L-N and reduced the speed to ~1801 RPM (60.03 Hz).

Test Result

The microinverter remained connected and supplied power to the load along with the synchronous generator. The microinverter, the generator, and the load successfully formed a small microgrid.

Conclusion

       This test demonstrated the ability of the microinverter to work in a microgrid environment where the utility frequency and voltage support was not always available. The load adjustment solution to reduce the reliance and minimize the impact of the utility grid during the isolation process proved to be effective. When connected to the Microgrid, the power output of the generator shall be adjusted to reduce the reliance on the utility grid.

2.3 SEL-735 Power Quality and Revenue Meter Test

The SEL-735 Power Quality and Revenue Meter Test ensures the SEL-735 works properly before connecting to the microinverter. Successful testing will qualify the SEL-735 as a replacement for the traditional Yokogawa WT130 digital power meter in measuring voltage, current, power, and power factor of the grid-tied solar system. This test will gather voltage, current, and power data from the SEL-735 to compare with the data from the WT130. Additionally, the user interface and ease of operation of the SEL-735 will be evaluated.

The test consists of the WT130, SEL-735, circuit breaker, and a variable three-phase load. A 120/208V Y-connected three-phase source is connected in series with the WT130 and to the SEL-735 through a circuit breaker. The output of the SEL-735 is connected to the variable three-phase load (Figure 20).
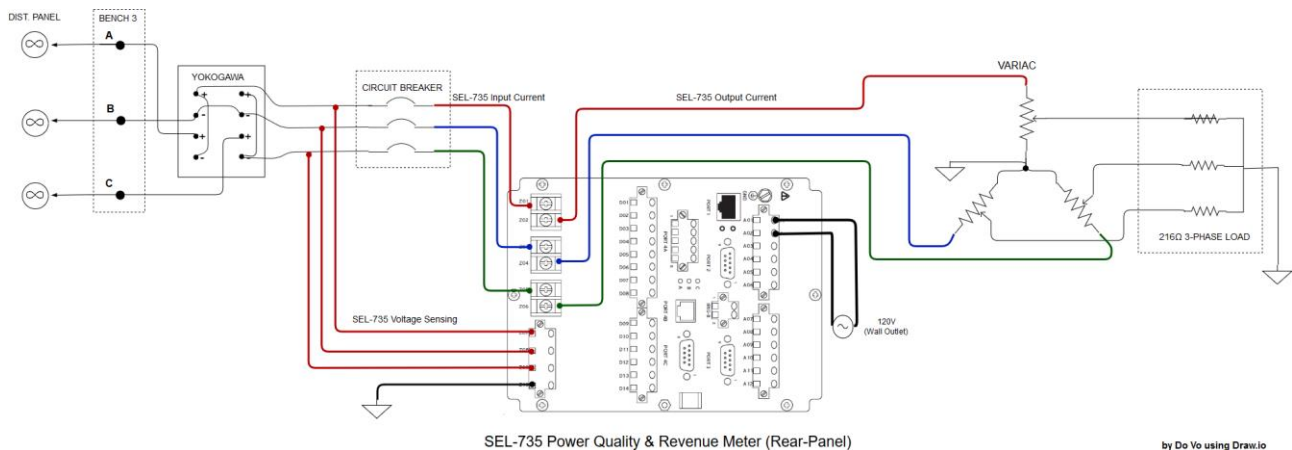
Figure 20. SEL-735 Power Quality and Revenue Meter Test Wiring Diagram

Prior to energizing the circuit, the SEL-735 shall be connected to a computer via an SEL C-662 USB serial cable with the acSELerator QuickSet SEL-5030 Software preinstalled (Section 1.2) for programming purposes. Detailed step-by-step communication setting and programming for the SEL-735 are attached at Appendix B. Actual test setup is shown in Figure 21.
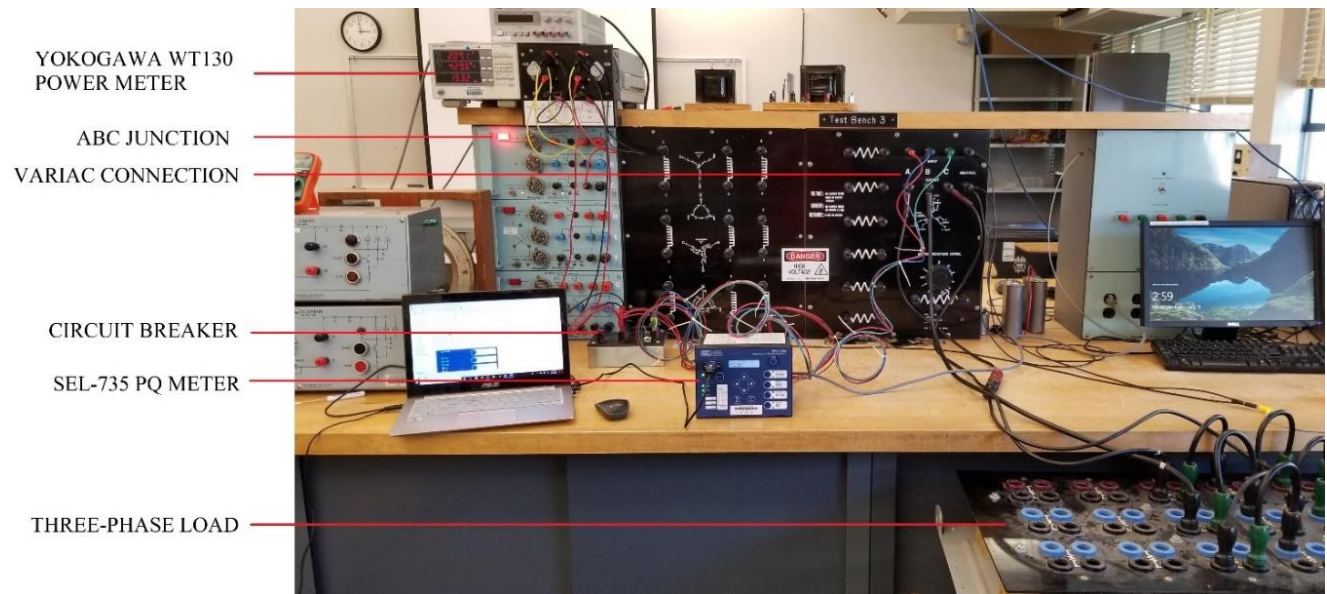
Figure 21. SEL-735 Power Quality and Revenue Meter Test Setup

Test Result

After closing the circuit breaker, the SEL-735 automatically meters the three-phase

current, voltage, power, and energy quantities. The RMS values are displayed on the front-panel

LED screen. Figure 23 shows the front-panel power display, other quantities can be displayed

using up/down arrows. Additionally, acSELerator QuickSet can display synchrophasor data,

phase/sequential components, near real-time waveforms…etc [6]. The Human Machine Interface

(HMI) (Figure 22) offers detailed metering data and replicates the front panel buttons providing a

convenient remote-control capability of the SEL-735.
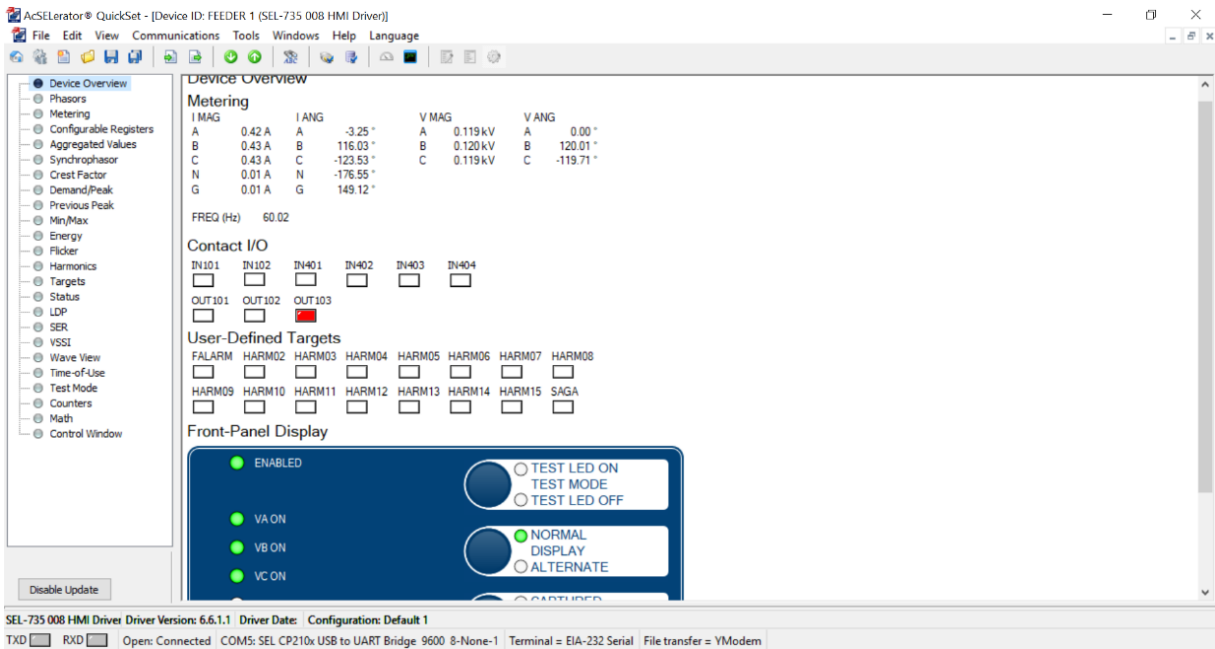
Figure 22. acSELerator QuickSet HMI for the SEL-735

Figure 23. SEL-735 Front Panel Display

Figure 24 shows the RMS values of the voltage, current and power as measured by the Yokogawa WT130. The voltage and current magnitudes of the WT130 (119.5VL-N/207VL-L, 422.5mA, and 153W) closely match with those measured by the SEL-735 (119VL-N, 0.42A, and 0.15kW).
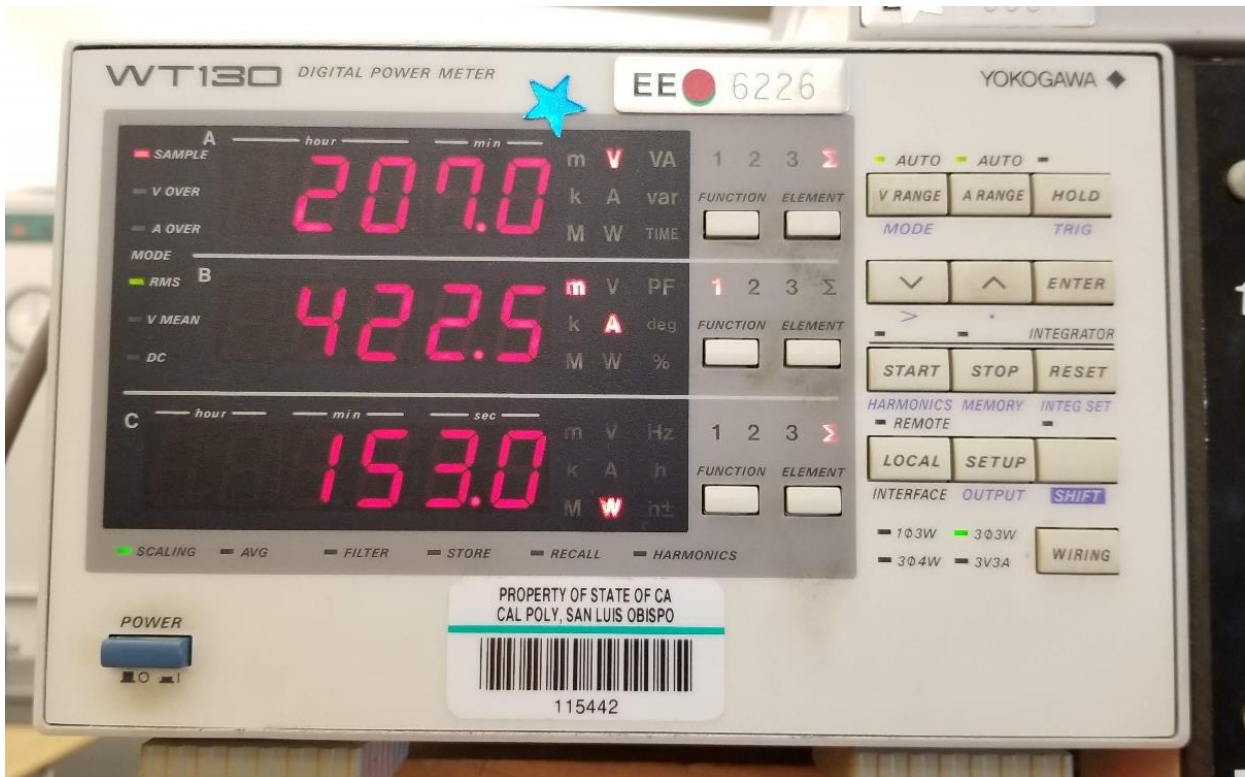
Figure 24. Yokogawa WT130 Front-Panel Display

Figure 25 shows the energy metering values. The SEL-735 calculates four-quadrant volt-ampere reactive (VAR) values following IEEE VAR sign convention (Figure 26). The meter updates the four-quadrant VAR metering every 10/12 cycles [6].
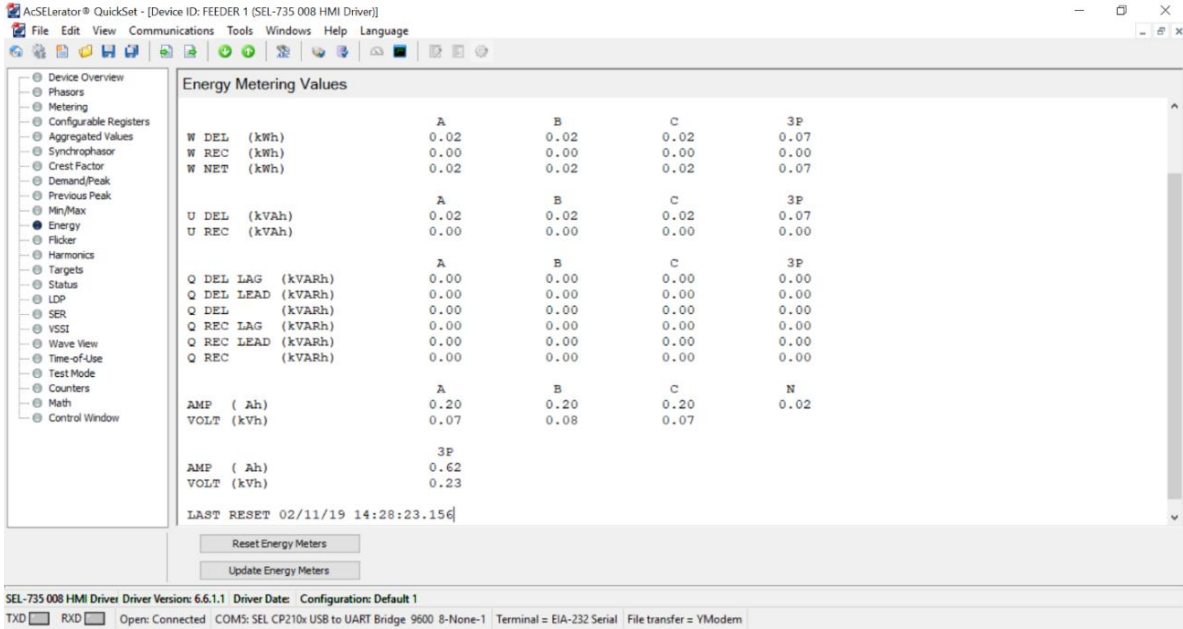
Figure 25. acSELerator QuickSet Energy Display
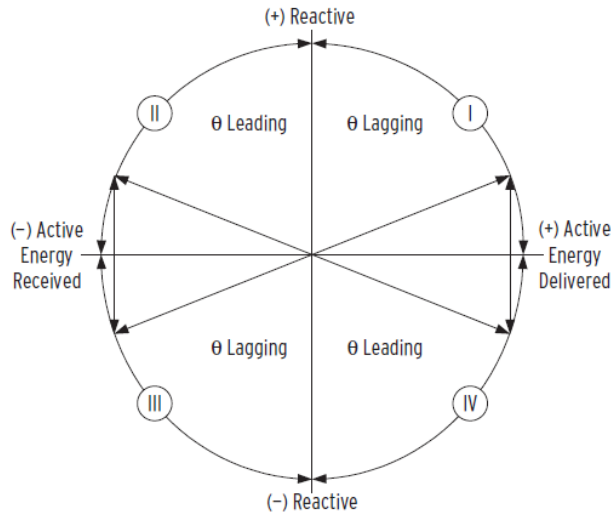
Quadrant	Power Factor	Power Factor Sign	Watts	Vars
I	Lag	+	Delivered (+)	Delivered (+)
II	Lead	−	Received (−)	Delivered (+)
III	Lag	−	Received (−)	Received (−)
IV	Lead	+	Delivered (+)	Received (−)

Figure 26. IEEE VAR Sign Convention (From SEL-735 Instruction Manual)

