GRID-TIED SOLAR SYSTEM

by

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SENIOR PROJECT

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CALIFORNIA POLYTECHNIC STATE UNIVERSITY
SAN LUIS OBISPO
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Abstract

Distribution level solar energy generation has gained importance and popularity, because it helps create a sustainable electricity system while reducing the harmful environmental impacts our current power systems have. This project proposes an alternative energy source, a laboratory-scale grid-connected photovoltaic system. A KC120-1 solar panel produces 120 Watts maximum. A grid-tied solar power inverter does DC-to-AC conversion and minimizes energy transfer losses. The inverter also has an anti-islanding feature, which senses a power outage and prevents back-feeding through isolating the circuit. The circuit breakers isolate electrical components and protect the circuit. Schweitzer Engineering Laboratories SEL-751 feeder protection relay and SEL-735 power quality meter protect and monitor the feeder before joining the Microgrid Lab.

Acknowledgements

I would like to express gratitude to Professors Dr. Ali Shaban, Dr. Majid Poshtan, Dr. Taufik, and Dr. Ahmad Nafisi for maintaining the Microgrid Project and supporting undergraduate and graduate students with their projects and theses. Without their efforts, the students would not have such an environment conducive to investigate simulation results, explore the effects of renewable energy resources integration, design and implement projects to minimize emissions, or model power systems protection schemes.

Dr. Ali Shaban has provided much technical assistance, advice and criticism invaluable to the project. His patience and willingness to help students with his deep power systems background have contributed to the completion of this report. It is truly a privilege to have worked with him.

I gratefully acknowledge the assistance of Dr. Majid Poshtan. He spent his personal time helping me troubleshoot the system setup and the microinverter. He has provided many helpful feedbacks and come up with alternative solutions to achieve desired results.

Dr. Taufik provided solar panels needed to implement and test the system. Special thanks to Dr. Taufik for giving so much help and suggestions on how to simulate the solar panels with a DC power supply for a successful microinverter testing.

I express my sincere gratitude to Mr. Do Vo. His insights and technical knowledge have been indispensable to the project. We’ve developed a very productive collaboration and a caring friendship. His devotion made it possible for me to build the foundation of this project and enrich my learning experience. It was a pleasure working with him.

Without Mr. Jaime Carmo's help, I would not have been able to purchase, deliver, and assemble the mechanical parts necessary to build the solar panel structures. The design and implementation process became less overwhelming with his support.

Mr. Robert Randle is always willing to aid and very understanding. He reached out to Mr. Chad Eastep, a network analyst at Cal Poly regarding the router registration in a timely manner. He also helped me install ETAP for a computer simulation and address the issue with the ECU not connecting to the school network.

I also want to thank the technicians at Mustang '60 and Aero Hangar machine shops because they provided a safe environment for me to use the machines. They gave very helpful tips including how to safely and efficiently cut and drill into metal bars and other mechanical parts.

Schweitzer Engineering Laboratories donated SEL-751 and SEL-735 equipment, which made it possible to implement the design.

This report is respectfully dedicated to my mother Yanqing Yan. Her unconditional love and support have helped me stay motivated and become more dedicated. She has made many sacrifices to allow the start and completion of this project.

Chapter 1. Introduction

Modern power systems have become more complex with unprecedented technological change and the increase of electricity demand. Therefore, the power systems become more vulnerable to utility power-related issues and natural disturbances. There has been an increasing number of disturbance events like wildfires, extreme heat events, hurricanes, and tornados, which have affected millions of U.S. citizens and lost more than $10 billion [1]. Potential cyber-attacks have also become a huge concern because the power grids are more dependent on computers and data-sharing. Without adequate power systems protection training, future engineers do not have the technical knowledge and skills required to design, implement, operate, and maintain a reliable power system. Understanding the importance of power-system protection, more universities start offering power systems protection courses at the graduate and/or postgraduate levels. The University of Saskatchewan, a Canadian public research university, offered the first power-system protection course 54 years ago [2].

In comparison, California Polytechnic State University, San Luis Obispo, developed the Microgrid Protection Student Laboratory (MPSL), which provides electrical engineering students the opportunities to learn power system protection theories through hands-on experiences. The MPSL emphasizes modern microprocessor-based relays utilization for overcurrent, overvoltage, directional comparison, and phase comparison protection. Students also gain practical experience by applying fault detection schemes in transformers, three-phase induction motors, and transmission lines. The MPSL also gives students the chance to design, implement, and test a proposed power systems project using other electrical equipment and devices like solar panels, power quality metering equipment, protection relays, circuit breakers, and batteries.

Modern power systems have drastically decreased their dependence on fossil fuels and conventional energy sources, because renewable energy sources like solar energy have become more acceptable and affordable [3]. The solar generation system integration to the utility grid becomes more popular nowadays since it can help achieve sustainable development goals. This paper proposes a grid-connected solar system, which absorbs sunlight, applies energy conversion, and feeds the electricity to the utility grid. The project focuses on how rooftop solar installations benefit and hinder the Microgrid Lab, how they impact the power grid regarding electric power quality and electricity reliability.

Chapter 2. Customer Needs, Requirements & Specifications

Chapter 2 assesses the main customer needs and list of marketing requirements and engineering specifications generated based on the customer needs.

2.1 Customer Needs Assessment

This project should provide Cal Poly Microgrid Lab users reliable and uninterrupted electrical power. Applying fault detection and protection knowledge and utilizing protective relaying equipment help meet customer needs. After asking the professors, students, and staff who use the Microgrid Lab regularly, the customers requested a reliable and high-quality system, which provides uninterrupted electricity. The customers also require user-friendly equipment. The equipment should have reasonable cost and meet IEEE safety standards which improve overall reliability.

2.2 Requirements and Specifications

Table I shows the marketing requirements and engineering specifications, which satisfy minimum customer needs. Most requirements and specifications optimize and maintain the system performance.

Table I. Grid-Tied Solar System Project Requirements and Specifications

Marketing Requirements	Engineering Specifications	Justification
4	1. The implementation cost (without labor cost) should not exceed $8,000.	Schweitzer Engineering Laboratories, Inc previously donated the protective relay and power quality meter. The Microgrid Lab currently has 3 unused solar panels. Through researching parts costs online, cost estimates are generated and the most pessimistic cost (excluding labor costs) does not exceed $8,000. Table II shows the cost estimates calculated.
1,5	2. The peak inverter efficiency should exceed 91%.	Peak efficiency calculates the ratio between AC power output and DC power input. A typical pure sine-wave solar inverter can achieve this efficiency. Through researching, the normal peak inverter efficiency varies between 94% and 96% [4]. The inverter power efficiency can reach 94% via PSpice design sensitivity analysis.
1,2,3,5	3. The entire system must operate in temperature range: -20°C ~ 65°C.	The system must maintain its performance in a stochastic environment [5]. Through researching product characteristics and electrical ratings, most equipment can meet this operational requirement.
1,2,3,4	4. Electrical components should fit inside a 3’x 3’ x 2’ transportable box.	A 100lbs student can easily carry the box around campus alone. It can also fit inside the Microgrid Lab. This specification satisfies customer need of user-friendly. The design’s

		accessibility allows technicians to easily test and repair the system.
1,2	5. The solar microinverter should exceed 14.8 A short-circuit current.	One KC120-1 solar panel has 7.45 A short-circuit current [6].
1,2	6. The solar microinverter must output 208 V 3-phase voltage.	The DC-to-AC microinverter must have 208 V AC voltage output to feed the electricity back to the power grid. Through research, the APsystems YC1000-3-208 solar microinverter has a true 3-phase output [7]. This inverter has a 900 W maximum AC output, 95% peak efficiency and costs about $266.67, which meet other project specifications.
1,5	7. The solar panels must have open-circuit voltage larger than 22 V.	The microinverter has a startup voltage of 22 V, which is the minimum voltage required from the solar panels [7]. Connecting the two solar panels in series gives approximately 41 V open-circuit voltage.
1,2,5	8. The power quality and revenue meter must have high-accuracy measurements within ±0.06 percent watt-hour at unity power factor and a ±0.02 percent typical rating.	The SEL-735 power quality and revenue meter meets this specification and exceeds the ANSI C12.20-2015.01 and IEC 62053-22 0.2 accuracy standards from 2 mA to 22 A current range and power factors of 0.5 and 1[9].

Marketing Requirements

1. Efficient.
2. Safety.
3. User-friendly.
4. Reasonable cost.
5. Accurate measurements.

Table II displays estimated deliverable dates which help track project progress.

Table II. Grid-Tied Solar System Project Deliverables

Delivery Date	**Deliverable Description**
February 20, 2018	Design Review
February 20, 2018	ABET Sr. Project Analysis
June 11, 2018	EE 461 Demo
June 10, 2018	EE 461 Report
October 14, 2018	EE 462 First Report
November 16, 2018	EE 462 Finished Draft Final Report
November 23, 2018	EE 462 Final Report
December 6, 2018	Senior Project Expo
December 10, 2018	EE 462 Demo

Chapter 3. Functional Decomposition

Chapter 3 describes the level 0 and level 1 grid-tied solar system design functionality and functional requirements.

In Figure 1, the level 0 grid-tied solar system design diagram shows the basic inputs and outputs identified.

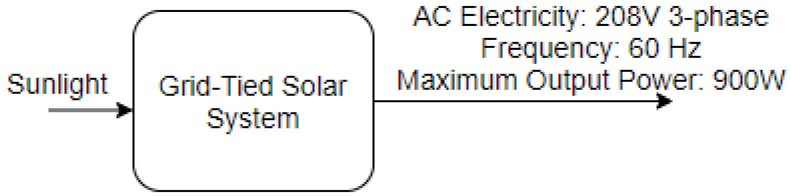


Figure 1. Level 0 Grid-Tied Solar System Design Functionality

Table III shows the level 0 grid-tied solar system functional requirement. The system output should produce 208 V 3-phase electricity and 900 W maximum AC power. The entire system absorbs the sunlight and provides AC electric power via energy conversion, DC-to-AC conversion, protective relaying, and power quality metering.

Table III. Level 0 Grid-Tied Solar System Functional Requirement

Module	Grid-Tied Solar System
Inputs	Solar Energy
Outputs	-AC voltage: 208 V 3-Phase - Frequency: 60 Hz - Maximum AC power: 900 W
Functionality	Captures the sun’s energy and provides the Microgrid Lab electricity via energy conversion, DC-to-AC conversion, protective relaying, and power quality metering.

In Figure 2, the level 1 grid-tied solar system design diagram shows the basic inputs and outputs. The level 1 architecture contains six main modules: solar panels, DC disconnect switch, solar microinverter, AC disconnect switch, SEL-751 feeder protection relay, and SEL-735 power quality and revenue meter.

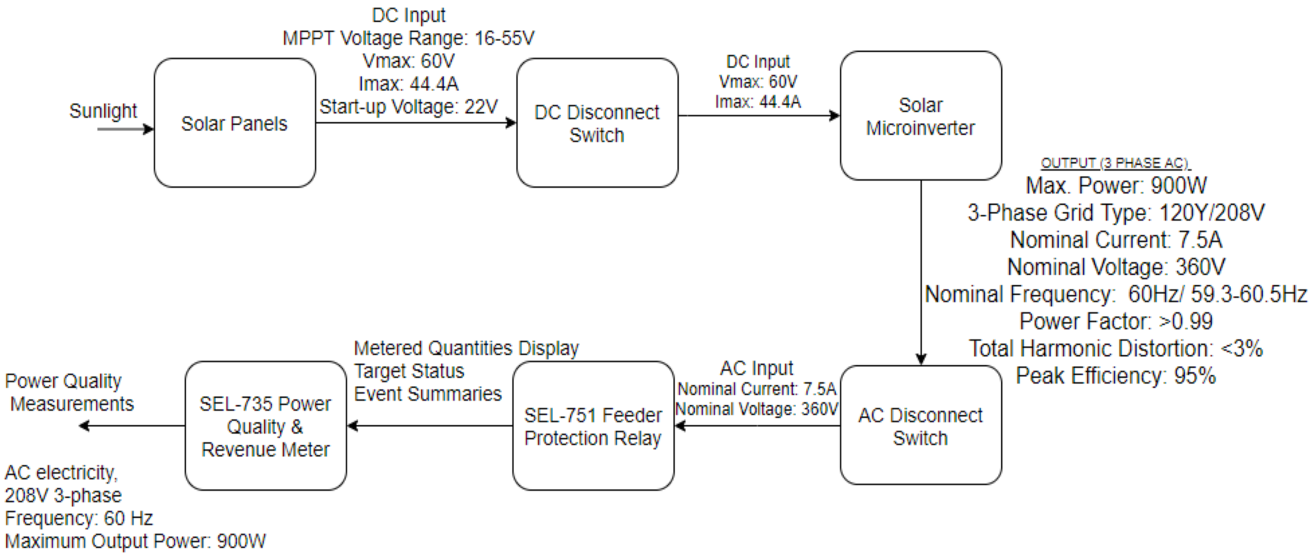


Figure 2. Level 1 Grid-Tied Solar System Design Functionality

Table IV shows the level 1 grid-tied solar system functional requirements, which contain all the subsystems. Each module has inputs, the corresponding outputs, and main functions. The solar panels absorb solar energy and converts it to DC voltage. The DC disconnect switch isolates the solar panels from the other parts of the circuit when power outages or other disturbances occur. The solar microinverter does the DC-to-AC three-phase voltage conversion and outputs AC three-phase voltage and current. The AC disconnect switch disconnects the solar panels and solar inverter from the rest of the circuit when a fault is detected. SEL-751 feeder protection relay has AC current and voltage inputs. It provides voltage, current, and temperature protection, logs the measurements, and provides contactor control [8]. The SEL-735 power quality meter also measures AC current and voltage signals and identifies any power system anomalies [9].