Figure 27 shows the phasor display of the SEL-735 in acSELerator QuickSet. The meter calculates the zero-, positive-, and negative-sequence components' magnitude and angle for both voltage and current. The meter updates the symmetrical components and analog quantities every half cycle [6].
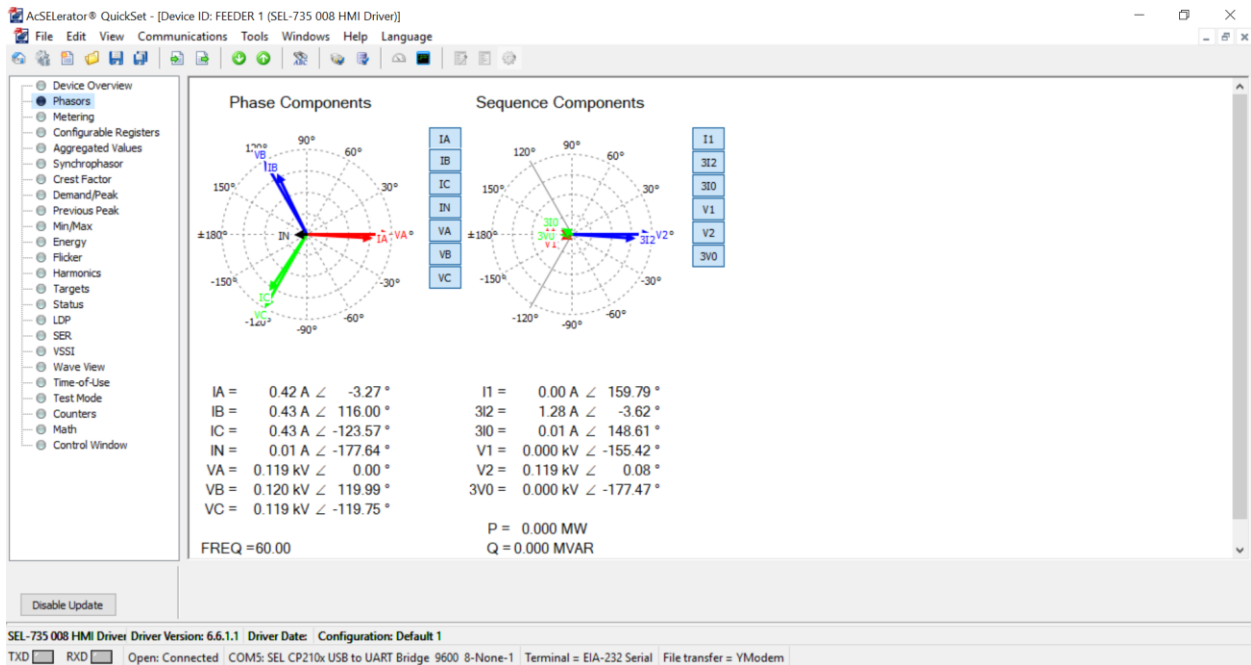
Figure 27. acSELerator QuickSet Phasor Display

Figure 28 and Figure 29 present the wave view feature in the acSELerator QuickSet for the SEL-735. The wave view offers near real-time oscilloscope-like waveforms and harmonic histogram of the current and voltage. The recorder can sample at 128 or 512 samples/cycle. The recording duration can vary from 2 to 60 cycles [6].
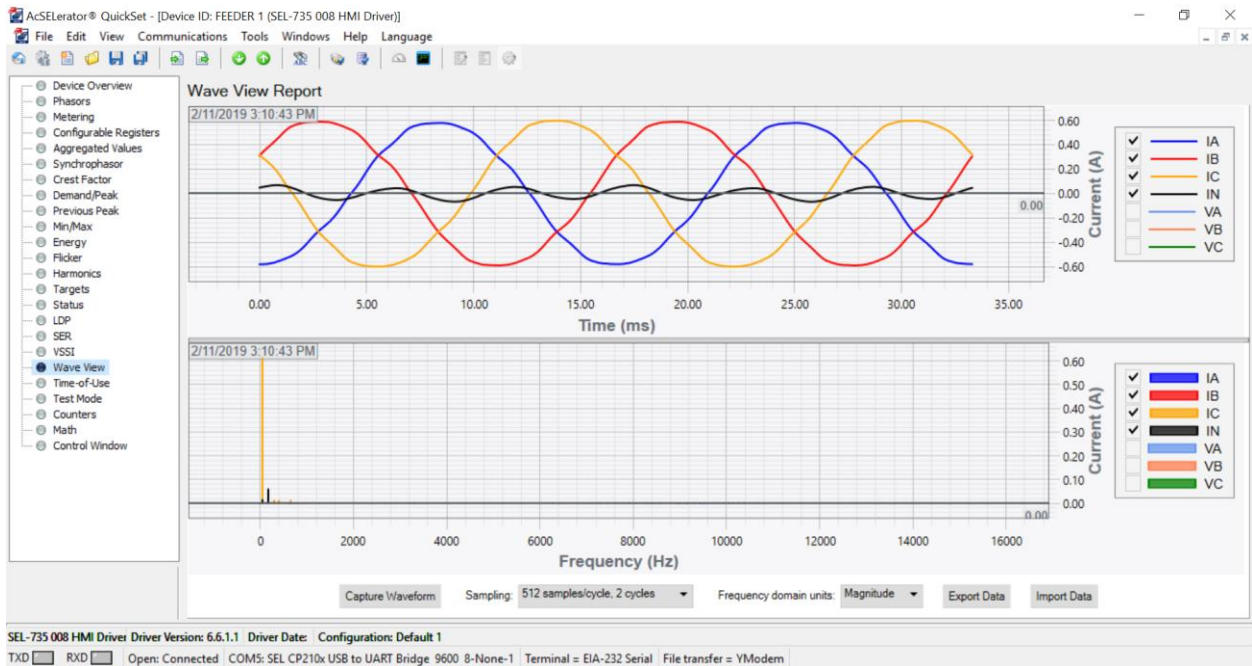
Figure 28. acSELerator QuickSet Current Waveform
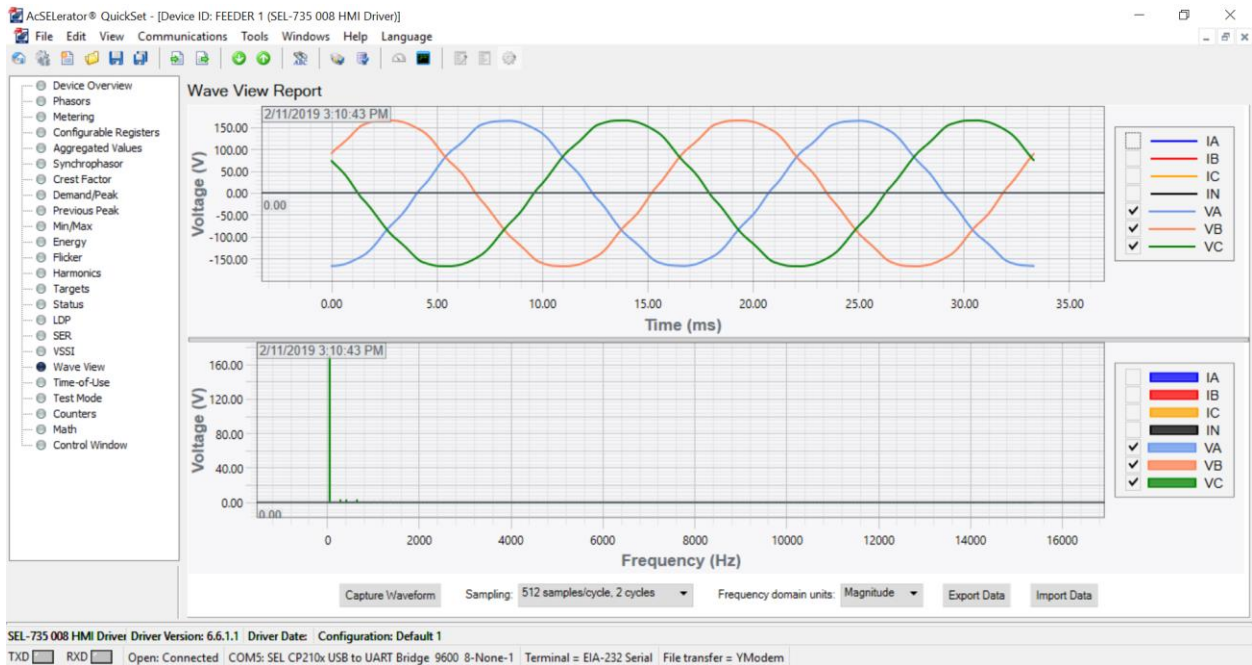
Figure 29. acSELerator QuickSet Voltage Waveform

Test Conclusion

The SEL-735 Power Quality and Revenue Meter Test was successful in evaluating the basic functionality of the SEL-735 Power Quality and Revenue Meter in metering voltage, current, power, and energy. This test qualified the SEL-735 to replace the traditional Yokogawa WT130. The back-panel connection of the SEL-735 was intuitive and simple. The SEL-735 quickly connected to the acSELerator QuickSet software via the C-662 USB serial cable to greatly expand its capability in displaying synchrophasors, symmetrical components, harmonics, and waveforms.

Although this test was limited in testing only the basic function, the remaining unutilized features such as sags, wells, and interruption detection, event report trigger, flicker measurement, time-of-use metering, and line-loss compensation prove the tremendous potential of the SEL-735. Future recommendations to maximize the SEL-735 capability is included in the Chapter 8. Future Work and Recommendation.

2.4 SEL-751 Feeder Protection Relay Test

The SEL-735 Feeder Protection Relay Test tests the basic protection function of the SEL-751 which includes the 50P instantaneous phase overcurrent element and 27P undervoltage element. This test verifies the circuit breaker's tripping capability when triggered by the SEL-751's trip signal. Successful testing will qualify the SEL-751 relay to protect the APsystem YC1000-3-208 microinverter whose protection has so far relied on the internal protection scheme of the microinverter. The test will analyze the event report generated by the SEL-751 following each overcurrent and undervoltage event.

The test consists of the Yokogawa WT130, SEL-751, a circuit breaker, a three-phase variac, and a variable three-phase load. A 120/208V Y-connected three-phase source is connected in series with the variac and to the WT130. The output of the WT130 is wired to the SEL-751 through a circuit breaker and to a variable three-phase load as seen in Figure 30.
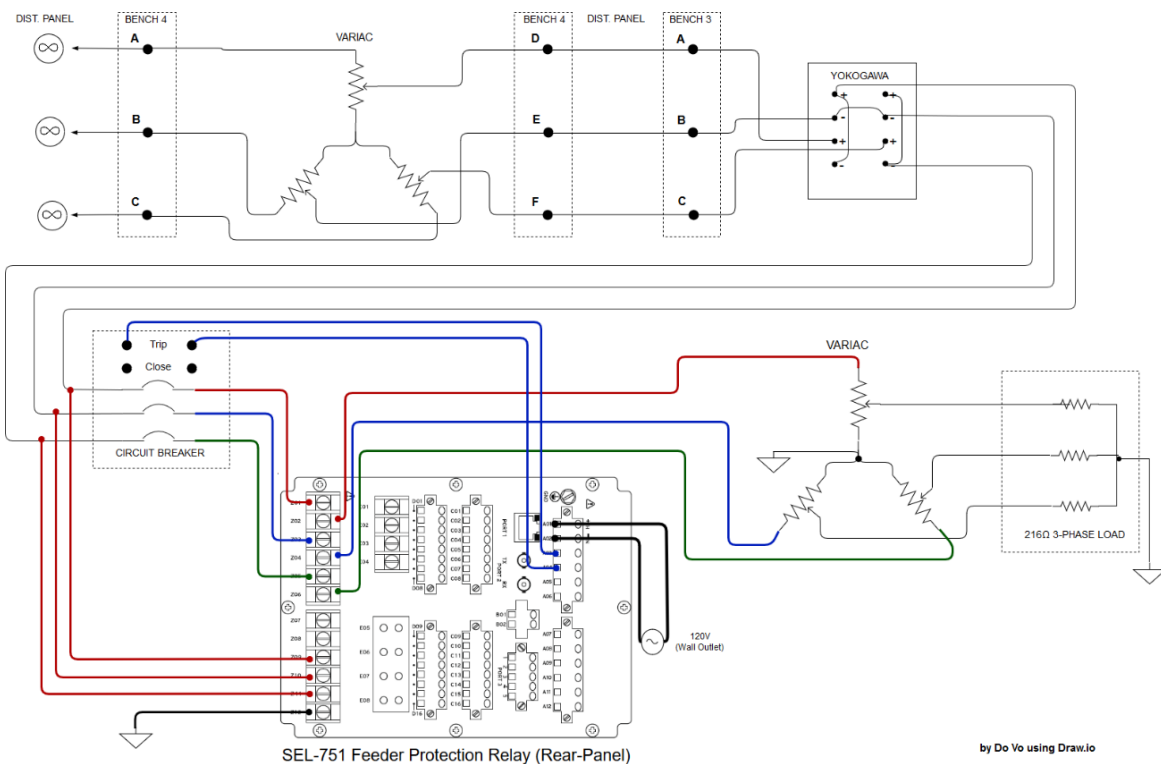
Figure 30. SEL-751 Feeder Protection Relay Test Wiring Diagram

Prior to energizing the circuit, the SEL-751 shall be connected to a computer via an SEL C-662 USB serial cable with the acSELerator QuickSet SEL-5030 Software preinstalled for programming purposes. Detailed step-by-step communication setting and programming for the SEL-751 are attached at Appendix C. Actual test setup is shown in Figure 31 and Figure 32.
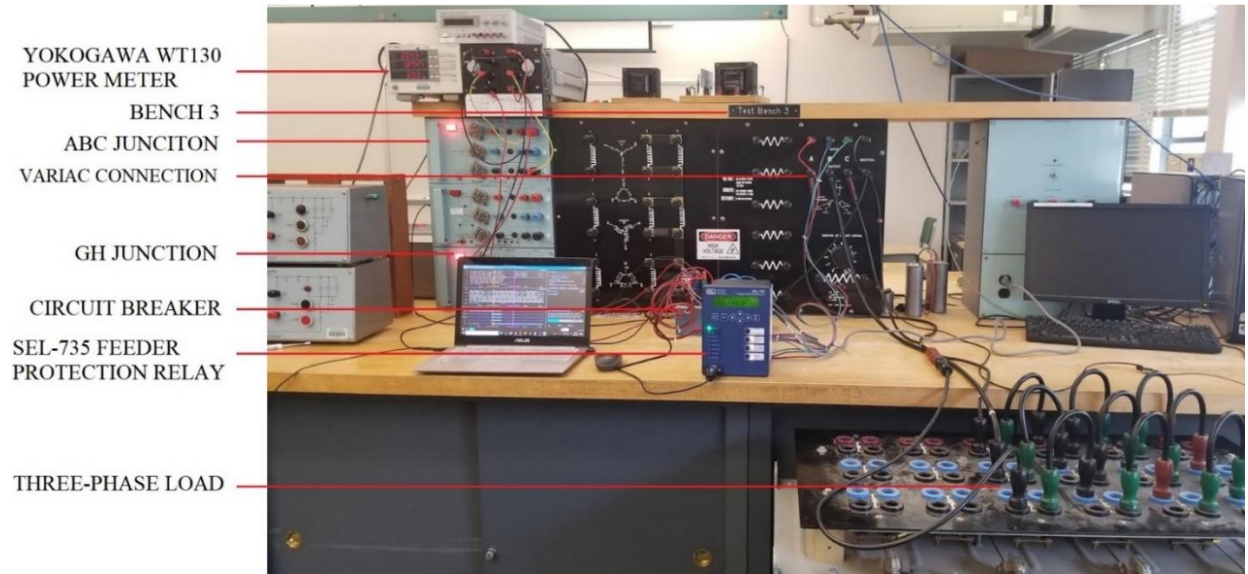

Figure 31. SEL-751 Feeder Protection Relay Bench 3 Test Setup (Part 1)
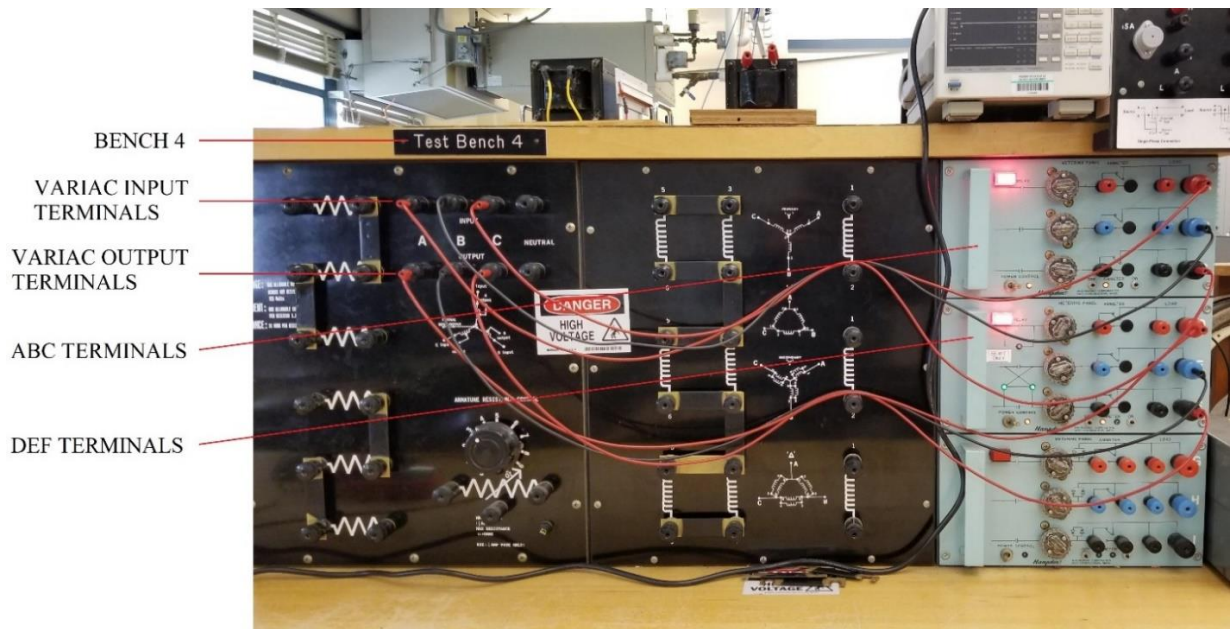
Figure 32. SEL-751 Feeder Protection Relay Test Bench 4 Setup (Part 2)

Figure 33 shows the distribution panel setup at the back of room 102 which provides the AC and DC power supply to the test. The distribution panel also consists of terminals associated with each test bench allowing convenient bench-to-bench connection.
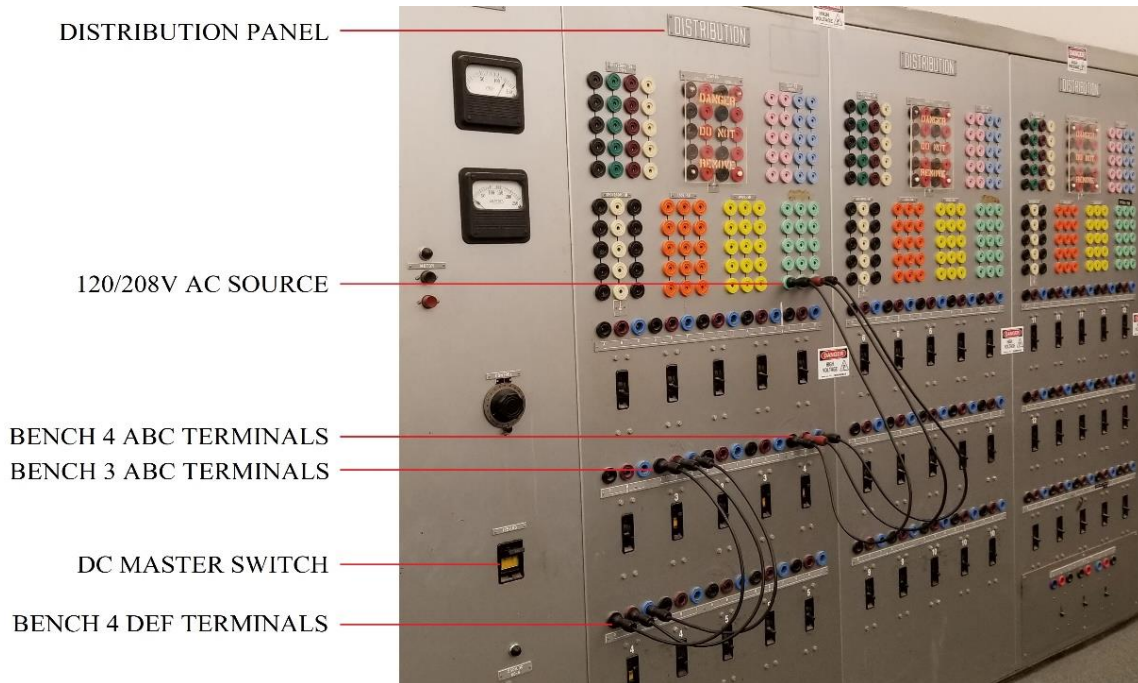
Figure 33. SEL-751 Feeder Protection Relay Test Distribution Panel Setup

Table 3 and Table 4 show the initial configuration and pick-up value settings for the SEL-751 Feeder Protection Relay Test. The CT and PT ratios are set to 1 since the voltage and current reported in this test have a small magnitude. The three-phase source and load are both Y-connected, thus, the transformer connection type is set to WYE. The overcurrent pick-up value is arbitrarily set to 0.5A which is corresponding to the variac position 8 (Table. 1). The undervoltage pick-up value is arbitrarily set to 113V. No delays have been added at this point.