Table IV. Level 1 Grid-Tied Solar System Functional Requirements

a) Solar Panel Functional Requirements

Module	Solar Panel x 2
Inputs	Sunlight
Outputs	-Max. Power: 240 W -Operating Voltage: 33.8 V (DC) -Max. Current: 7.10 A -Start-up Voltage: 22 V
Functionality	Absorb sunlight and apply energy conversion.

b) DC Disconnect Switch Functional Requirements

Module	DC Disconnect Switch
Inputs	-Max. Voltage: 60 V -Max. Current: 44.4 A
Outputs	-Max. Voltage: 60 V -Max. Current: 44.4 A
Functionality	Separates the solar panels and the rest of the circuit when a power outage or natural disturbances occur.

c) Solar Microinverter Functional Requirements

Module	Solar Microinverter
Inputs	-Max. Voltage: 60 V -Max. Current: 44.4 A
Outputs	-Output Current: 2.50 A x 3-phase -Output Voltage: 208 V x 3-phase -Maximum Output Power: 900 W
Functionality	Does DC-to-AC three-phase conversion.

d) AC Disconnect Switch Functional Requirements

Module	AC Disconnect Switch
Inputs	-Output Current: 2.50 A x 3-phase -Output Voltage: 208 V x 3-phase
Outputs	-Output Current: 2.50 A x 3-phase -Output Voltage: 208 V Y x 3-phase
Functionality	Disconnects the circuit when a power outage or natural disturbances occur.

e) SEL-751 Feeder Protection Relay Functional Requirements

Module	SEL-751 Feeder Protection Relay
Inputs	-Output Current: 2.50 A x 3-phase -Output Voltage: 208 V x 3-phase
Outputs	-Metered Quantities Display -Target Status -Event Summaries
Functionality	Provides voltage, current, and temperature protection. It logs data and provides contactor control.

f) SEL-735 Power Quality & Revenue Meter Functional Requirements

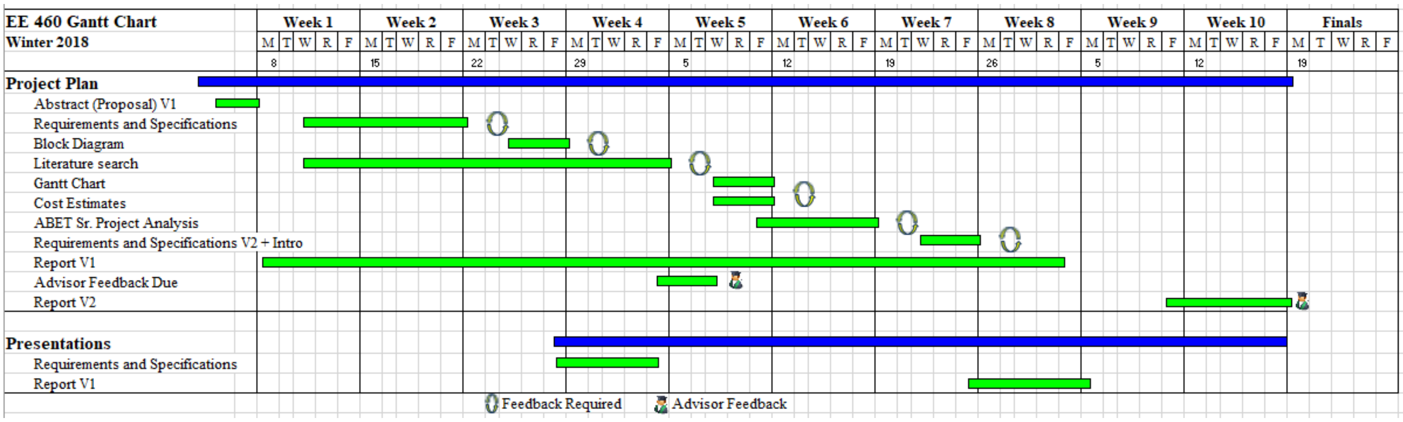
Module	SEL-735 Power Quality & Revenue Meter
Inputs	-Output Current: 2.50 A x 3-phase -Output Voltage: 208 V x 3-phase
Outputs	-Power Quality Measurements -AC Electric Power, 208 V/60 Hz -Output Current: 2.50 A x 3-phase -Output Voltage: 208 V x 3-phase - Maximum Output Power: 900 W
Functionality	Generates power meter reports, identifies power system anomalies and diagnose system problems.

Chapter 4. Project Planning

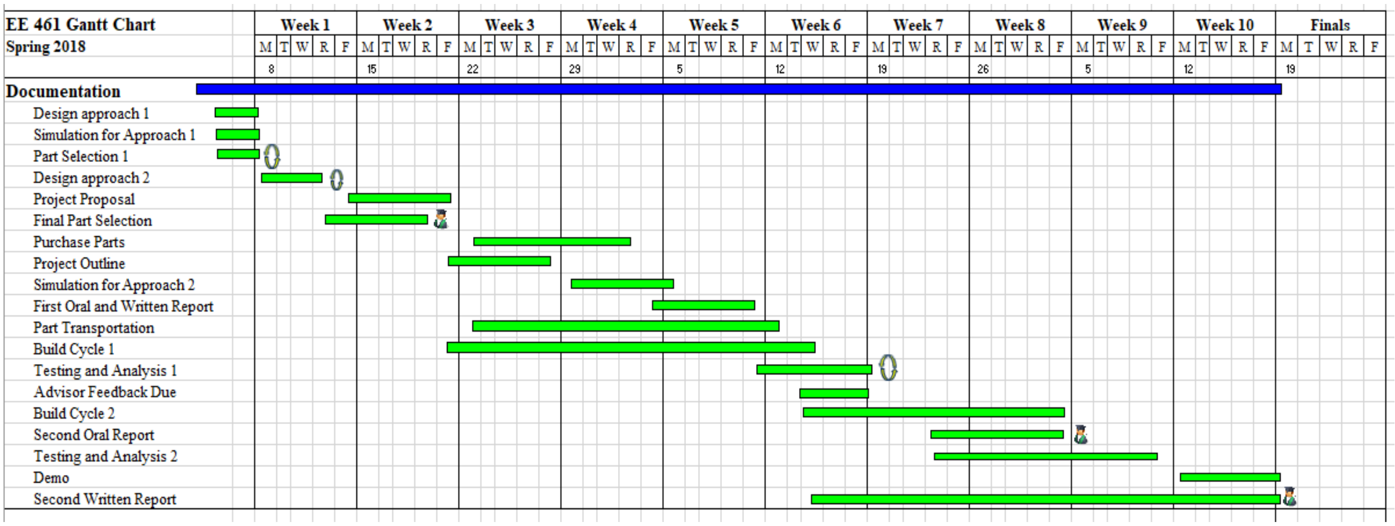
Chapter 4 suggests 3 separate Gantt charts, whch provides adequate time to complete the senior project. It also estimates the total parts cost and labor costs of the project.