Table 3. Modified Configuration Settings

Setting Prompt	Setting Name	Selected	Range/Selections
Phase A, B, C CT Ratio	CTR	1	1 – 5000
Neutral (IN) CT Ratio	CTRN	1	1 – 5000
PT Ratio	PT	1	1 – 10000
Synch. Voltage (VS) PT Ratio	PTRS	1	1 – 10000
Transformer Connection	DELTA_Y	WYE	WYE, DELTA
Line Voltage, Nominal Line-to-Line (volts)	VNOM	208.00	20 – 480, OFF

Table 4. Initial Pick-Up Value Settings

Setting Prompt	Setting Name	Selected	Range/Selections
Maximum Phase Overcurrent Trip Pickup	50P1P	0.5	0.25 – 100.00, OFF (A)
Maximum Phase Overcurrent Trip Delay	50P1D	0	0.00 – 400.00 (Sec)
Undervoltage Trip 1 Pickup	27P1P	113.00	2.00 – 300.00 (V)
Undervoltage Trip 1 Delay	27P1D	0	0.00 – 120.00 (Sec)
Phase-Phase Undervoltage Trip 1 Pickup	27PP1P	197.00	2.00 – 520.00 (V)
Phase-Phase Undervoltage Trip 1 Delay	27PP1D	0	0.00 – 120.00 (Sec)

The trip logic setting is rather intuitive in which the trip logic equation is asserted to logical 1 once the listed element, such as 50P1P or 27P1, is asserted to logical 1. Following a fault, the trip signal remains asserted until all the following conditions are true [5]:

- Minimum trip duration time (TDURD) passes (Ex: 27P1D, 50P1D)

- The TR logic equation de-asserts to logical 1

- One of the following occurs:

  - Unlatch Trip logic equation ULTRIP asserts to logical 1

  - Target Reset equation RSTTRGT asserts to logical 1

  - Target Reset Relay TRGTR asserts (Front-panel TARGET RESET is pressed)

The unlatch trip logic plays a significant role in maintaining the trip asserted until the fault is eliminated. Therefore, the 50P1P and 27P1 elements are both included in the trip and unlatch trip logic equations as shown. Additionally, the 50P1P and 27P1 are included in the event report trigger equation for further fault analysis.

- Trip logic: TR = ORED50T OR ORED51T OR ORED81T OR REMTRIP OR OC OR SV04T OR 50P1P OR 27P1

- Unlatch trip logic: ULTRIP = NOT (51P1P OR 51G1P OR 51N1P OR 52A OR 50P1P OR 27P1)

- Event Report Trigger: ER = R_TRIG 51P1P OR R_TRIG 51G1P OR R_TRIG 50P1P OR R_TRIG 50G1P OR R_TRIG 51N1P OR R_TRIG CF OR R_TRIG 27P1

  Finally, the output OUT101 (A03 and A04) of slot A is used to connect to the trip terminal of the circuit. The trip logic TR is added onto the OUT101 SELogic control equation which drives OUT101.

- OUT101 = HALARM OR SALARM OR AFALARM OR TR

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Test Result

After closing the circuit breaker, the element 50P1P instantaneous overcurrent pick-up asserted, thus, causing the SEL-751 Relay to trip the circuit. The 50P1P's pick-up triggered an event report (Figure 34) which was analyzed in SEL synchroWAVe software. The current spike circled in white in Figure 34 lasted approximately 30ms (1.8 cycles). Although the magnitude of the transient current was high, the duration of the transient was very short and caused no harm to the system. However, this transient current spike caused an unwanted trip which must be eliminated.
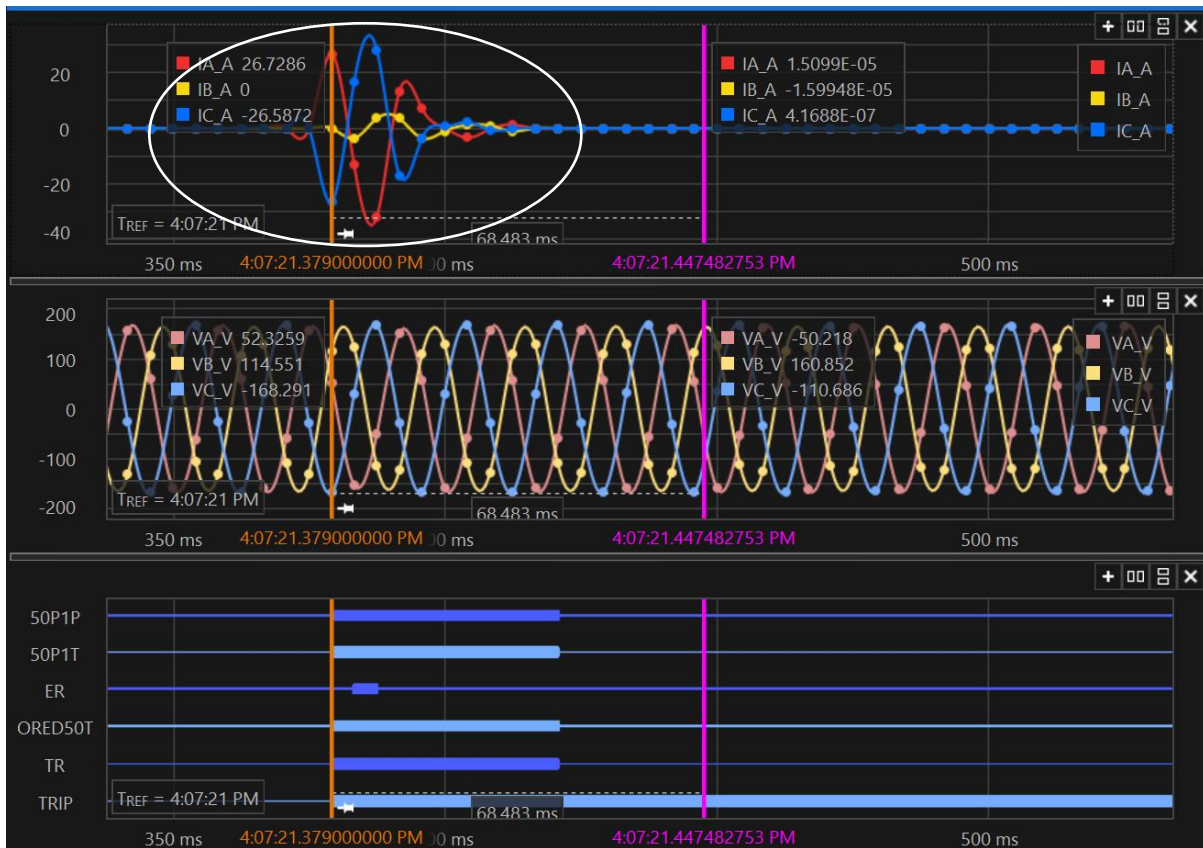
Figure 34. Overcurrent Event Report (Current Spike at Top Graph)

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Investigation

The source of this transient current was suspected to come from the damping of the unintentionally created R-L circuit by combining the variac and the three-phase load. While the three-phase load is purely resistive, the variac was made of the copper winding wrapped around a steel core which was inherently inductive [11]. To further verify the cause of the spike, the investigation eliminated both variacs and repeated the test three times with a fixed voltage (120/208V) and fixed three-phase load (216 Ω).

After removing the variacs, the circuit behaved normally and the SEL-735 no longer tripped shortly after the circuit breaker closed. It was concluded that the combination of the variacs and the resistive load created an R-L circuit whose damping caused the transient spike.

Solution

To avoid the unwanted trip from the transient current, a time delay was added to the 50P1P element for the purpose of this test, although in practice, the 51P1P time-over current element would be preferred for its inherent time delay. The modification included changing the phase overcurrent trip delay 50P1D from 0 to 0.25 second to bypass the transient current duration. This delay required the 50P1T to replace the 50P1P in the TR equation (Figure 35) to take effect [5].
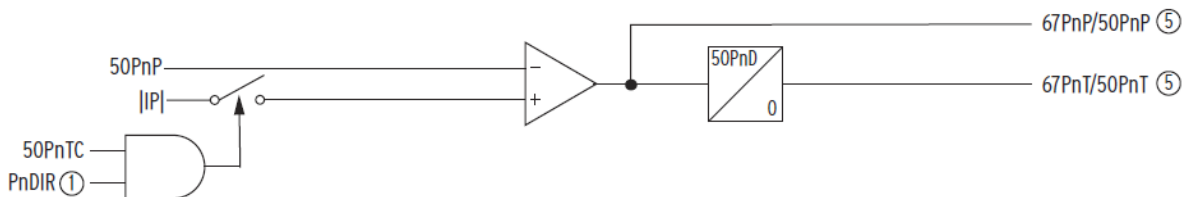
Figure 35. Graphical Logic of the Maximum Phase Overcurrent [5]

→   Trip logic: TR = ORED50T OR ORED51T OR ORED81T OR REMTRIP OR OC OR SV04T OR **50P1PT** OR 27P1
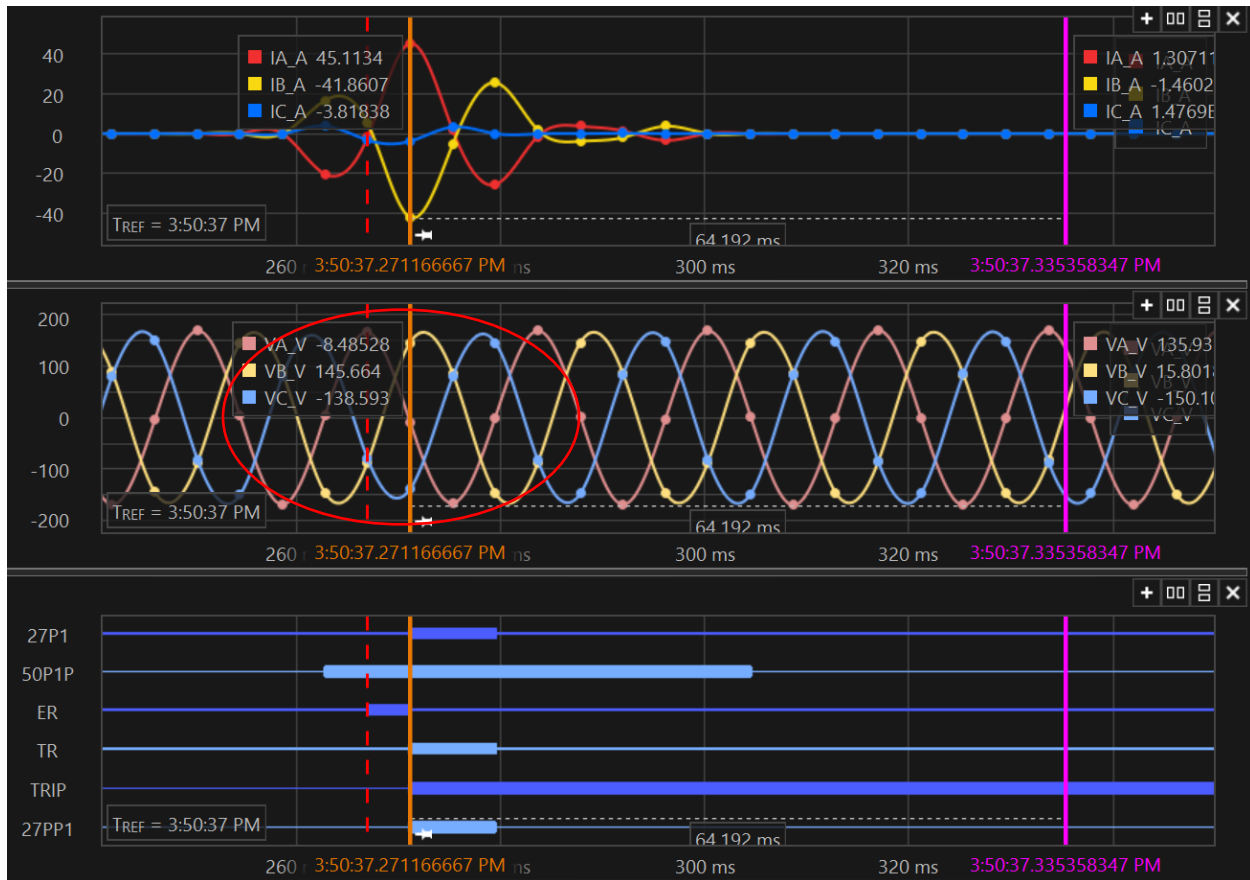
Figure 36. Undervoltage Event Report (After adding time-delay to 50P1P)

Although the time delay has been added to the 50P1P element, the SEL-751 still tripped

the circuit right after closing the circuit breaker. Further analysis in the event report showed the

phase-to-phase undervoltage element asserted and caused the 27P1, thus, the TR equation to

assert (Figure 36). It was observed that when the transient current occurred, the voltage dipped

below the pick-up value of the 27PP1 undervoltage element (197V L-L) . To bypass this

transient current, a 0.25 second time delay was also added to the 27PP1 using phase- and phase-

to-phase undervoltage delay 27P1D and 27PP1D, respectively to bypass the duration of the

spike. To reflect this time delay addition, the 27P1T replaced the 27P1 logic in the TR equation.

→   Trip logic: TR = ORED50T OR ORED51T OR ORED81T OR REMTRIP OR OC OR

SV04T OR **50P1PT OR 27P1T**

After the time delay was introduced to the 50P1, 27P1, and 27PP1, the SEL-751

accurately bypassed the current spike period upon the circuit breaker closure. As the variac of the

three-phase variable load approached position 8, the load drew approximately 0.514A (Table 1)

per phase which was above the threshold of the overcurrent pick-up value (0.5A). Consequently,

the element 50P1P asserted and 50P1T became asserted to logical 1 after the added delay in

50P1D expired (Figure 37). The trip equation TR asserted, thus, the SEL-751 tripped the circuit.

Figure 37. Overcurrent Trip Event Report

Similarly, as the input voltage variac's knob was turned down to lower the voltage below

the pick-up value of 113V L-N, the undervoltage element 27P1P expectedly picked up. The

27P1T became asserted to logical 1 after the added delay in 27P1D expired (Figure 38) causing

the trip equation TR to assert, thus, the SEL-751 tripped the circuit.

Figure 38. Undervoltage Trip Event Report

Conclusion

The SEL-751 Feeder Protection Relay Test was successful in testing the basic protection function of the SEL-751. The test verified that the 50P1 instantaneous phase overcurrent element and 27P1 undervoltage element asserted to logical 1 when the current exceeded the threshold, or the voltage dipped below the threshold. Since both protection elements were included in the trip equation TR, the SEL-751 sent a trip signal upon any 50P1 or 27P1's assertion. This test also verified that the circuit breaker successfully executed the trip signal from the SEL-751 and isolated the circuit. During this test, the transient current spike, as a result of an R-L circuit's damping, caused unwanted trips by the SEL-751. The solution was to add a short time-delay to bypass the current spike's duration. The test used SEL synchroWAVe to analyze the event

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reports generated by the SEL-751. The event reports captured the magnitude of the voltage and

current that caused the trip and displayed a timing diagram of the element that asserted. The

wiring of the SEL-751 was simple and straightforward. All the pick-up values and logic

equations could be programmed via acSELerator QuickSet.

Although this test was limited in testing only the basic protection function, the remaining

unutilized features such as directional overcurrent, arc-flash detection, fault location, high-

impedance fault detection, auto-reclosing, and over- and underfrequency applications show the

tremendous potential of the SEL-751 to protect the microinverter as well as the Microgrid from

disturbance. Future recommendations to maximize the SEL-751 capability is included in Chapter

8. Future Work and Recommendation.

2.5 Renewable Energy Integration Test

The Renewable Energy Integration Test is the final test to evaluate the overall operation of the Grid-Tied Solar System when connected to the Microgrid. The test observes the performance of the microinverter as well as the generators and adjusts necessary parameters such as generator output power and terminal voltage to ensure successful islanding process between the Microgrid and the utility grid.

The test consists of two solar panels, two circuit breakers, the APsystem three-phase grid-tied microinverter, the SEL-751 Feeder Protection Relay, SEL-735 Power Quality & Revenue Meter, and the existing Microgrid (Figure 39). The solar panels are installed at the hallway between room 20-101 and building 20A and connected to the microinverter inside the power lab room 20-102. The inverter output terminals are wired to the input of the SEL-735 via a circuit breaker. The output of the SEL-735 is connected directly to the input of the SEL-751. Lastly, the output of the SEL-751 and trip signal cable are connected to the circuit breaker before interconnecting to the Microgrid. All voltage sensing wires from the SEL-735 and SEL-751 are connected at the incoming terminals of the circuit breakers (Figure 40).

Before the isolation process takes place, the power generation of the generator shall be adjusted to receive 50W to 100W from the utility grid using the DC motor current knob. Too much or too little power imported from the utility could cause voltage and frequency collapse when isolating the Microgrid from the utility grid. No power shall be delivered to the utility grid at any given time. The Yokogawa Power Meter on test bench 6 is configured to display the power delivered/received from the utility grid. The SEL-751's phase undervoltage element pick-up 27P1P is set at 90V while the line undervoltage element pick-up 27PP1P is set at 156V with 0.25s delay. Lastly, the overcurrent element pick-up 50P1P is set at 2A with 0.25 seconds delay.

These two protection elements are set based on the specification of the microinverter and the

rated power of the solar panels for the purpose of this test. The Renewable Energy Integration

Test Procedure is attached at Appendix D.
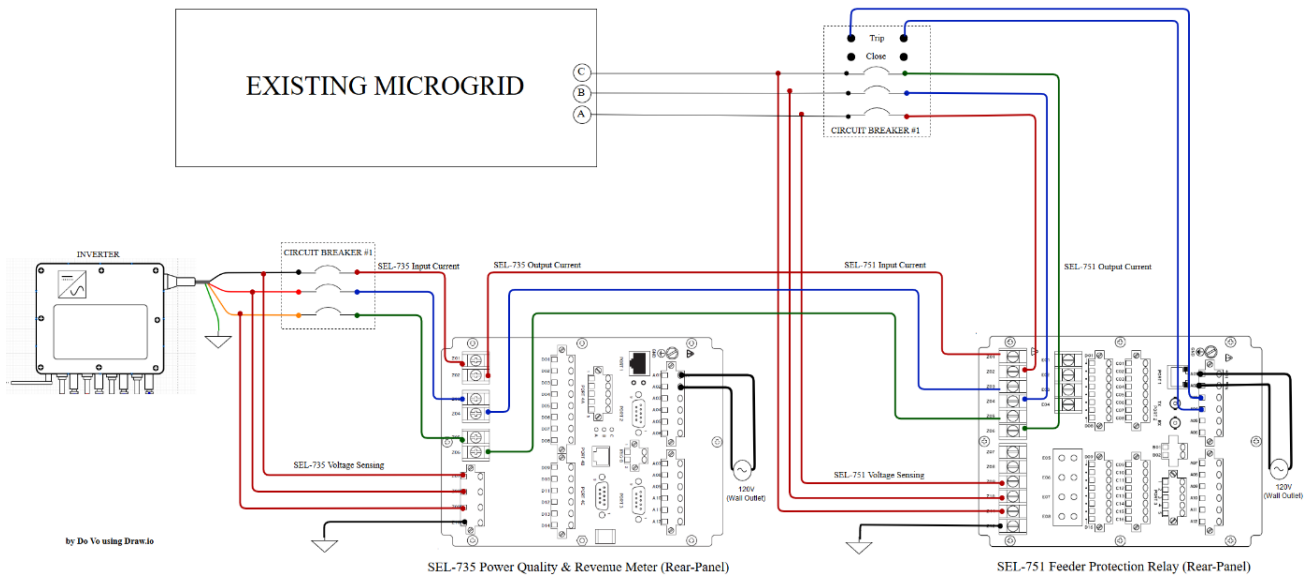
Figure 39. Renewable Energy Integration Test Wiring Diagram

Figure 40 shows the actual setup of the Renewable Energy Integration Test. The blue box

indicates the existing Microgrid while the red boxes indicate the generators. The renewable

energy branch is located on the black cart at the bottom of the figure. The solar panels and DC

transmission line were not included.
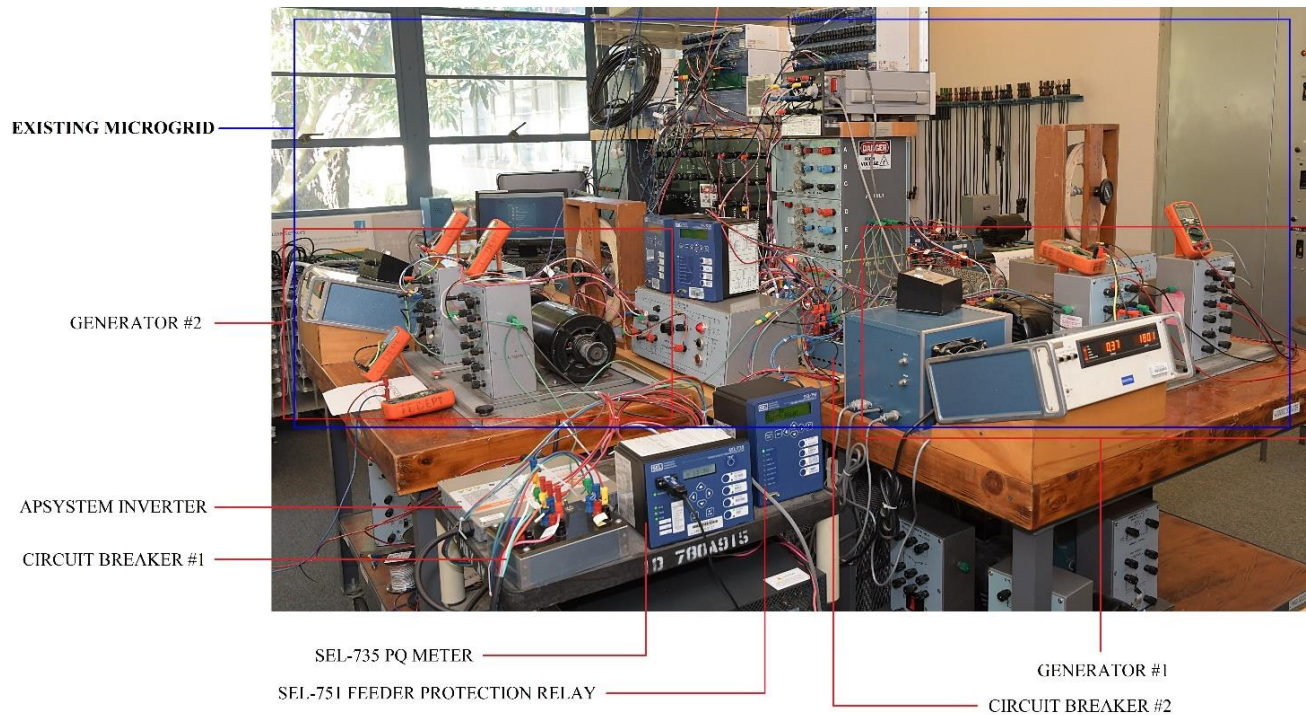
Figure 40. Renewable Energy Integration Test Setup

Test Data

Before isolation, the total power output of the generators and microinverter was 343.3W

as observed on the power meter (Figure 41). The microinverter outputted approximately 176.4W

(Figure 42) and the generators generated about 166.9W. The terminal voltages of both generators

were adjusted to 120V L-N while the speed remained fixed at 1800RPM (60Hz) since the system

was still synchronized to the utility grid. At this point, two static loads (~130W each) and the

induction motor (~70W) were turned on. The modelled line resistance and transformer also

consumed approximately 75W. The Microgrid, as a result, received an extra 69W from the utility

grid.

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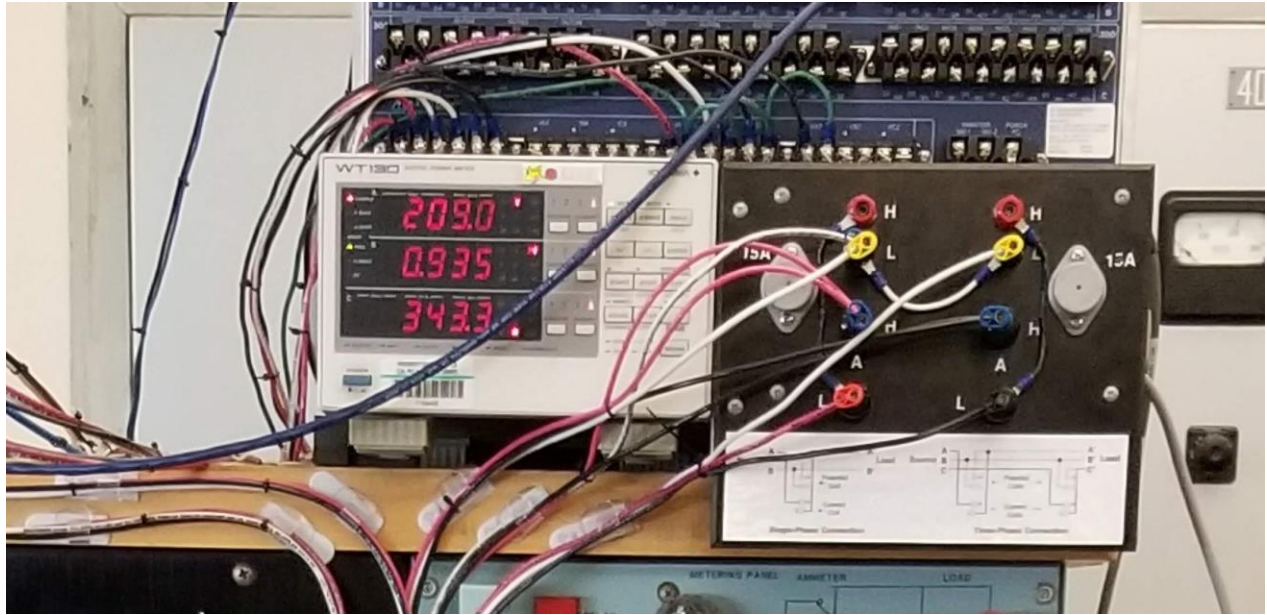
Figure 41. Total Power Generation of the Microgrid
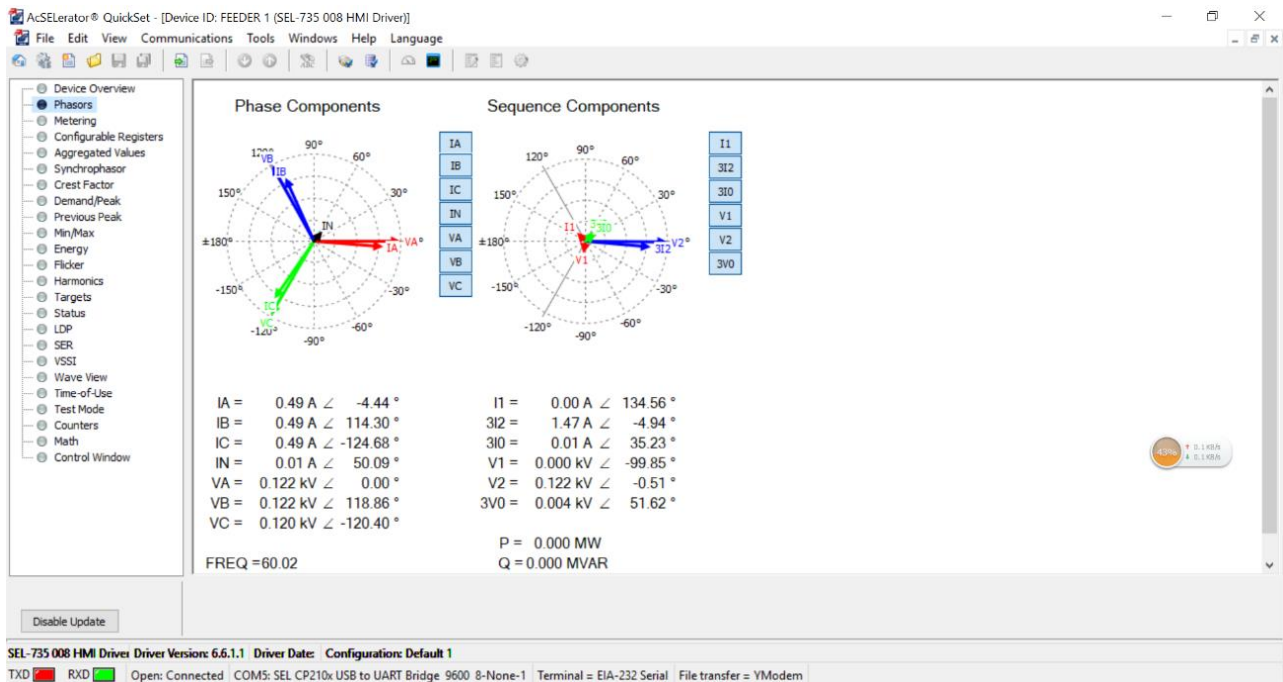
Figure 42. The acSELerator Quickset Phasors Display

Figure 43 shows the output power of the APsystem microinverter at the time of this test.

The Energy Communication Unit (ECU) gathered the microinverter's output data and uploaded

it to the APsystem Energy Monitoring & Analysis (EMA) server for online performance

monitoring.

Figure 43. Output Power of the Microinverter using EMA

After the utility switch was turned off, the Microgrid became isolated from the utility

grid. The generators and microinverter remained online. The terminal voltage of the generator

immediately dropped to 113V L-N and the speed increased to 1805 RPM (~60.16 Hz). Field

current was injected to bring the terminal voltage back to 120V L-N and the speed eventually

decreased to 1801 RPM (60.03 Hz). The output power of the generators and microinverter

remained unchanged. On the load side, the voltage across the static load and induction motor

dropped to 104V L-N. The islanded Microgrid's frequency and voltage was sensitive to the

output power of the solar panels. At one point, the "Senior Project Sign", which was taped on the

bottom edge of the right solar panel, was flipped by the wind which then covered a few

photovoltaic cells. The power production of the solar panels immediately decreased which

caused the speed of the generators to drop to 1795 RPM (59.83 Hz) and the terminal voltage of

the generator to drop to 118V L-N. Manual adjustment of the DC motor current to increase the

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output power of the generators was able to bring the speed to 1800 RPM (60 Hz) and the terminal voltage to ~120V L-N.

Test Result

The microinverter was able to remain connected and supplied power to the microgrid despite the momentary frequency change and voltage dip from the isolation process. The generators also remained online and provided frequency support for the microinverter.

Test Conclusion

The Renewable Energy Integration Test was successful in evaluating the performance of the microinverter and adjusted the appropriate voltage and power of the generators for the microinverter to remain connected after isolation from the utility grid. The success of this test qualified the solar panels, the APsystem three-phase grid-tied microinverter, the SEL-751 Feeder Protection Relay and SEL-735 Power Quality & Revenue Meter to permanently connect and become a part of the Microgrid representing the renewable energy generation. Future work to automatically adjust the voltage and frequency to combat the power generation fluctuation of the solar panel is necessary. Additionally, in-depth pick-up value selection for the protection element as well as protection scheme to maximize the ability to detect and eliminate grid disturbances are included in Chapter 8. Future Work and Recommendation.

Chapter 3. Market Research

There are only two generating units, synchronous generators, that ensure the self-sustainability factor of the Microgrid. However, the current grid has changed dramatically from distributed to non-distributed power generation due to the growing presence of roof-top solar at residential level, and solar farm at commercial level. From the California Energy Commission, the total of renewable energy generation of the State in 2017 was 29% while solar accounts for 11% (Figure 44) [4]. As these figures continue to grow, there is an urgent need to include renewable energy as an additional source to the Microgrid to more accurately represent the modern electric grid. The Grid-Tied Solar System, by Virginia Yan, provided the hardware capability and readiness to build a modern electric grid [1]. Four solar panels working together could provide up to approximately 480W DC and approximately 400W AC power. The uniqueness of the Grid-Tied Solar System is in its small scale three-phase DC-to-AC inverter APsystem YC1000-3-208 rated at 900W. The microinverter is also equipped with enhanced wireless monitoring. The solar panel cart has capability to maximize efficiency using the single-axis tracker.

2017 Total System Electric Generation in Gigawatt Hours

Fuel Type	California In-State Generation (GWh)	Percent of California In-State Generation	Northwest Imports (GWh)	Southwest Imports (GWh)	California Energy Mix (GWh)	California Power Mix
Coal	302	0.15%	409	11,364	12,075	4.13%
Large Hydro	36,920	17.89%	4,531	1,536	42,987	14.72%
Natural Gas	89,564	43.40%	46	8,705	98,315	33.67%
Nuclear	17,925	8.69%	0	8,594	26,519	9.08%
Oil	33	0.02%	0	0	33	0.01%
Other (Petroleum Coke/Waste Heat)	409	0.20%	0	0	409	0.14%
Renewables	61,183	29.65%	12,502	10,999	84,684	29.00%
Biomass	5,827	2.82%	1,015	32	6,874	2.35%
Geothermal	11,745	5.69%	23	937	12,705	4.35%
Small Hydro	6,413	3.11%	1,449	5	7,867	2.70%
Solar	24,331	11.79%	0	5,465	29,796	10.20%
Wind	12,867	6.24%	10,015	4,560	27,442	9.40%
Unspecified Sources of Power	N/A	N/A	22,385	4,632	27,017	9.25%
Total	206,336	100.00%	39,873	45,830	292,039	100.00%

Figure 44. California Energy Portfolio [4]

There is no small-scale three-phase microgrid available on the market. The Cal Poly Microgrid is unconventional for its purpose to give the students the ability to experiment. The Grid-Tied Solar System is also the first of its kind designed to inject as little as 900W to a three-phase microgrid.

Chapter 4. Customer Archetype

The customers will be Cal Poly students especially those who concentrate in power system as well as those who want to explore what power systems have to offer. The Microgrid Renewable Energy Integration once completed will provide hands-on experience on renewable energy generation and grid-tie connection that are similar to real world solar projects.