4.1 Gantt Charts

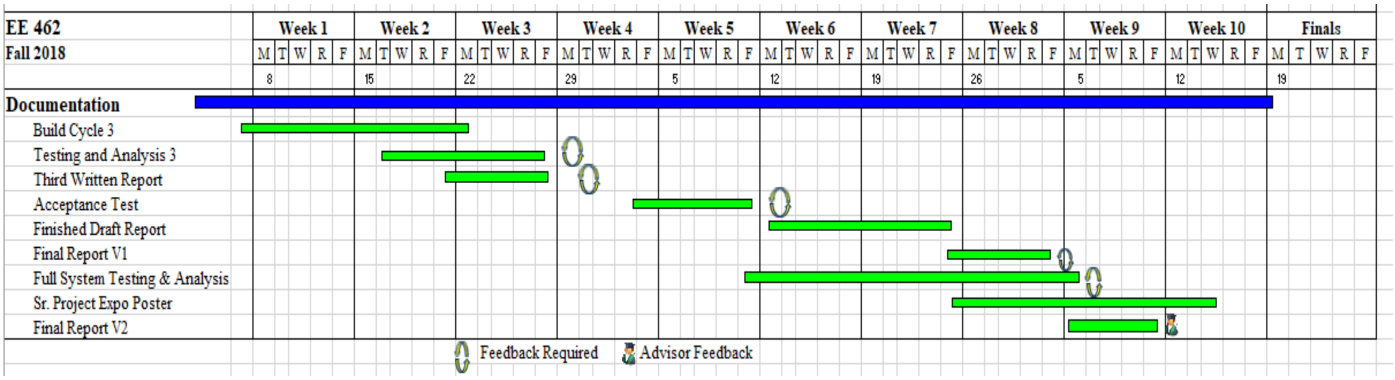
Figure 3 shows the EE 460, EE 461, and EE 462 Gantt charts. They include adequate time to generate 2 design approaches during EE 461, 3 design-build-test iterations during EE 461 and EE 462. It also anticipates the part selection time, purchase time, and part shipment time. Project documentation happens throughout the quarters.



a) EE 460 Gantt Chart



b) EE 461 Gantt Chart



c) EE 462 Gantt Chart

Figure 3. EE 460, EE 461, and EE 462 Gantt Charts

4.2 Cost Estimates

The project uses existing solar panels, donated feeder protection relay SEL-751 and power quality meter SEL-735. Table V shows the grid-connected solar system project cost estimates. It is calculated using Equation (1) from *Design for Electrical and Computer Engineers* [10].

$$Cost = \frac{Cost_{Pessimistic} + 4Cost_{Most\ Likely} + Cost_{Optimistic}}{6} \tag{1}$$

.

Optimistically, the project requires 8 man-hours every week, while it requires 26 hours per week pessimistically. It should most likely require 18 man-hours per week. Hence, assuming it pays a $40.00 hourly wage over a 25-week period, the calculated cost using equation (1) becomes $17,666. This project should take about 25 weeks maximum.

$$Cost = \frac{26x40x25 + 4x18x40x25 + 8x40x25}{6} = \$17{,}666$$

Table V shows the grid-tied solar system project cost estimates, including the pessimistic costs, most likely costs, optimistic costs, and calculated costs.

Table V. Grid-Connected Solar System Project Cost Estimates

Item	Pessimistic Cost	Most Likely Cost	Optimistic Cost	Calculated Cost
KC120-1 Solar Panel	$0.00	$0.00	$0.00	$0.00 (Loaner Equipment)
DC-AC Inverter	$3608.00	$1,500.00	$500.00	$1684.667
SEL-751 Feeder Protection Relay	$0.00	$0.00	$0.00	$0.00 (Donation)
SEL-375 Power Quality Meter	$0.00	$0.00	$0.00	$0.00 (Donation)
Circuit Breakers	$700.00	$484.00	$450.00	$514.33
Gauge- 12 Stranded Wire (Cost per Foot)	$20.00	$10.00	$8.00	$11.33
Gauge- 16 Stranded Wire (Cost per Foot)	$20.00	$10.00	$8.00	$11.33
Banana Screw-On Connectors	$35.00	$25.00	$20.00	$25.83
Total Parts Costs	$4,383.00	$2,029.00	$986.00	$2,247.487
Labor ($40.00 per Hour)	$26,000.00	$18,000.00	$8,000.00	$17,666.667
Total	$30,383.00	$20,029.00	$8,986.00	$19,914.154

Chapter 5. System Design

In chapter 5, major elements of the system design are examined in terms of their capabilities, requirements, and limitations.

5.1 Solar Panel

Kyocera model KC120-1 is used to generate DC electricity. It has a 120 Watts maximum power, 7.45 A short-circuit current, and 21.5 V open-circuit voltage [6]. This project uses 2 solar panels connected in series to energize the microinverter. The minimum voltage required to energize the inverter is 22 $V_{DC.}$ With the solar panels in series, it gives 43 V maximum open-circuit voltage.

5.2 Solar Microinverter

The solar microinverter is the APsystems commercial microinverter YC1000-3-208, which has a maximum of 900 W AC output and a true 3-phase 208 V output [7]. It has a total of 4 channels and uses Maximum Power Point Tracking (MPPT) technique to maximize power extraction in the PV system. Figure 4 shows the APsystems YC1000-3-208 solar microinverter schematic. The microinverter contains DC-to-DC and DC-to-AC conversion features as well as the Electromagnetic Interference (EMI) filtering feature. The EMI filter is used to reduce high frequency noise which may cause electromagnetic interference. There is no additional grounding required since the equipment ground is provided in the AC bus cable. Ground fault protection is integrated into the microinverter.