The growing renewable energy industry leads to a highly competitive market of DC-to-AC inverters. There are currently four major solar microinverter manufactures (Table 5), SMA Solar Technology, EN, Solar Edge, and APsystems.

Table 5. Major Inverter Manufacturer in the U.S. Market

SMA	SMA Solar Technology AG is a German solar energy equipment supplier founded in 1981 and headquartered in Niestetal, Northern Hesse, Germany. SMA is a producer and manufacturer of solar inverters for photovoltaics systems with grid-tied, off-grid power supply, and backup operations.
ENPHASE	Enphase Energy is an energy technology company headquartered in Fremont, California. Enphase designs and manufactures software-driven home energy solutions that span solar generation, home energy storage and web-based monitoring and control.
APsystems ALTENERGY POWER	APsystems was founded in Silicon Valley in 2009 and is now based in Seattle, WA. APsystems offers advanced, powerful solar microinverter technology for residential and commercial systems. The APsystems microinverter solution combines highly efficient power inversion with a user-friendly

	monitoring interface and energy communication unit to track and bring you reliable, intelligent energy.
solar**edge**	SolarEdge Technologies Inc. is a provider of power optimizers, solar inverters and monitoring solutions for photovoltaic arrays based in Herzliya, Israel. Solar Edge products aim to increase energy output through module-level Maximum Power Point Tracking.

APsystems is particularly a growing company emphasizing in microinverters for residential and commercial businesses. APsystems provide small-scale single-phase and three-phase microinverter in 120V/208V and 240V/480V voltage class that are suitable to connect to the Microgrid (120V/208V Y-Connection) [9]. On the other hand, there are currently two major US companies providing services in the field of microgrid products and power system protection, Schweitzer Engineering Laboratories (SEL) and General Electric (GE). Both companies offer educational services throughout the United States. There are also European companies that hold a fair market share in the power industry worldwide, Siemens, Schneider Electric, and ABB.

Table 6. Major Protection Relay Manufacturer and Microgrid Product in the U.S. Market

	Schweitzer Engineering Laboratories, Inc. (SEL) is a US based company headquartered in Pullman, WA. SEL designs, manufactures, supports products and services ranging from generator and transmission protection to distribution automation and control systems. Founded in 1982 by Edmund O. Schweitzer III, SEL shipped the world's first digital protective relay.
	General Electric Company (GE) is a US based company headquartered in Boston, MA. The company operates in the various industries including appliances, water/power, oil/gas, energy management, aviation, medical device, life sciences, pharmaceutical, software development and engineering. GE was one of the earliest companies to manufacture and sell electromechanical relays used in power system.

Chapter 5. Market Description

Business Model: **Microgrid Renewable Energy Integration**

Key Partners:
- Project advisor: Dr. Poshtan
- EE faculties: Dr. Nafisi, Dr. Shaban, Dr. Taufik
- Equipment: Schweitzer Engineering Labs (SEL) Relays, APSystems Microinverter and Energy Communication Unit
- EE students

Key Activities:
- Conduct Islanded Mode Test and Microgrid Test
- Protect the outgoing feeder
- Monitor power delivered to the Microgrid

Value Proposition:
- Tests, protects, and monitors renewable energy to the Microgrids
- Ensure renewable energy can fully be integrated into the microgrid

Key Resources:
- EE Power Faculty
- EE Senior Students
- Grid-Tied Solar System Project Report by Virginia Yan

Customer Relationships:
- EE students
- EE professors
- Cal Poly IEEE Power and Energy Society

Channels:
- Directly to the student via Electrical Engineering Department Lab
- Utilities and universities representatives

Cost Structure:
- Electrical engineering department fund
- Components gifted by industry partners
- Equipment used to conduct testing (Circuit breaker, DC disconnect switch, cable)

Revenue Streams:
- Lab Notebook
- Lab Kit

Customer Segments:
- EE students concentrating in power systems
- Students with interest in renewable energy
- Other colleges and university

Figure 45. Business Model

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Product/Project Name: **Microgrid Renewable Energy Integration**

Unmet Customer Need: Test the newly designed Grid-Tied Solar System and install protection element before integrating to the Microgrid.

Unique Value Proposition: provides, protects, and monitors renewable energy to the Microgrid

Pricing and Availability:
• $45,214.00
• Senior Project Presentation/Expo
• Winter 2018

Target Customer: Electrical engineering students specializing in renewable energy, power distribution, and protection.

Product Objectives: Diversifying energy input to the microgrid

Positioning: Ensure successful integration and secured connection to the microgrid

Customer Benefits:
• Reliable and secured connection to the Microgrid
• Study about how solar panel and associated equipment work to deliver power
• Secured power flow and monitoring capability

Sustainable Differentiation:
• By the students and for the students design
• Islanded Mode Test that replicates the Microgrid
• Protected by modern SEL relays

Disruptive Go-to-Market:
• Provide on-site experiment
• Intuitive and step-by-step operation manual
• Expandable capability

Figure 46. Market Data

Chapter 6. Engineering Requirements and Specifications

Table 7. Engineering Requirements and Specifications

	Engineering Requirement	Market Requirement	Reasoning
1	Parallel power generation	Sustainability	The microinverter must deliver power to the load together with the synchronous generator to sustain the Microgrid.
2	Islanded mode operation	Independence	The synchronous generator and microinverter operating off-grid reduce the reliance on the utility grid.
3	Power quality and metering	Energy monitoring	The SEL-735 meters and tracks energy production from the solar panel and microinverter to fully inform the Microgrid operator.
4	Protection against faults	Secure and reliable	The SEL-751 feeder protection relays detect disturbance and isolate the system from disturbance using a circuit breaker.
5	Communication to other SEL devices	Expandability	Unused digital and analog input/output ports allow future communication with other SEL units for automation and back-up protection.
6	Ability to recreate test setups	Experiment	Step-by-step procedures allow tests to be recreated experimentally and troubleshooted.

Chapter 7. Schedule and Milestones

The Deliverable Deadlines table keeps the work flow defined and organized.

Table 8. Deliverable Deadlines

Deadline	Deliverable
10/05/18	Test Method Proposal
12/05/18	Islanded Mode Test
01/11/19	Modified Islanded Mode Testing
02/12/19	SEL-735 Power Quality and Revenue Meter
02/21/19	SEL-751 Feeder Protection Relay Test
03/16/19	Renewable Energy Integration Test
03/22/19	Project Report Due

These Gantt charts include the tentative schedule and coordination with senior project advisor to keep track of the testing process and increase work efficiency.
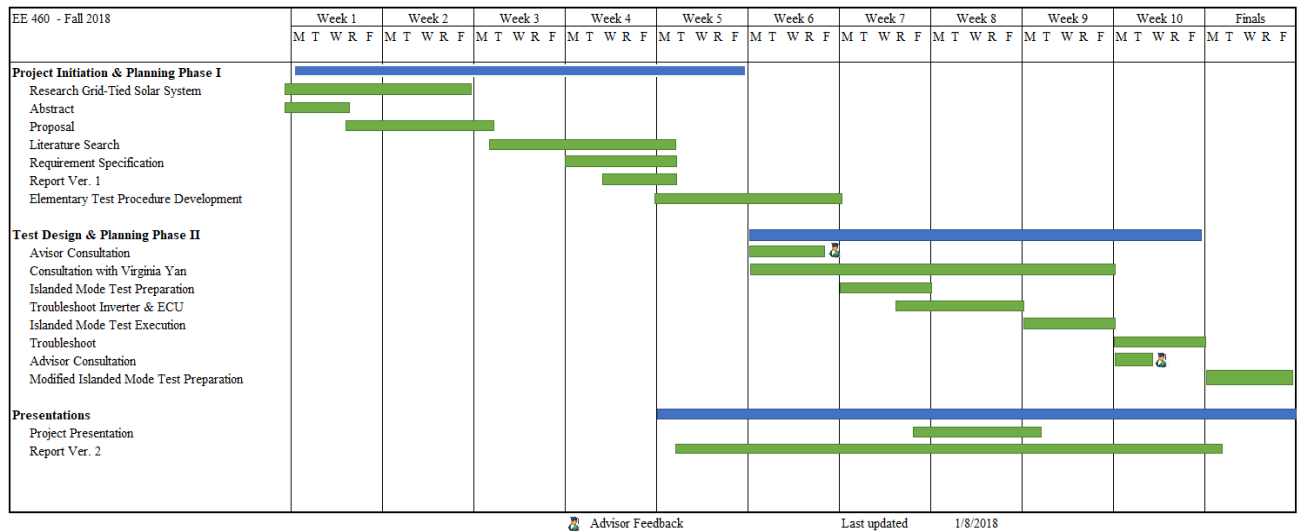
Figure 47. Project Schedule for Fall 2018

EE 461/462 - Winter 2018	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9	Week 10	Finals
	M T W R F	M T W R F	M T W R F	M T W R F	M T W R F	M T W R F	M T W R F	M T W R F	M T W R F	M T W R F	M T W R F
Relay Installation & Testing Phase II											
Islanded Mode Test Execution											
SEL-735 Power Meter Installation											
SEL-751 Feeder Protection Installtion											
Overcurrent & Voltage Elements											
SEL-735 Test											
SEL-751 Test											
Troubleshoot											
Final Test / Documentation											
Renewable Energy Integration Preparation											
Advisor Consultation											
Renewable Energy Integration Execution											
Troubleshoot											
Demo											
System Labelling											
Report Ver. 3											
Documentation											
Future Work Recommendation											
Final Report											

Advisor Feedback   Last updated   3/20/2018

Figure 48. Project Schedule for Winter/Spring 2019

Chapter 8. Recommendation and Future Work

The solar panels are weather dependent and cannot always be reliable. During cloudy days the solar panels of Grid-Tied Solar Systems only produce 10% to 20% of its rated output power. This energy is not enough to power the Microgrid whose static load is approximately 400W. Since Cal Poly, San Luis Obispo is located in the Northern Hemisphere, the Sun's declination angle to South is at its maximum during the months of November, December, January [10]. During this time, the hallway between Building 20A and Building 20 where the solar carts are installed is only unshaded for three to four hours which limits availability of the solar panels. During the Spring quarter (April, May, and June), the power lab room 20-102 is occupied by many EE 295 Energy Conversion Laboratory sections which reduces the time frame to setup and run the solar panels. It is, therefore, necessary to use a solar array simulator. The solar array simulator's output voltage and current follow the typical I-V curves of solar panels. The modern solar array simulators also include a software to easily change the I-V curves and irradiance profiles (sunny day, cloudy day, slow ramp, and fast ramp) to replicate actual weather condition. The most important benefit of a solar array simulator is the ability to operate at any time.

The SEL-751 Feeder Protection Relay is capable of providing many smart protection schemes to better protect the inverter as well as the Microgrid from disturbance. Fault current calculation, contingency analysis and zone of protection shall be carefully considered when setting protection elements. The recommended protection schemes include:

- Instantaneous and time overcurrent
- Under- and overvoltage
- Under- and overfrequency

- Directional

- High impedance fault

- Reclosing

As wildfires caused by electrical faults of the power line become more and more frequent due to increasingly severe weather condition, it is recommended to include a protection scheme to prevent or mitigate fire ignition. Although the Microgrid is an indoor experiment, this effort to modernize Microgrid will give the students an opportunity to solve real world problems.

The SEL-735 Power Quality & Revenue Meter can optimally operate with the acSELerator Quickset software for real time metering purposes. It is recommended to designate a monitor to display the acSELerator Quickset features of the SEL-735. In addition, the SEL-735 can be programmed to detect declining power output from the microinverter and signal corrective action to stabilize the Microgrid. The corrective action could include starting up an additional generating unit (if available) to compensate from the power loss.

The DC motor's input power and synchronous generator's field current are manually controlled using the potentiometers. The inability to automatically adjust voltage and frequency in response to various load conditions can destabilize the Microgrid and potentially lead to voltage and frequency collapse. It is recommended to install a control system to automatically adjust the DC motor's speed and field current of the synchronous generator. The existing SEL-700G automation and metering features can provide real time voltage, frequency, and load condition data with a controller that can adjust the DC input current and synchronous motor field current.

Bibliography

[1] Yan, Virgnia, "Grid-Tied Solar System", Senior Project Report, Dept. Elect. Eng., California Polytechnic State University, San Luis Obispo, December 2018. Available: https://digitalcommons.calpoly.edu/eesp/439/. [Accessed: January 07, 2019]

[2] A. Richter, E. van der Laan, W. Ketter and K. Valogianni, "Transitioning from the traditional to the smart grid: Lessons learned from closed-loop supply chains," *2012 International Conference on Smart Grid Technology, Economics and Policies (SG-TEP)*, Nuremberg, 2012, pp. 1-7. Dec. 2018.

[3] A. Elrayyah, Y. Sozer, I. Husain and M. Elbuluk, "Power flow control in a microinverter based microgrid," *2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Orlando, FL, 2012, pp. 1933-1939. Dec. 2018.

[4] "Total System Electric Generation." *California Energy Commission*. [Online]. Available: https://www.energy.ca.gov/almanac/electricity_data /total_system_power.html. [Accessed: Jan. 22, 2019].

[5] *SEL-751 Feeder Protection Relay*, Schweitzer Engineering Laboratories Inc., Pullman, WA, Instruction Manual, 2018. Available: https://selinc.com/products/751/ [Accessed: Jan. 05, 2019]

[6] *SEL-735 Power Quality and Revenue Meter*, Schweitzer Engineering Laboratories Inc., Pullman, WA, Instruction Manual, 2018. Available: https://selinc.com/products/735/ [Accessed: Jan. 10, 2019]

[7] SEL-5030 acSELerator QuickSet Software, Schweitzer Engineering Laboratories Inc., Pullman, WA, Instruction Manual, 2018. Available: https://selinc.com/products/5030/ [Accessed: Jan. 05, 2019]

[8] Eric Osborn, "Protection Automation and Frequency Stability Analysis", Master's Thesis, Dept. Elect. Eng., California Polytechnic State University, San Luis Obispo, July 2018. Available: https://digitalcommons.calpoly.edu/theses/1828/. [Accessed: Oct. 20, 2018]

[9] APsystems YC1000-3 Commercial Microinverter, APsystem Inc., Washington, Seattle. Instruction Manual 2018. Available: https://usa.apsystems.com/portfolio-item/apsystems-yc1000-3-208/. [Accessed: July 07, 2018]

[10] "Declination Angle." *PVEducation*. [Online]. Available: https://www.pveducation.org/ pvcdrom/properties-of-sunlight/declination-angle. [Accessed: Feb. 10, 2019].

[11] Elliott, Rod. "Transformers - The Variac." *The Audio Pages*. 20 Feb. 2009. Available: http://sound.whsites.net/articles/variac.htm. [Accessed: Feb. 11, 2019].

[12] "Environmental Impacts of Solar Power." *Union of Concerned Scientists*. [Online]. Available: https://www.ucsusa.org/clean_energy/our-energy-choices/renewable-energy/environmental-impacts-solar-power.html. [Accessed: March 08, 2019]

[13] Ozro Corulli, "Motor protection lab experiment using SEL-710," Senior project report, Dept. Elect. Eng., California Polytechnic State Univ., San Luis Obispo, June 2013, pp. 13-14. Available: https://digitalcommons.calpoly.edu/eesp/223/. [Accessed: Oct. 08, 2018]

Appendix A – Islanded Mode Test Program

Islanded Mode Test Program

By Virginia Yan, Do Vo

Updated Time: 12/04/18

Safety Message: **STOP WORK** *immediately,* **PRESS** *the emergency power-off button, and* **REPORT** *to the EE department faculties of the system's suspicious behaviors that include, but are not limited to, loud and inconsistent noise and shaking from the generator, DC motor, smoke, arcing, corona, and equipment damage. The emergency power-off button is located at the window corner of power lab room 20-102.*

Note: This Microinverter Isolation Mode Test Procedure is meant for the testing of YC1000-3-208 microinverter when isolated from the infinite bus. APsystems microinverters are designed to only operate when they can sense power coming from the grid. Even if they are plugged into the PV array, they will not turn themselves on until they can read power from the grid. When DC power is first applied to the unit, it flashes red once, and then green three times.

Preparation procedure:

□ Step 1: Setup PV portable cart Troy at a spot where the solar panels are directly and fully exposed to the sunlight.

□ Step 2: Verify open-circuit voltage at the PVs (approx. 40V for two panels) with DC disconnect switch CLOSED.

□ Step 3: Lay the AC transmission line along the pavement from the PVs to the microgrid lab

□ Step 4: Connect the solar tracker controller to a 12-V battery; make sure it is in automatic mode by pressing the "Set" button on the remote.

□ Step 5: Connect positive and negative terminals of the circuit breaker to port GH on bench 3.

□ Step 6: Plug the ABC cables from the microinverter to the circuit breaker. Short the trip terminal and verify that the circuit breaker is OPEN.

□ Step 7: Connect the ABC cables from the circuit breaker to the Yokogawa WT130 Power Meter as shown in Figure 49A.
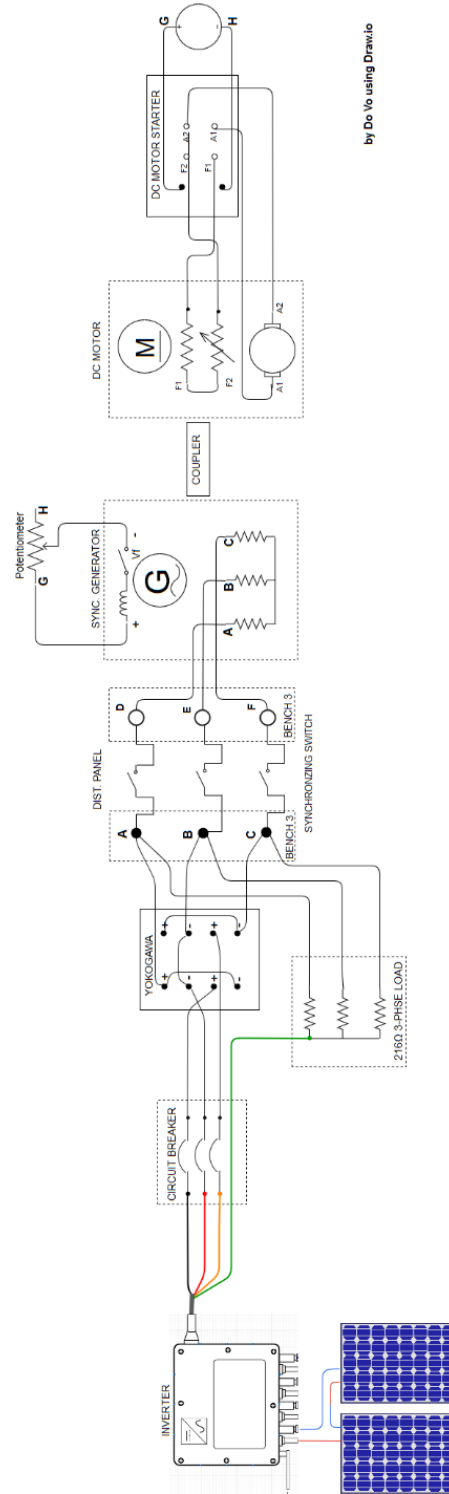
Figure 49A. Islanded Mode Test Wiring Diagram

Test Procedure:

☐ Step 8: TURN on ABC, DEF, and GHI switch on the distribution panel.