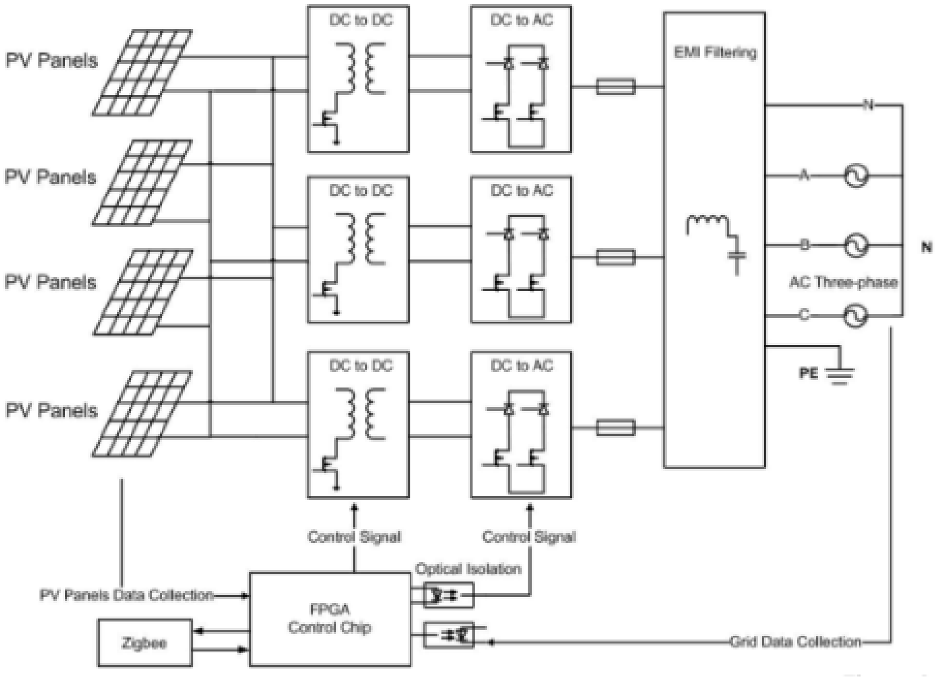


Figure 4. Schematic of the APsystems YC1000-3-208 Solar Microinverter [28]

Two series-connected solar panels are plugged to the leftmost channel (channel 4), which is next to the antenna mounting thread. The other two solar panels are connected to channel 3, as shown in Figure 5. Figure 5 also displays the layout configuration of the microinverter. MC4 connectors are used to connect the DC input cables to the microinverters.

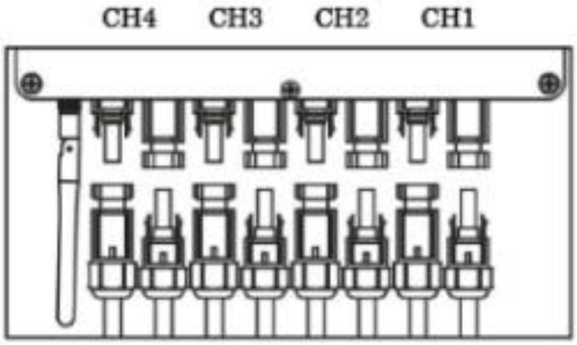


Figure 5. Layout Configuration of the Solar Microinverter [28]

5.3 Energy Communication Unit (ECU)

Figure 6 shows the key elements of the utility-interactive grid-tied solar system. It includes the PV modules, microinverter, branch junction box, SEL-735, SEL-751, DC and AC disconnect switches, Energy Communication Unit (ECU), and Energy Monitoring & Analysis (EMA) website. The ECU connects and delivers real-time module-level data through the Zigbee wireless technology. It requires no additional wiring besides the plug-and-power setup at the Microgrid Lab. The ECU must be within 200-300 feet distance from the microinverter considering the antenna placement and signal reception. The monitoring of the microinverter array is done through the EMA software online as well as the EMA app on a cell phone.

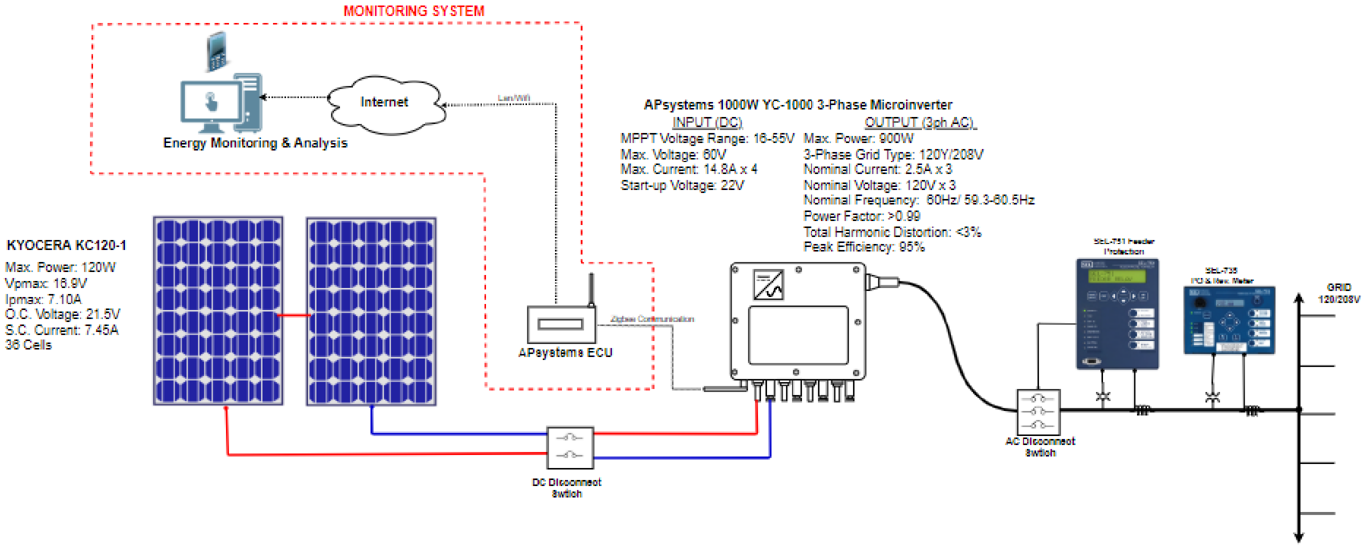


Figure 6. Key Elements of the Grid-Tied Solar System

5.4 Solar Panel Mounting Structure and DC System Design

Figure 7 shows the solar panel wiring diagram. 12-gauge wires are used to connect the solar panels to circuit breakers and microinverter. The AC bus cable is a 5-wire 14-gauge cable that is about 20 feet long. It needs to connect from the infinite bus in room 102 to outside of the window so that the solar panels can be exposed to as much sunlight as possible. 12-gauge and 14-gauge silver electro-galvanized slotted strut channels are used to assemble the solar panel mounting structure. The structure is transportable with wheels which can hold more than 400 pounds of weight. The solar panel and electrical enclosure are mounted on the sides of the structure. The electrical enclosure includes the two SEL equipment, ECU, and the two circuit breakers. It has a 16’’x 16’’x 8’’ dimension. The solar panels are assembled to rotate around the longitudinal axis.

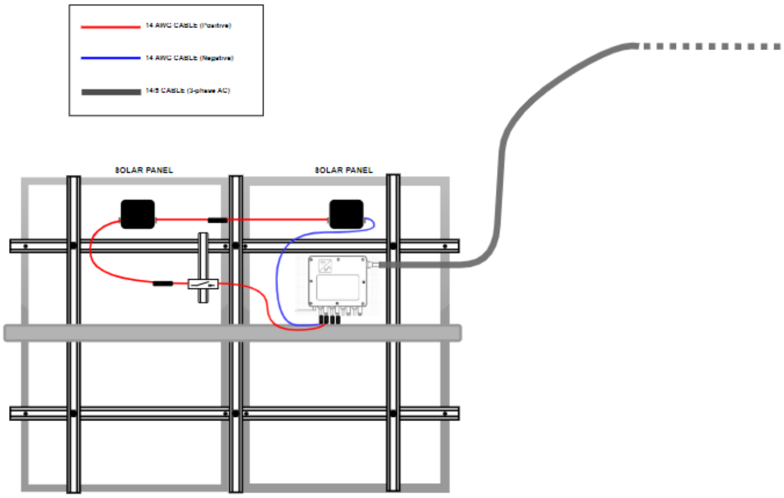
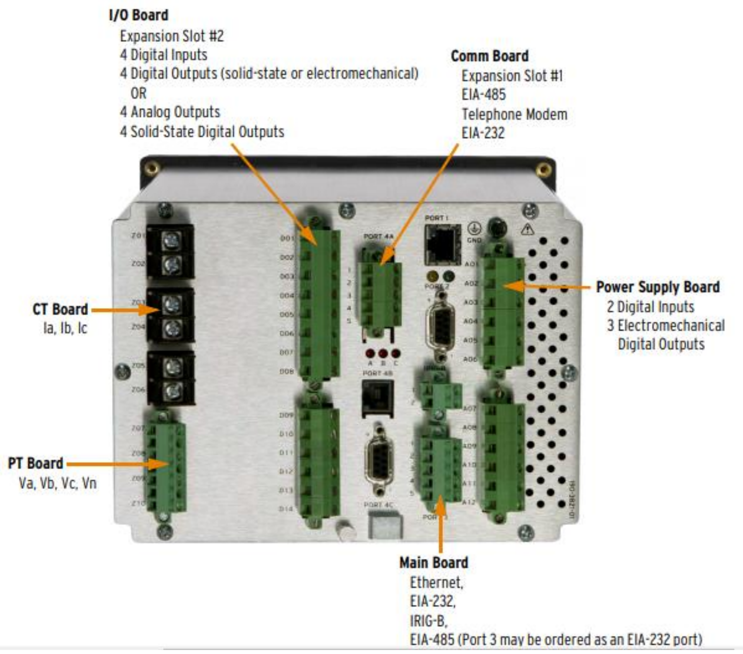


Figure 7. Solar Panel Wiring Diagram

5.5 SEL-735: Power Quality and Revenue Meter

SEL-735 Power Quality and Revenue Meter provides accurate revenue metering. It generates power quality reports to help identify and troubleshoot power quality disturbance, with compliance to IEC 61000-4-30 Class A. It records standard current measurements as well as fault current measurements. Figure 8 shows the SEL-735 front panel and rear panel layouts. The front panel shows the meter status, pushbuttons, and measurements. The pushbuttons also allow user to do manual meter settings and communication settings. The back panel shows the different parts that made up the meter, the inputs, and outputs. There are three ways to wire the SEL-735 meter, which are 3-element, four-wire wye-connection, 2-element, three-wire delta-connection, and 2 1/2-element, four-wire wye-connection. This report will explore the four-wire wye connection wiring methods.

a) SEL-735 Front Panel Layout



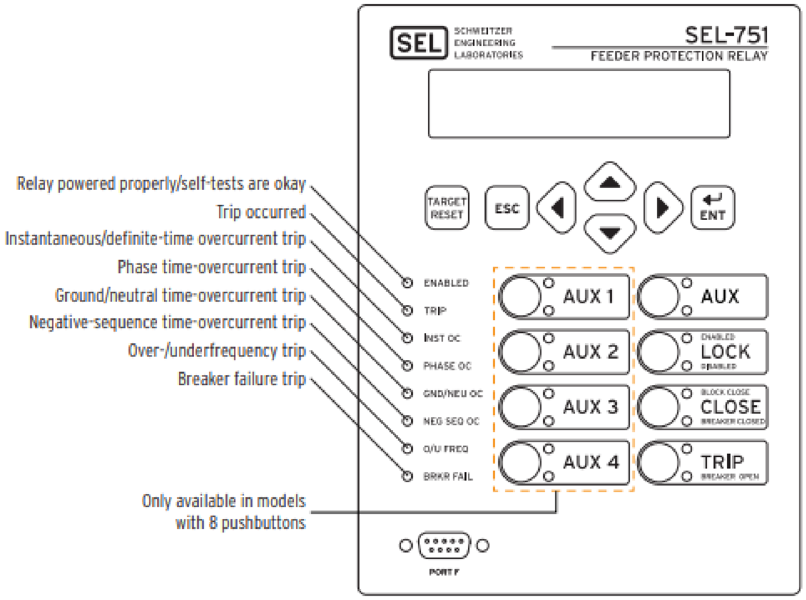
b) SEL-735 Rear Panel Layout

Figure 8. SEL-735 Front Panel and Rear Panel Layouts [9]

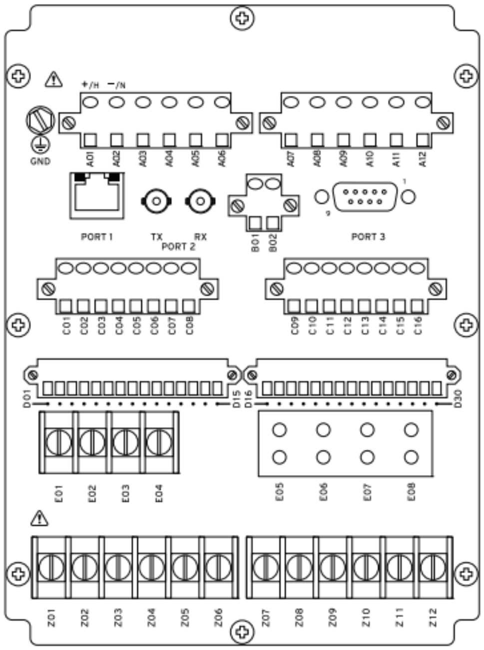
5.6 SEL-751A: Feeder Protection Relay

The SEL-751A Feeder Protection Relay is suitable for medium and high-voltage protection. It is commonly used for overcurrent protection, under- and overvoltage protection, over- and under-frequency protection and is useful for many more protection schemes. Figure 9 shows the front panel and rear panel layouts of the SEL-751. In Figure 9a), the front panel layout shows the display, buttons, and the LEDs which indicated the status of the electrical system. The front panel can display measurements, calculated values, input and output status, device status, and configuration parameters. It shows the type of trip that has occurred through turning on the LEDs on the left.