☐ Step 9: Press the "START" button on the DC starter to run the DC motor.

☐ Step 10: Switch from Induction Start to Sync Run on the synchronous generator.

☐ Step 11: Adjust the DC motor speed to 1800 rpm and the generator's output voltage to 208V using the rheostat.

☐ Step 12: Close the synchronizing switch on bench 3 to synchronize the generator using One-Dark-Two-Bright method.

☐ Step 13: Verify the line voltages on the grid side of the circuit breaker (205V to 210V).

☐ Step 14: Connect the DC transmission line's MC4 to channel 4 of the microinverter.

☐ Step 15: Verify one red blink followed by three short green blinks on the microinverter's LED.

☐ Step 16: CLOSE circuit breaker.

☐ Step 17: Verify the line voltages on the inverter side of the circuit breaker (205V to 210V).

☐ Step 18: Wait for 5 minutes of the microinverter internal safety delay.

☐ Step 19: Verify flashing fast green lights (2-sec gap).

     (indicates that microinverter is producing power with no ECU)

☐ Step 20: Record voltage, current, and power measurements from the Yokogawa.

☐ Step 21: TURN-OFF the switch at the ABC terminals to isolate from the infinite bus.

☐ Step 22: Record the generator speed, terminal voltage, and the inverter output current.

Housekeeping:

☐ Step 23: OPEN circuit breaker.

☐ Step 24: OPEN DC disconnect switch.

☐ Step 25: Disconnect MC4 connectors from the microinverter.

☐ Step 26: Disconnect the AC cable from microinverter to circuit breaker.

☐ Step 27: Turn off power in Microgrid Lab and disconnect all components.

☐ Step 28: Fold Troy and locate it to the PES room.

Note 1: Utility Interconnection Voltage and Frequency Trip Limits and Trip Times
Voltage and frequency limits for utility Interaction

Condition	Simulated utility source		Maximum time (sec) (cycles) at 60 Hza before cessation of current to the simulated utility
	Voltage (V)	Frequency (Hz)	
A	< 0.50 Vnor	Rated	80ms
B	0.50 Vnor ≤ V < 0.88 Vnor	Rated	200ms
C	1.10 Vnor < V < 1.20 Vnor	Rated	200ms
D	1.20 Vnor ≤ V	Rated	80ms
E	Rated	f > 60.5	160ms
F	Rated	f < 59.3	160ms

Figure 50A. Microinverter Internal Protection

Appendix B – Modified Islanded Mode Test Program

Modified Islanded Mode Test Program

By Virginia Yan, Do Vo

Updated Time: 01/10/19

*Safety Message: **STOP WORK** immediately, **PRESS** the emergency power-off button, and **REPORT** to the EE department faculties of the system's suspicious behaviors that include, but are not limited to, loud and inconsistent noise and shaking from the generator, DC motor, smoke, arcing, corona, and equipment damage. The emergency power-off button is located at the window corner of power lab room 20-102.*

Note: This Modified Microinverter Isolation Mode Test Procedure is meant for the testing of YC1000-3-208 microinverter when isolated from the infinite bus with a variable three-phase load added. APsystems microinverters are designed to only operate when they can sense power coming from the grid. Even if they are plugged into the PV array, they will not turn themselves on until they can read power from the grid. When DC power is first applied to the unit, it flashes red once, and then green three times.

Preparation procedure:

□ Step 1: Setup PV portable cart Troy at a spot where the solar panels are directly and fully exposed to the sunlight

□ Step 2: Verify open-circuit voltage at the PVs (approx. 40V for two panels) with DC disconnect switch CLOSED.

□ Step 3: Lay the DC transmission line along the pavement from the PVs to the microgrid lab

□ Step 4: Connect the solar tracker controller to a 12-V battery; make sure it is in automatic mode by pressing the "Set" button on the remote.

□ Step 5: Connect positive and negative terminals of the circuit breaker to port GH on bench 3.

□ Step 6: Plug the ABC cables from the microinverter to the circuit breaker. Short the trip terminal and verify that the circuit breaker is OPEN.

□ Step 7: Connect the ABC cables from the circuit breaker to the Yokogawa WT130 Power Meter as shown.

□ Step 8: Wire the three-phase load to the variac and connect the input of the variac to the ABC terminals of bench 3 as shown in Figure 51B.
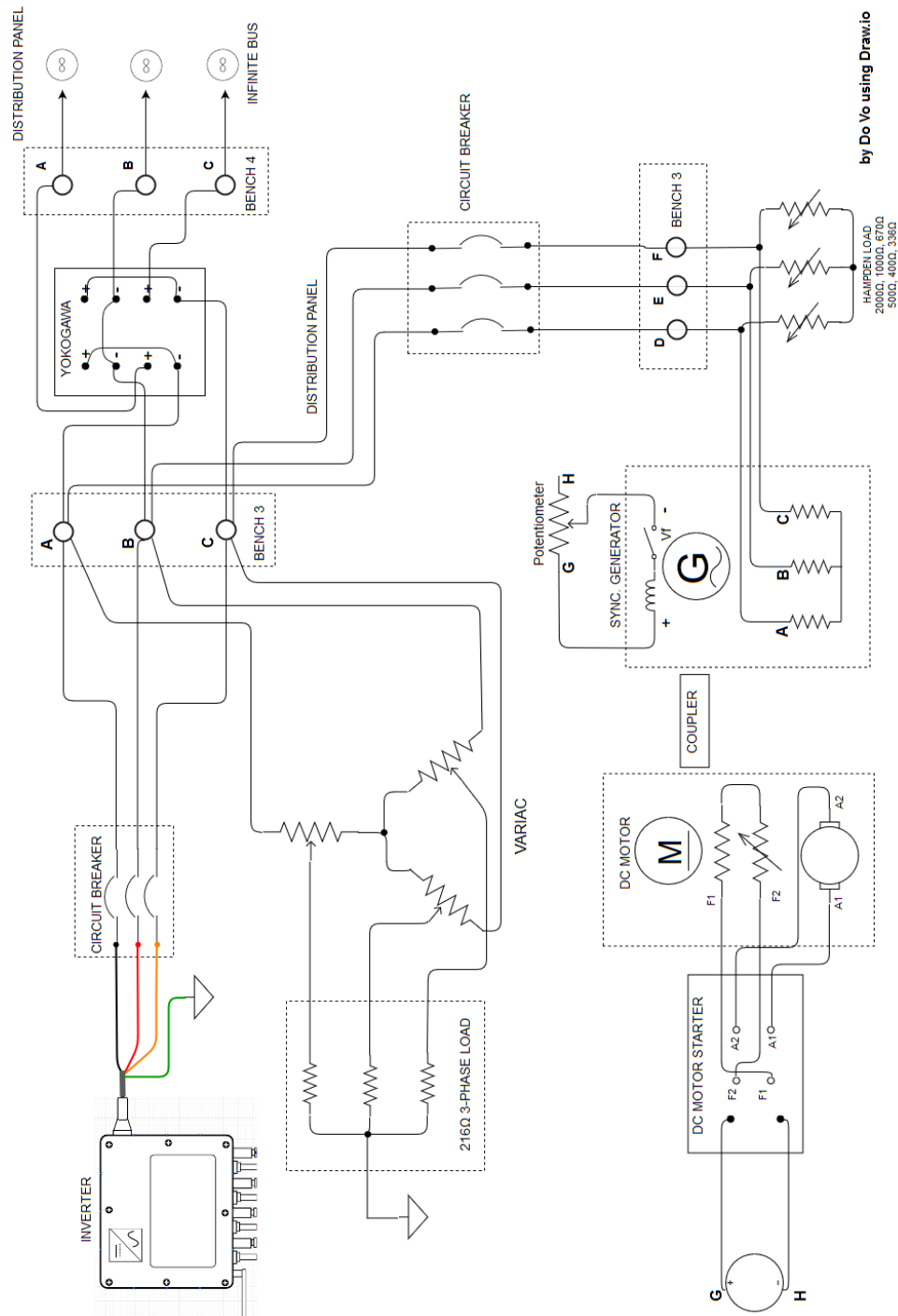

Figure 51B. Modified Islanded Mode Test Wiring Diagram

Test Procedure:

☐ Step 9: Turn on the ABC, DEF, and GHI switches on the distribution panel.

☐ Step 10: Press "START" button on the DC starter to run the DC motor.

☐ Step 12: Switch from Induction Start to Sync Run on the synchronous generator.

☐ Step 13: Adjust the DC motor speed to 1800 rpm and the generator's output voltage to 208V using the rheostat; Verify the measurements with a multimeter.

☐ Step 14: CLOSE the synchronizing switch on bench 3 to synchronize the generator using One-Dark-Two-Bright method.

☐ Step 15: Verify approximately 0W reading from Yokogawa power meter display.

☐ Step 16: Verify the line voltages on the inverter side of the circuit breaker (205V to 210V).

☐ Step 17: Connect the DC transmission line's MC4 to channel 4 of the microinverter.

☐ Step 18: Verify one red blink followed by three short green blinks on the microinverter's LED.

☐ Step 19: CLOSE circuit breaker.

☐ Step 20: Wait for 5 minutes of the microinverter internal safety delay.

☐ Step 21: Check line voltages on the secondary side (from PV).

☐ Step 22: Verify flashing fast green lights (2-sec gap).

     (Indicating that microinverter is producing power with no ECU)

☐ Step 23: Turn the variac's knob clockwise until the Yokogawa displays approximately 0W.

☐ Step 24: Record voltage, current, and power measurements from the Yokogawa.

☐ Step 25: TURN OFF the switch at the ABC terminals to isolate from the infinite bus.

☐ Step 26: Record the generator speed, terminal voltage, and the inverter output current.

Housekeeping:

☐ Step 27: OPEN circuit breaker.

☐ Step 28: OPEN DC disconnect switch.

☐ Step 29: Disconnect MC4 connectors from the microinverter.

☐ Step 30: Disconnect the AC cable from microinverter to circuit breaker.

☐ Step 31: Turn off power in Microgrid Lab and disconnect all components.

☐ Step 32: Fold Troy and locate it to the PES room.

Note 1: Utility Interconnection Voltage and Frequency Trip Limits and Trip Times
Voltage and frequency limits for utility Interaction

Condition	Simulated utility source		Maximum time (sec) (cycles) at 60 Hza before cessation of current to the simulated utility
	Voltage (V)	Frequency (Hz)	
A	< 0.50 Vnor	Rated	80ms
B	0.50 Vnor ≤ V < 0.88 Vnor	Rated	200ms
C	1.10 Vnor < V < 1.20 Vnor	Rated	200ms
D	1.20 Vnor ≤ V	Rated	80ms
E	Rated	f > 60.5	160ms
F	Rated	f < 59.3	160ms

Figure 52B. Microinverter Internal Protection

Appendix C – SEL-735 Communication Setting and Programming

SEL-735 Communication Setting and Programming
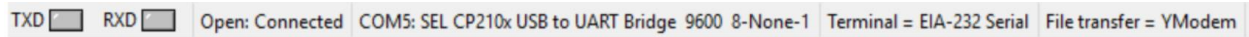
By Do Vo

Updated Time: 02/11/19

*Safety Message: **STOP WORK** immediately, **PRESS** the emergency power-off button, and **REPORT** to the EE department faculties of the system's suspicious behaviors that include, but are not limited to, loud and inconsistent noise and shaking from the generator, DC motor, smoke, arcing, corona, and equipment damage. The emergency power-off button is located at the window corner of power lab room 20-102.*

Note: All pictorial illustrations in the procedures are used as examples to aid the students. Actual display might vary based on the SEL device model and firmware version.

Initiation procedure:

□ Step 1: Plug the power cord of the SEL-735 to a 120V wall outlet.

□ Step 2: On the front panel:

    a. Press the **ENT** button to enter the main menu

    b. Press the **DOWN ARROW** button (4 times) → Press the **ENT** button to select S̲et/Show

    c. Press the **DOWN ARROW** button once → Press the **ENT** button to select P̲ort Settings

    d. Press the **ENT** button to select F̲ront Port

       (If a back-panel port is used, select the corresponding Port 1, Port 2, or Port 3)

    e. Press the **DOWN ARROW** to scroll down and record the following parameters:

      Data speed: _____   Data Bits: _____   Stop Bits: _____   Parity: _____

□ Step 3: Connect the SEL C-662 USB serial cable from Port F at the front panel of the SEL-735 to a USB port on a computer.

□ Step 4: Open acSELerator QuickSet software.

□ Step 5: On the menu bar, select **C̲ommunication** → **Parameters** (or press **Ctrl + R**)

□ Step 6: Under Active Connection Type, select **Serial** and choose the SEL C-662 USB COM port under Device.

□ Step 7: Select the corresponding parameters as recorded in step 2 and click **Apply**.

□ Step 8: Verify connection status shown as "Connected" at the bottom left corner.

□ Step 9: Select the **Terminal Icon** (or press **Ctrl + T)** to open a terminal window.

□ Step 10: Type "**= ID"** and record the following series.

FID =_____

PARTNO =_____
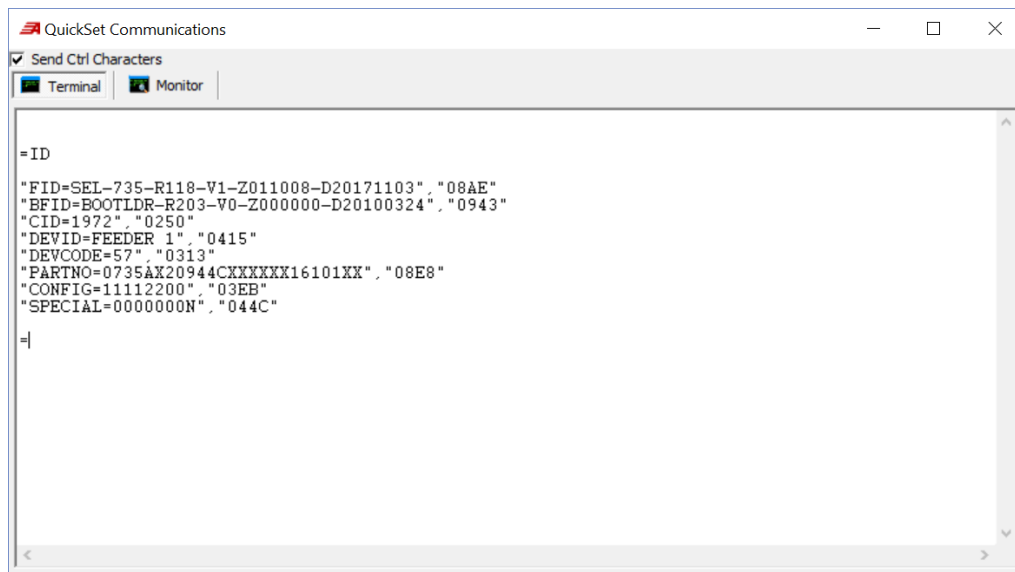
Figure 53C. Example Terminal of the SEL-735

□ Step 11: On the menu bar, select **File** → **New** (or press **Ctrl + N).**
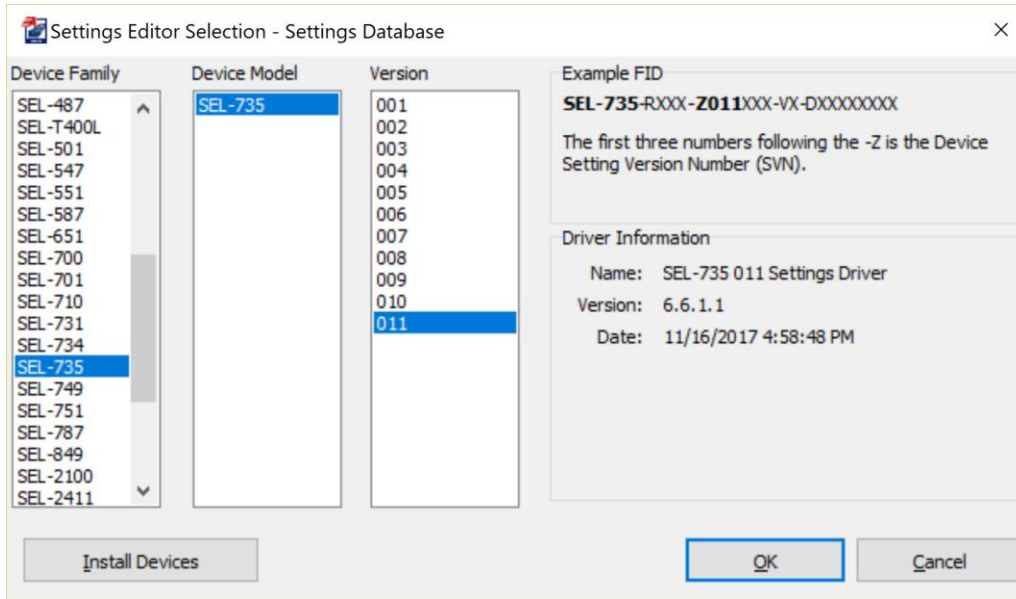
Figure 54C. Example Settings Database for the SEL-735

☐ Step 12: Select **SEL-735** and the corresponding version. Click **OK.**

(The first three numbers following the -Z in FID series is the Device Setting Version Number)

☐ Step 13: Under the Device Part Number window, complete the following parameters to match the recorded PARTNO in Step 10. Click **OK**

- Power Quality and Recording
- Meter Form
- Slot A, Power Supply
- Slot B, Main Board Communications
- Slot C, SELect Boards
- Slot D. SELect Boards
- Communication Protocol
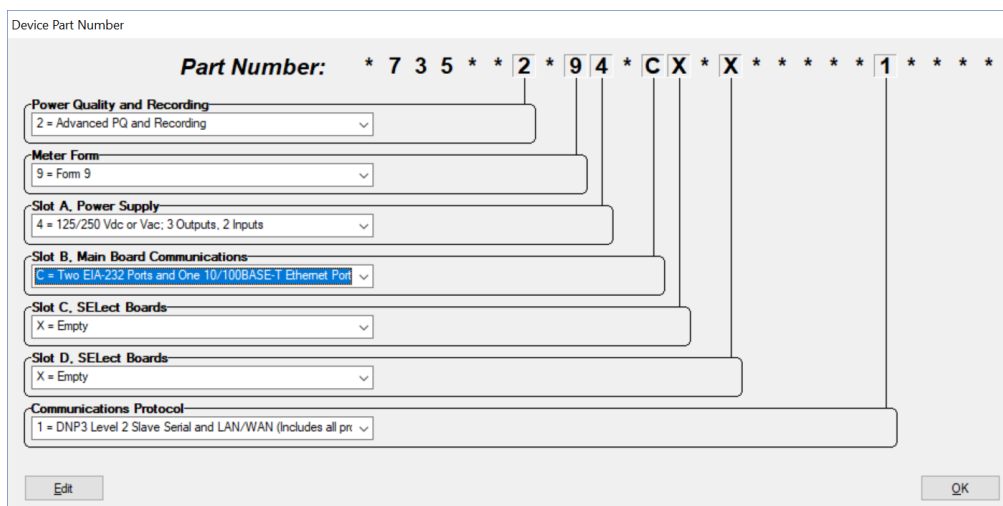
Figure 55C. Example Device Part Number Selection

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Programming procedure:

□ Step 14: On the left column, select **General → Identifier and Scaling**

□ Step 15: Set the following settings

- CTR = 1
- PTR = 1
- VOLT_SCA = KILO

- POWR_SCA = KILO
- ENRG_SCA = KILO
- PRI_SCA = Y

Figure 56C. Example Device Part Number Selection

□ Step 16: On the menu bar, select **File → Database Manager → New** to create a new database to store future settings.