The LEDs are programmable and the 8 pushbuttons on the lower-right side of the panel are the operator controls. The operator control functions can be changed using SELogic control equations. The AUX operator control pushbuttons are used to enable and disable user-programmed auxiliary control. The LOCK operator control pushbutton engages or disengages the lock function. The device state TRIP and CLOSE are unchangeable unless the lock function is disengaged. The CLOSE pushbutton allows the operator to close the circuit and the TRIP pushbutton opens the circuit breaker. The rear panel shows the digital and analog inputs and outputs, and communication ports.



a) Front Panel Layout with Configurable Labels and Display



b) Rear Panel Layout with Inputs and Outputs

Figure 9. Front Panel and Rear Panel Layout of the SEL-751 [8]

5.7 Solar Tracker

A single-axis solar tracker has been installed on one of the solar panel carts to track sunlight. It is designed to withstand 150 kg of weight and solar panels with 1 kW power. The linear actuator can handle a maximum of 3 A current, and the solar tracking controller can handle a maximum of 8 A current. It is waterproof and lightweight, but it requires 12 V_{DC} to run the controller. It has two modes of operations: automatic and manual modes. When it is in automatic mode, the linear actuator moves depending on how much sunlight the light sensor senses. When it is in manual mode, a remote is used to determine how much the solar panels are tilted.

Chapter 6. Testing

Chapter 6 examines the grid-tied solar system tests performed and test results. Initial solar panel performance testing is included in section 6.1. In section 6.2, the microinverter initial testing setup design, lab setup details, procedure, and test outcomes are described.

6.1 Initial Solar Panel Performance Testing

Open-circuit voltage of each solar panel varied from 20.95 V to 21.04 V, but the total open-circuit voltage of two series-connected solar panels was measured to be around 42 V. The measured open-circuit voltage yields a 2.33% error when compared to the nominal open-circuit voltage.

6.2 Microinverter Initial Testing

The initial testing of the YC1000-3-208 microinverter was performed with one solar panel cart, which could provide up to 240 W power. Assuming the full capacity of the solar panels is not reached due to factors like weather conditions, degradation of the solar panels, shade, and solar panel angle, about 200 W is used to calculate the load needed for testing. Using Equation (2), the equivalent resistance of the load in each phase is calculated to be approximately 216 Ω.

$$R = \frac{V^2}{\frac{P}{3}} = \frac{(120V)^2}{(200W)/3} = 216\,\Omega \tag{2}$$

Figure 10 shows the wiring diagram for the microinverter testing. It consists of solar panels, microinverter, two circuit breaker modules, ECU, Yokogawa power meter, and a 3-phase Wye-connected load. The circuit breakers allow isolation between the microinverter and the rest of the circuit. The power, current, voltage measurements are taken and displayed on the Yokogawa power meter.