□ Step 17: Select **File → Save** (or press **Ctrl + S)** to save the setting at the newly created database.

□ Step 18: Select the **Send Active Setting** to export the setting to the SEL-735

Appendix D – SEL-751 Communication Setting and Programming

SEL-751 Communication Setting and Programming

By Do Vo

Updated Time: 02/20/19

*Safety Message: **STOP WORK** immediately, **PRESS** the emergency power-off button, and **REPORT** to the EE department faculties of the system's suspicious behaviors that include, but are not limited to, loud and inconsistent noise and shaking from the generator, DC motor, smoke, arcing, corona, and equipment damage. The emergency power-off button is located at the window corner of power lab room 20-102.*

Note: All pictorial illustrations in the procedures are used as examples to aid the students. Actual display might vary based on the SEL device model and firmware version.

Initiation procedure:

□ Step 1: Plug the power cord of the SEL-751 to a 120V wall outlet.

□ Step 2: On the front panel:

    a. Press the **ENT** button to enter the main menu.

    b. Press the **DOWN ARROW** button (4 times) → Press the **ENT** button to select S̲et/Show

    c. Press the **DOWN ARROW** button twice → Press the **ENT** button to select P̲ort Settings.

    d. Press the **ENT** button to select Port F̲.
       (If a back-panel port is used, select the corresponding Port 1 to 4)

    e. Press the **DOWN ARROW** button twice → Press the **ENT** button to select C̲omm Settings.

    f. Press the **DOWN ARROW** to scroll down and record the following parameters:
       Data speed: _____ Data Bits: _____ Stop Bits: _____ Parity: _____

□ Step 3: Connect the SEL C-662 USB serial cable from Port F at the front panel of the SEL-735 to a USB port on a computer.

□ Step 4: Open acSELerator QuickSet software.

□ Step 5: On the menu bar, select <u>**Communication**</u> → **Parameters** (or press **Ctrl + R)**

□ Step 6: Under Active Connection Type, select **Serial** and choose the SEL C-662 USB COM port under Device.

□ Step 7: Select the corresponding parameters as recorded in step 2 and click **Apply**.

□ Step 8: Verify connection status shown as "Connected" at the bottom left corner.

| TXD ☐ | RXD ☐ | Open: Connected | COM5: SEL CP210x USB to UART Bridge | 9600 8-None-1 | Terminal = EIA-232 Serial | File transfer = YModem |

□ Step 9: Select the **Terminal Icon** ▨ (or press **Ctrl + T)** to open a terminal window.

□ Step 10: Type "**= ID"** and record the following series.

           FID =_____

           PARTNO =_____

```
QuickSet Communications                              —    □    ×
☑ Send Ctrl Characters
  ▣ Terminal   ▨ Monitor

 ID

 "FID=SEL-751-R200-V4-Z007003-D20170922","08AF"
 "BFID=BOOTLDR-R501-V0-Z000000-D20140224","0947"
 "CID=9DC9","0276"
 "DEVID=SEL-751","03C7"
 "DEVCODE=77","0315"
 "PARTNO=751401A0X0X70851230","069E"
 "CONFIG=111112010","041B"
 "iedName =","0380"
 "type =","028F"
 "configVersion =","0629"

 =|
```

Figure 57D. Example Terminal of the SEL-751

□ Step 11: On the menu bar, select <u>**File**</u> → **New** (or press **Ctrl + N)**.

□ Step 12: Select **SEL-751** and the corresponding version. Click **OK**.

(The first three numbers following the -Z in FID series is the Device Setting Version Number)
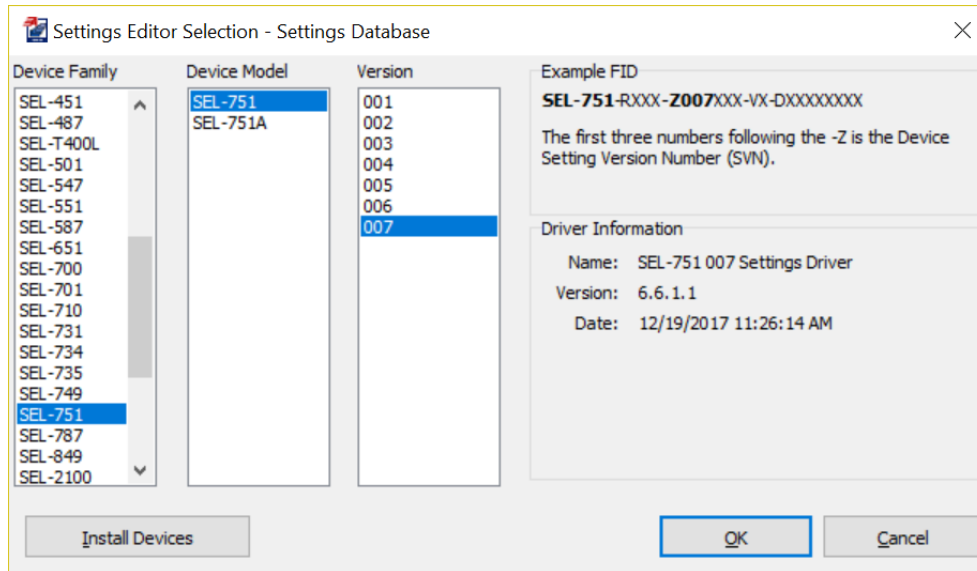
Figure 58D. Example Settings Database for the SEL-751

□ Step 13: Under the Device Part Number window, complete the following parameters to match the recorded PARTNO in Step 10. Click **OK**.

- Firmware Option
- User Interface
- Position C
- Position D

- Position E
- Position Z
- Front Panel Options

- Communications Ports
- Protocols
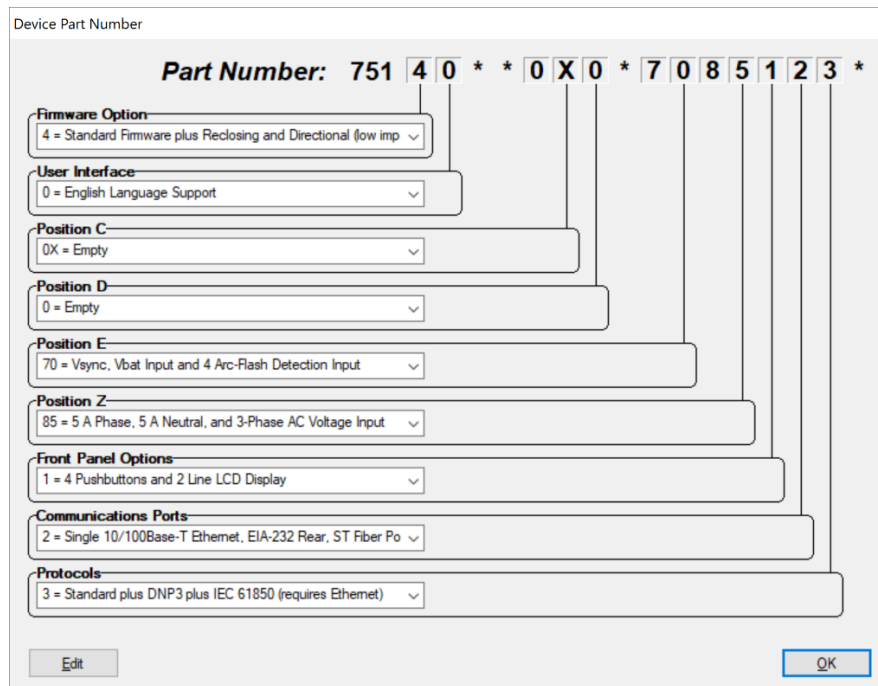
Figure 59D. Example Device Part Number of an SEL-751

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Programming procedure:

□ Step 14: On the left column, select **Group 1 → Set 1 → Main**

□ Step 15: Set the following settings:

- CTR = 1
- CTRN = 1
- PTR = 1.00

- PTRS = 1.00
- DELTA_Y = WYE
- VNOM = 208

□ Step 16: Select **Group 1 → Set 1 → Overcurrent Element → Maximum Phase Overcurrent**

□ Step 17: Set the following elements:

- 50P1P = 0.5

- 50P1D = 0.25
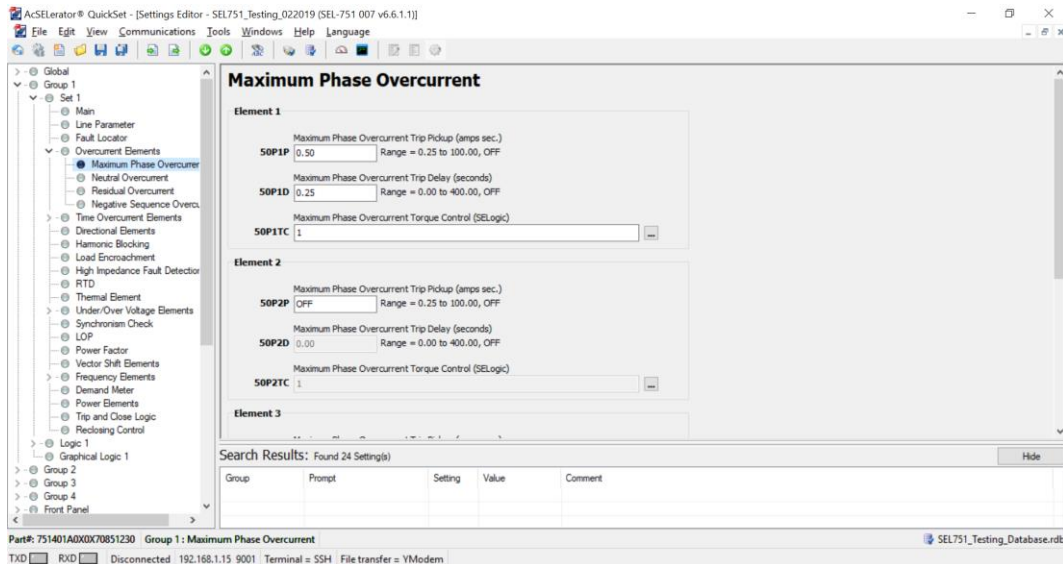
Figure 60D. Example Maximum Phase Overcurrent Setting of the SEL-751

□ Step 18: Select **Group 1 → Set 1 → Under/Over Voltage Elements → Undervoltage Elements**

- 27P1P = 113.00

- 27P1D = 0.25

- 27PP1P = 197.00

- 27PP1D = 0.25
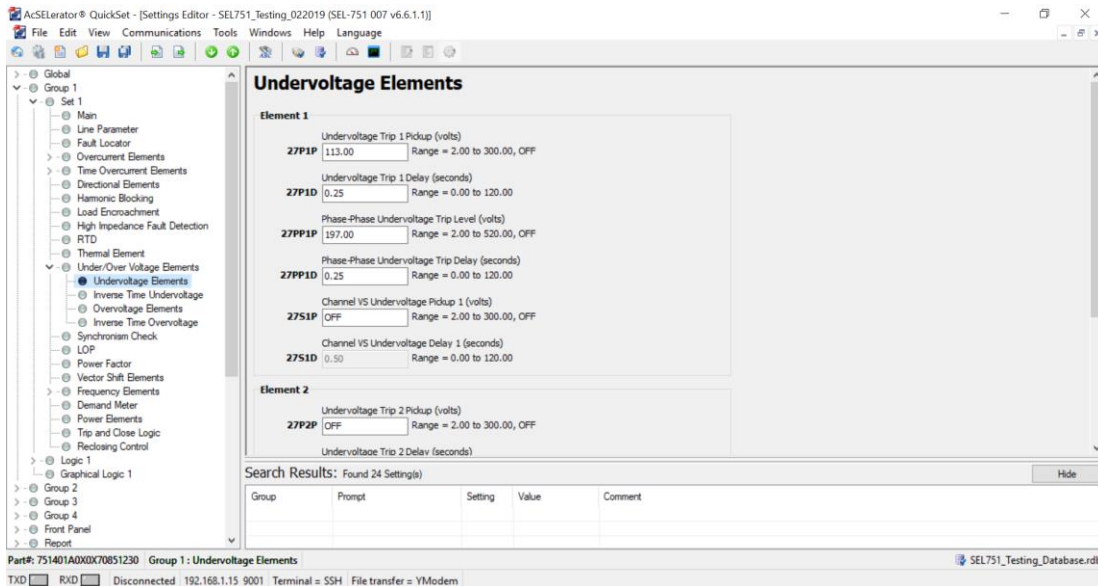
Figure 61D. Example Undervoltage Elements Setting of the SEL-751

□ Step 19: Select **Group 1 → Set 1 → Trip and Close Logic.**

Add "**OR 50P1T OR 27P1T**" to the TR equation

Add "50P1P OR 27P1" to the ULTRIP equation with the existing parenthesis
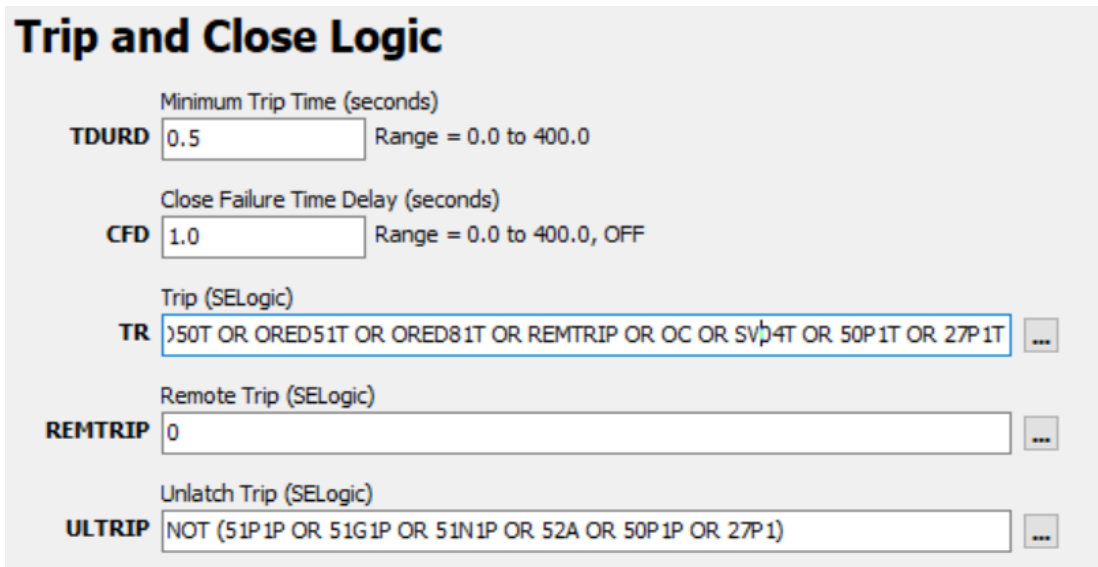
Figure 62D. Example Trip and Close Logic Setting of the SEL-751

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Step 20: Select **Group 1** → **Logic 1** → **Slot A**. Add "**OR TR**" to the OUT101 logic equation.

Figure 63D. Example Slot Setting of the SEL-751

□ Step 21: On the menu bar, select **File** → **Database Manager** → **New** to create a new database to store future settings.

□ Step 22: Select **File** → **Save** (or press **Ctrl + S**) to save the setting at the newly created database.

□ Step 23: Select the **Send Active Setting** to export the setting to the SEL-735

Appendix E – Renewable Energy Integration Test Program

Renewable Energy Integration Test Program

By Do Vo

Updated Time: 03/14/19

*Safety Message: **STOP WORK** immediately, **PRESS** the emergency power-off button, and **REPORT** to the EE department faculties of the system's suspicious behaviors that include, but are not limited to, loud and inconsistent noise and shaking from the generator, DC motor, smoke, arcing, corona, and equipment damage. The emergency power-off button is located at the window corner of power lab room 20-102.*

Note: This Renewable Energy Integration Test Procedure is meant for the testing of YC1000-3-208 microinverter when connected to the existing Microgrid [8].

Operating procedure:

□ Step 1: Turn on GH terminal switches (125V DC power supply) on bench 5 and bench 6. Verify all circuit breakers' LEDs illuminate.

□ Step 2: Turn on ABC terminal switch (utility switch) on bench 6. Verify line voltage reading on bench 6's Yokogawa (205V – 209V).

□ Step 3: Close circuit breakers CB-1, CB-2, CB-3, and CB-4 on bench 6. Verify circuit breakers closed (red LEDs illuminate).

□ Step 4: Close circuit breaker CB-8, CB-9, and CB-10 on bench 5. Verify power reading on bench 6's Yokogawa (70W – 80W).

□ Step 5: Turn on the DC starter of generator #1.

□ Step 6: Tune the DC motor knob to draw more than 0.35A.

□ Step 7: Press the "Start" button on the DC starter.

□ Step 8: Turn the DC motor knob clock-wise to increase the speed to 1801 RPM to 1814 RPM.

□ Step 9: Turn the potentiometer simultaneously to increase terminal voltage to ~108V L-N.

□ Step 10: Verify circuit breaker CB-11 closed and generator speed (1799 RPM – 1801 RPM)

□ Step 11: Repeat step 5 to step 9 on generator #2.

□ Step 12: Verify circuit breaker CB-12 closed and generator speed (1799 RPM – 1801 RPM).

(At this point, both generators are synchronized to the utility grid)

□ Step 13: Turn the DC motor knob of generator #1 and generator #2 to increase the total output power to ~200W (displayed on bench 5's Yokogawa) with each generator outputting approximately ~100W.

□ Step 14: Turn the potentiometers of generator #1 and generator #2 to increase the terminal voltage to 120V L-N.

□ Step 15: Close circuit breaker CB-7. Turn on the static load #1's switches one-by-one.

□ Step 16: Turn the potentiometers of generator #1 and generator #2 to increase the terminal voltage back to 120V L-N.

□ Step 17: Turn on circuit breaker CB-5 on bench 6 to start the induction motor. Verify circuit breaker CB-6 automatically closed to connect the capacitor banks.

□ Step 18: Turn the potentiometers of generator #1 and generator #2 to increase the terminal voltage back to 120V L-N.

□ Step 19: Close circuit breaker CB-13.

□ Step 20: Measure the phase voltages at the grid-side terminals of circuit breaker CB-14. Proceed if the voltage is from 117V L-N to 122V L-N, otherwise, turn the potentiometer of either generator to adjust the voltage.

□ Step 21: Plug the MC4 connectors from the solar panels to channel 4 of the APsystem microinverter. Verify 1 red blink followed by 3 short green blinks on the microinverter's LED.

□ Step 22: Close circuit breaker CB-14 and start a 5-minute timer.

□ Step 23: Verify the output power increase from bench 5's Yokogawa once the 5-minute interval expired.

□ Step 24: Connect the SEL C-662 USB serial cable from Port F at the front panel of the SEL-735 to a USB port on a computer.

(Refer to Appendix C – SEL-735 Communication Setting and Programming to initialize)

□ Step 25: Open acSELerator Quickset HMI to observe the output power of the microinverter.

□ Step 26 (optional): Decrease the generators' terminal voltage to 120V L-N.

□ Step 27: Turn the DC motor knob of generator #1 and generator #2 counter-clock-wise to decrease the output power of generator #1 and generator #2 equally until bench 6's Yokogawa power reading reads 50W to 100W.

□ Step 28: Turn off the ABC terminal switch of bench 6 to isolate the Microgrid from the utility grid.

(At this point, the Microgrid becomes isolated from the utility grid)

□ Step 29: Verify the microinverter on the acSELerator Quickset HMI remain outputting power.

□ Step 30: Increase the terminal voltage of the generators to 120V L-N and adjust the speed to 1800 RPM.

Housekeeping:

□ Step 31: Open circuit breaker CB-14 to disconnect the microinverter.

□ Step 32: Press the "Stop" button on each DC starter to de-energize the generator.

□ Step 33: Open all circuit breakers.

□ Step 34: Turn off GH terminal switches (125V DC power supply) on bench 5 and bench 6.

□ Step 35: Retract the DC transmission line and store underneath the microinverter cart.

□ Step 36: Verify all components of the Microgrid have been deenergized except SEL relays.

Appendix F – Circuit Breaker

The Microgrid Renewable Energy Integration's tests use circuit breakers to isolate the inverter from the grid. These breakers were designed by a former Cal Poly electrical engineering student, Ozro Corulli. The circuit breaker can operate as a relay-controlled circuit breaker, three-phase fault switch, recloser, and disconnector. For the purpose of this MREI project, the circuit breakers are used as relay-controlled circuit breakers and switches. Figure 64F and figure 65F show the diagram and the top view of the circuit breaker.
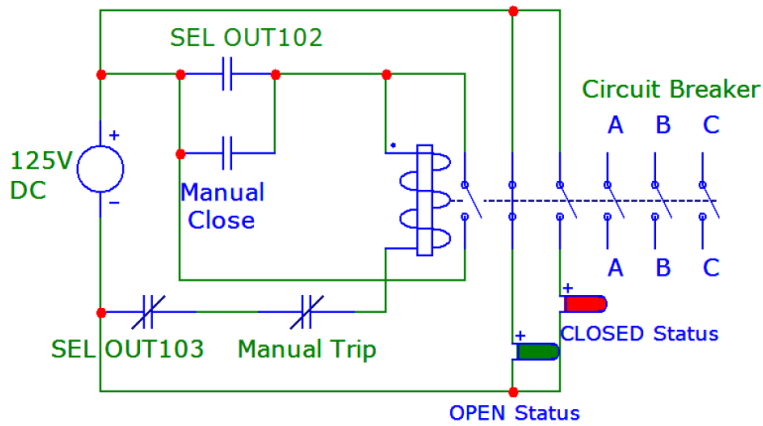

Figure 64F. Circuit Breaker Diagram [13]
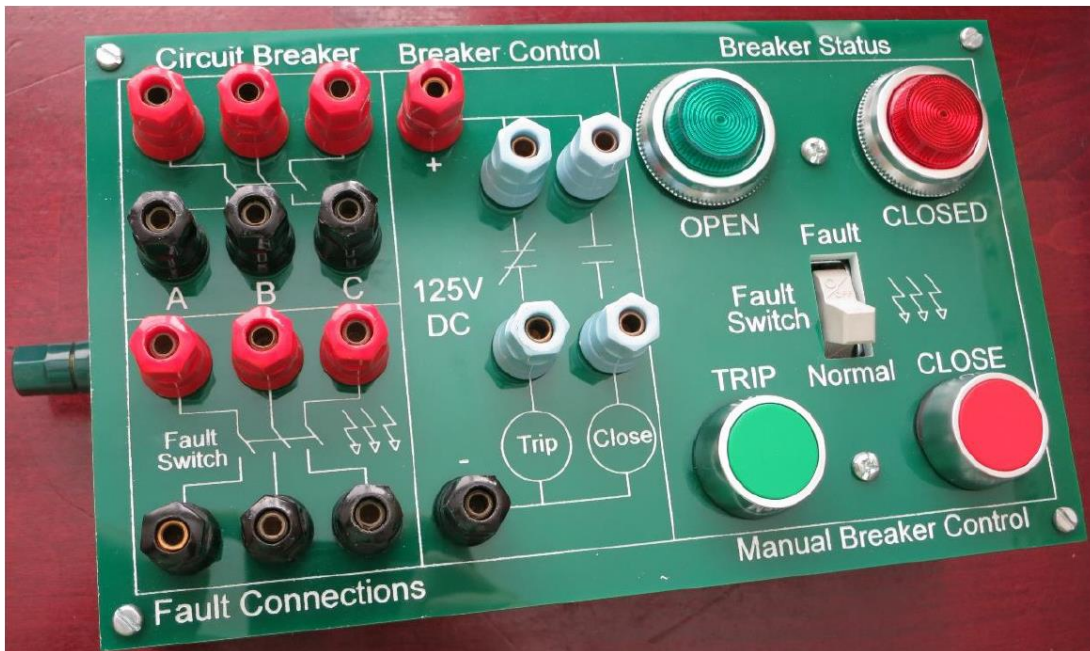
Figure 65F. Circuit Breaker Top View [13]

An input voltage of 125V DC connecting across the red terminal with "+" sign label and black terminal with "-" sign label (Figure 65F) is required to energize the circuit breaker. The green LED illuminates indicating the circuit break is energized and opened. Upon initial 125V DC application, the breaker defaults to the Open status. The breaker also is rated for 3A continuous current and 12A momentary current per phase while the control circuitry of the breaker can carry a maximum of 0.25A current [13].

The green and red push buttons are used to close or open the circuit breaker manually. To operate the circuit as a switch, the trip terminals (colored in light blue) shall be shorted. To operate the breaker as a relay-controlled circuit breaker, the trip signal from the SEL relay shall be connected across the trip terminals of the circuit breaker. The reclose signal can also be connected across the adjacent reclose terminals to enable the reclosing capability. Although the fault simulating feature of this circuit breaker is not utilized in this project, the fault switch can be switched to the "fault" position to create faults. These various fault conditions, such as line-to-ground and three-phase bolted faults, require corresponding connections at the fault terminals (bottom left corner of the circuit breaker). For example, a three-phase bolted fault requires all the black terminals at the fault connections section to be shorted together.

Appendix G – List of Equipment Prices

Power Systems Protection and Microgrid Laboratory

20-101

11/9/2018

By Electrical Engineering Faculty, Dr. Ali Shaban

Table 9. List of equipment needed for the Power System Protection and Microgrid Laboratory

Equipment	Ratings	Units	Price/Bench	6 Benches	4 Benches
Benches	1	0			
1-phase Transformer	3000 VA 240/120V	3	$1,500	$9,000	$6,000
3-pahse Variac	240V	1	$600	$3,600	$2,400
3-phase Wattmeter (Yokogawa)		1	$3,500	$21,000	$14000
Dynamometers (MAGTROL) with readout units	50 lb-in	1	$15,000	$90,000	60000
3-pase Induction motors	1/3 hp 208V	1	$1,800	$10,800	7200
DC Motors	1/3 hp 120V$_{dc}$	1	$2,600	$15,600	10400
DC Starter		1	$2,700	$16,200	10800
Synchr. Machines	1/3 hp 208V	1	$3,800	$22,800	15200
Carts for the machines		1			
SEL Racks		1			
Chocks	8A	6	$720	$4,320	2880
Power Resistors	5A	6	$300	$1,800	1200
Electronic Loads/Power resistors	?	1	$0		
SEL-311L	TL Relay	1	$0		
SEL-587	Transformer Relay	1	$0		
SEL-387E	Transformer Relay	1	$0		
SEL-710	IM Relay	1	$0		
SEL-700G	Generator Relay	1	$0		
SEL-3530	RTAC	1	$0		
Total			$32,520	$195,120	129780

This table is used as a reference to estimate the cost of the Microgrid Renewable Energy Integration project in Table 10.

Appendix H – Senior Project Analysis

Project Title: Microgrid Renewable Energy Integration (MREI)
Student's Name: Do Vo
Student's Signature: *D. V.*
Advisor's Name: Majid Poshtan
Advisor's Initial:

1. Summary of Functional Requirement

    a. Primary Capabilities

        i. The MREI includes a series of tests to ensure successful integration of renewable energy to the Microgrid.

        ii. The Islanded Mode Test aims to test the inverter's response when the system is isolated from the utility bus. The modified islanded mode test provides a solution to keep the inverter connected after isolation from the utility grid and form a small scale microgrid.

        iii. The SEL-735 Power Quality and Revenue Meter Test observes the metering capabilities of the SEL-735. The test gathers voltage, current, and power data from the SEL-735 and compares with the same measurements of the Yokogawa WT130. User interface and ease of operation of the SEL-735 is evaluated to qualify the SEL-735 as a replacement for the Yokogawa WT130.

        iv. The SEL-751 Feeder Protection Relay Test is designed to verify basic protection function of the SEL-751 which includes the 50P instantaneous phase overcurrent element and 27P undervoltage element based on arbitrarily chosen pick-up values. This test evaluated the circuit breaker's tripping capability when

commanded by the SEL-751's trip signals. Each trip event is analyzed to determine the cause of the trip and the elements that asserted.

   v.   The Renewable Energy Integration Test connects the Grid-Tied Solar System to the existing Microgrid and applies the changes and modifications obtained from the previous tests. This final test qualifies the Grid-Tied Solar System to be permanently integrated as a part of the Microgrid.

b. Secondary Capabilities

   i.   The MREI provides detailed procedures of all test for recreation and improvement purposes.

   ii. The MREI includes recommendation for future work.

2. Primary Constrain

a. The microinverter must detect 120/208V grid voltage and 60Hz grid frequency before activating synchronism. This requires a synchronous generator or infinite bus with the appropriate voltage and frequency to connect to the inverter before it starts to deliver power.

b. When connected with the synchronous generator, the microinverter attempts to push all the power generated by the solar panels to the grid. The generator's load transfers to the microinverter and causes frequency and voltage fluctuation.

c. When isolated from the utility grid, the generator drops its speed and voltage which triggers the internal protection scheme of the microinverter to disconnect itself.

d. Heavy reliance on the weather causes delay in testing. Cloudy days are not suited for testing due to low and fluctuation output power of the solar panels.

3. Economic

   a. Human Capital: This project uses a variety of high-power equipment, such as, variacs, three-phase loads, SEL relays, and a Yokogawa power meter that support the manufacturers, engineers, and assemblers who designed and assembled the products.

   b. Financial Capital: The power system and renewable energy courses could use the project to guide the students through experimenting the microinverter's behavior in the Microgrid which could save money from buying and installing a new renewable energy system.

   c. Natural Capital: The MREI uses microprocessor-based equipment that consist of semiconductors. The photovoltaic cells are made of polycrystalline silicon as raw materials.

   d. Cost: The MREI uses available lab equipment that belong to the Cal Poly's Electrical Engineering. The only major cost comes from the inverter and solar panel carts of the Grid-Tied Solar System with an estimated cost of $19,914.154 including labor costs and part costs [1].

4. If manufactured on a Commercial Basis

   a. Beside the Grid-Tied Solar System which costs approximately $19,914.154, MREI's tests use additional equipment such as, two three-phase variacs, one Magtrol dynamometer with readout unit, one Hampden synchronous machine, one Yokogawa power meter, one Hampden DC motor, and one DC starter.

b. Table 10 shows the estimated cost of the MREI project to be $45,21415.

Table 10. MREI Equipment Cost

Equipment	Ratings	Units	Price
Grid-Tied Solar System [1]		1	$19,914.15
3-Phase Variac	240V	2	$1,200
Dynamometers (Magtrol)		1	$15,000
Hampden DC Motor	1/3 HP 120VDC	1	$2,600.00
DC Starter		1	$2,700.00
Synchronous Machine	1.3 HP 208V	1	$3,800.00
Total			$45,214.15

c. The price of the listed equipment is reported by the senior project advisor to be higher than the market price due to customization for the power lab experiments. The actual price is generally one fourth the above prices. If 500 Grid-Tied Solar Systems are manufactured, the estimated cost per system is $4000 [1]. The estimated cost of the MREI is $10,325.00.

5. Environmental

a. The MREI uses microprocessor-based protection relay and power meter that consists integrated circuits. Each computer integrated circuit takes roughly 10 gallons of water which would be disposed as waste along with many toxic chemicals that are harmful to the environment. The solar panel's manufacturing process also requires water and hazardous materials such as hydrochloric acid, sulfuric acid, nitric acid, hydrogen fluoride that can become harmful to both worker and the environment if not disposed properly [12].

6. Manufacturability

a. The MREI's tests can be recreated by connecting the appropriately available equipment at the Electrical Engineering department at Cal Poly, San Luis Obispo

detailed in Chapter 2 and following the procedures from Appendix A through Appendix D.

    b. The test facility must have a 120/208V three-phase source with adequate protection to detect and eliminate faults. An emergency power-off button is necessary to safely and quickly shutdown the electrical system on the test bench in case of emergency.

7. Sustainability

    a. The MREI main source of energy comes from four photovoltaic panels mounted on two movable carts that allow easy access to the sunlight spot on campus. Solar energy harvesting from the photovoltaic panels generates electricity with zero carbon footprint.

    b. All equipment is readily available in the power lab room. Test setups are applicable to test other SEL devices.

8. Ethical Considerations

    a. The ethical implication of MREI primarily centers safety for the students and faculties when working with high voltage and current. The MREI's test connection diagrams are intentionally designed to go through a distribution panel to take advantage of the 5A and 10A fuses for protection. The inverter's internal protection scheme as well as generator's internal fuse provides an additional layer of protection. Most importantly, the newly added SEL-751 relay and the circuit breaker employs the most reliable protection to the students and faculties.

    b. The MREI offers detail connection diagrams and procedures to avoid fatal mistake and misunderstanding when running the inverter and generator.

9. Health and Safety

   a. The MREI's tests involve high voltage and current that may present safety hazard if instructions are not followed correctly and the system is not grounded properly. All users should immediately stop working and report the system's suspicious behaviors or damaged equipment to EE faculty members.

10. Social and Political

   a. The MREI's tests are the last step before integrating renewable energy to the Microgrid. The tests' results provide a solution to the newly discovered problems, evaluation of the SEL equipment, and insightful recommendation. The students are equipped with tools to learn and improve the Microgrid as well as the Grid-Tied Solar System in the future.

   b. The MREI serves as an effort to bring renewable energy to the student's experiments and reduces the reliance on traditional synchronous generators. The project shows initiative in the education sector to equip the students with knowledge in renewable energy and aligns with State of California's goal to bring more renewable energy to the state [4].

11. Development

   a. The MREI's tests preparation and execution relies significantly on the SEL-735 and SEL-735 instruction manuals provided by Schweitzer Engineering Laboratories Inc. and APsystem YC1000-3-208 microinverter instruction manual provided by APsystem. Technical support discussion with the manufacturer such as APsystem was conducted to better understand the inverter. The SEL on-campus training provides basic knowledge in operating the SEL-751 and SEL-735.

b. Reading and understand senior project and master thesis reports from previous generation students help improve the test setups.