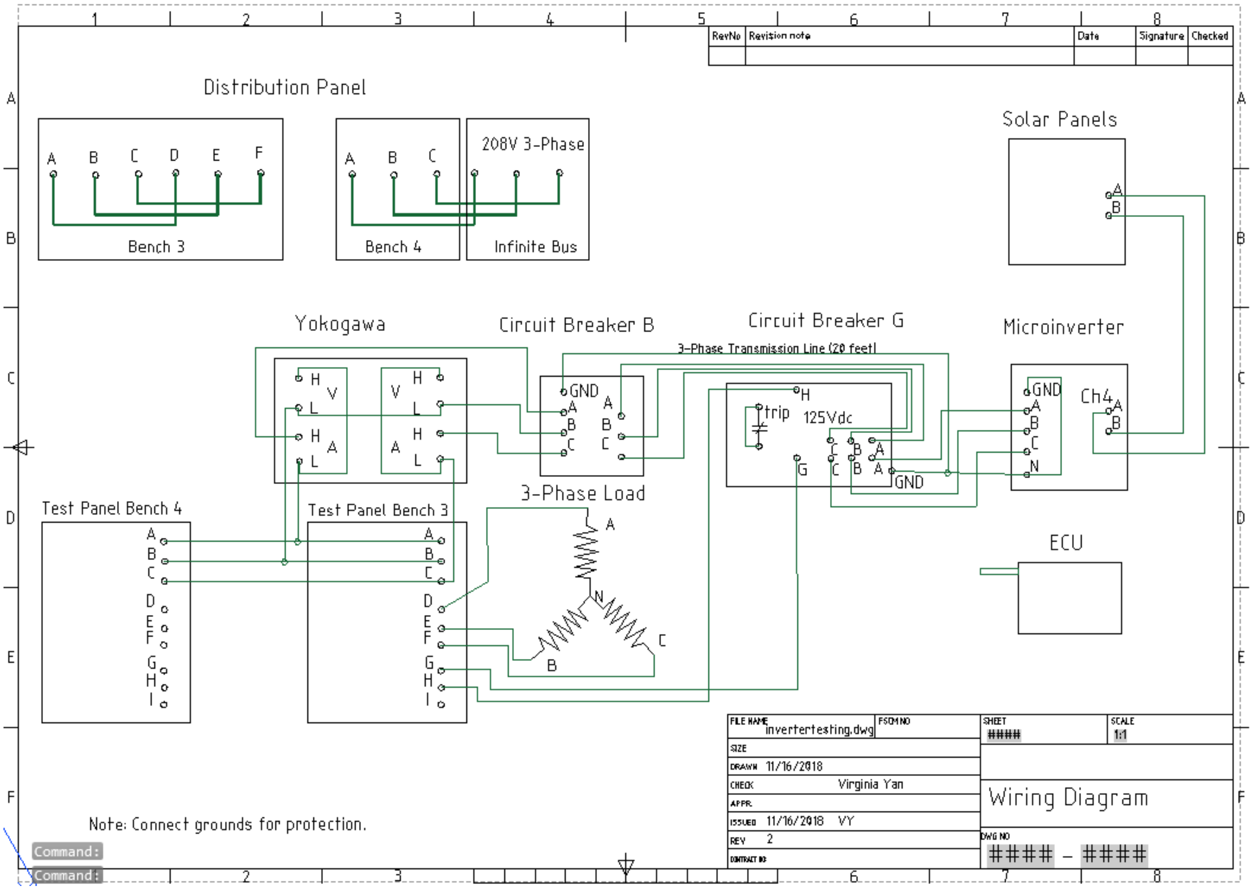


Figure 10. Wiring Diagram for Solar Microinverter Initial Testing

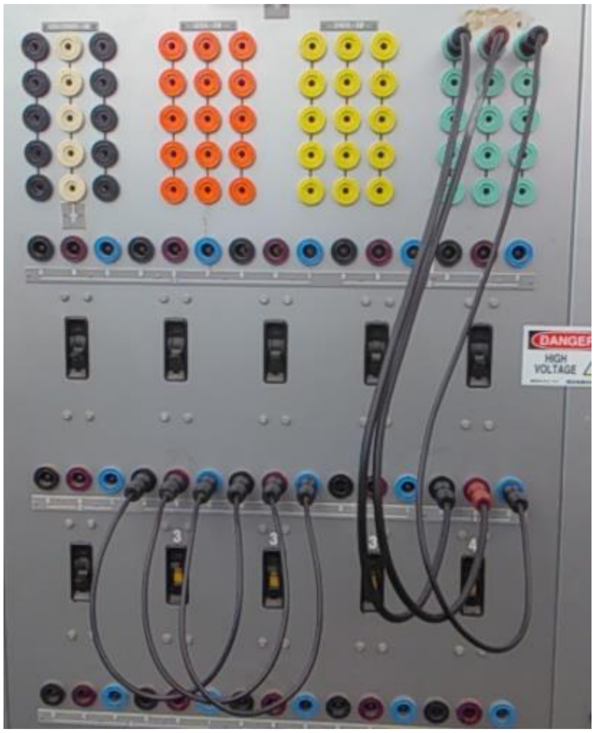
A start procedure is followed during the microinverter testing. The open-circuit voltage of the solar panels is measured using a multimeter and verified to be approximately 40 V. The fuse inside the Yokogawa, circuit breaker modules, and other components are checked to be in good conditions. All the mechanical and electrical connections are made and double-checked before powering on the system. First, the DC and AC sources on the main distribution panel are turned on. Then the circuit breaker B on the AC side is closed. DC disconnect switch under the solar panels is then closed to verify that the LED on the microinverter blinks green 3 times. After closing the circuit breaker G on the DC side, the entire system is powered on and connected. The line voltages are verified to be around 208 V by measuring the circuit breaker terminals AB, BC, and CA with a Fluke multimeter. After 5 minutes of the safety delay, the LED is verified to flash green with a 10-second gap, which means the PV system is producing power and communicating with the ECU. This procedure is followed without the 3-phase resistive load initially to ensure the system is running. The load is then added to the system by switching on sources D, E, and F on Bench 3.

Figure 11 shows the setup used on the DC side in the initial testing. Two Kyocera KC120-1 solar panels, an APsystems YC-1000-3-208 microinverter, a DC disconnect switch, and a circuit breaker module are used in the testing.

Figure 11. Solar Panel Cart (Troy) and APsystems Microinverter Used in the Testing

The resistive load configuration to achieve approximately 216 Ω resistance is a Wye-connected load comprises 3 resistors in series on each line as shown in Figure 12a). Each resistor was measured to have about 72 Ω resistance. During the setup, the equivalent resistance of the load in each line was measured to be around 216 Ω. The Wye-connection was already made internally, and the white wire was the neutral wire. On the main distribution panel, sources A, B, and C were connected to D, E, and F on Bench 3 so that the circuits can be further protected and can be isolated by the switches on the test panel for troubleshooting. Sources A, B, and C on Bench 4 are connected to the 3-phase 208 V terminals on the main distribution panel. The main distribution panel connections are displayed in Figure 12b).

a) Resistive Load Configuration



b) Main Distribution Panel Connections

Figure 12. Resistive Load Configuration and Main Distribution Panel Connections for the Microinverter Testing

Figure 13 shows the test panel and Yokogawa connections for the microinverter system testing inside the Microgrid Lab. Sources A, B, and C on Bench 3 are connected to the sources A, B, and C on Bench 4 using banana-to-banana wires. Sources D, E, and F are connected to the 3-phase load, which allows the load to be isolated from the system with the internal switch. Sources A, B, and C are also connected to the Yokogawa power meter. Sources G and H provides about 125 V DC to the circuit breaker G.

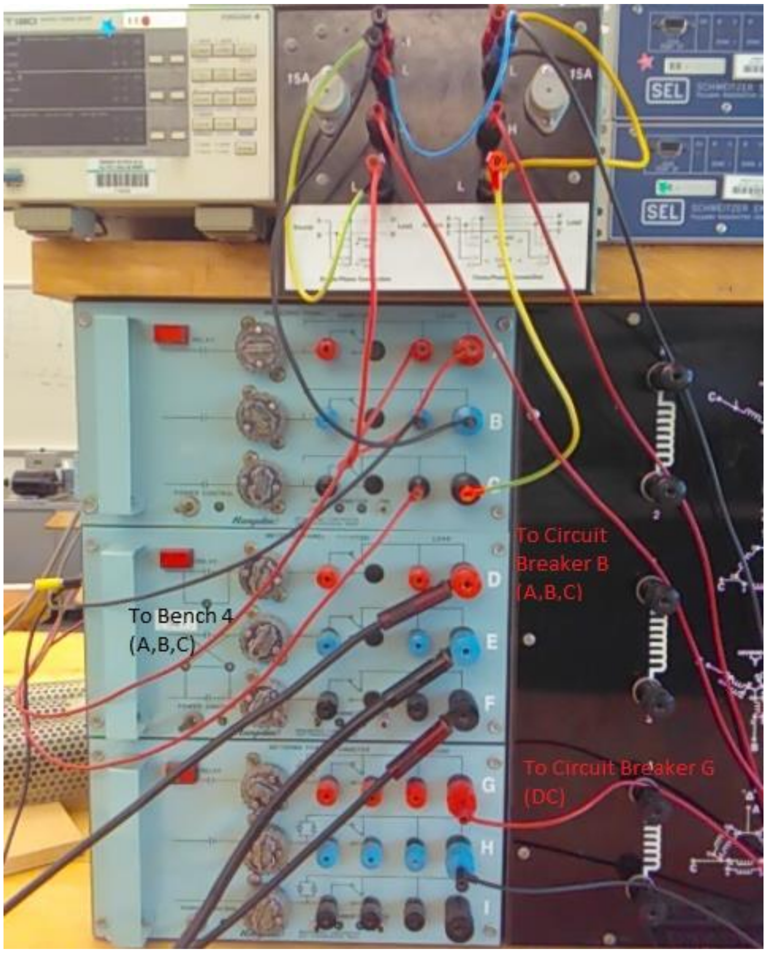


Figure 13. Connections on Bench 3 Panel and Yokogawa Power Meter

One of the circuit breakers used in the testing is a product of a previous senior design [30]. It was designed for students to experiment with different types of faults within the Microgrid Lab and is suitable for many power systems applications. As shown in Figure 14, the primary side of the circuit breaker is connected to the microinverter and the secondary side is connected to the circuit breaker B on the Microgrid side. 125 V DC positive and negative connections go to the DC sources G and H on the test panel. Neutral of the microinverter is connected to the ground terminal of the circuit breaker G. In order to use the LEDs and buttons, the trip terminals must be shorted using a short banana-to-banana cable.

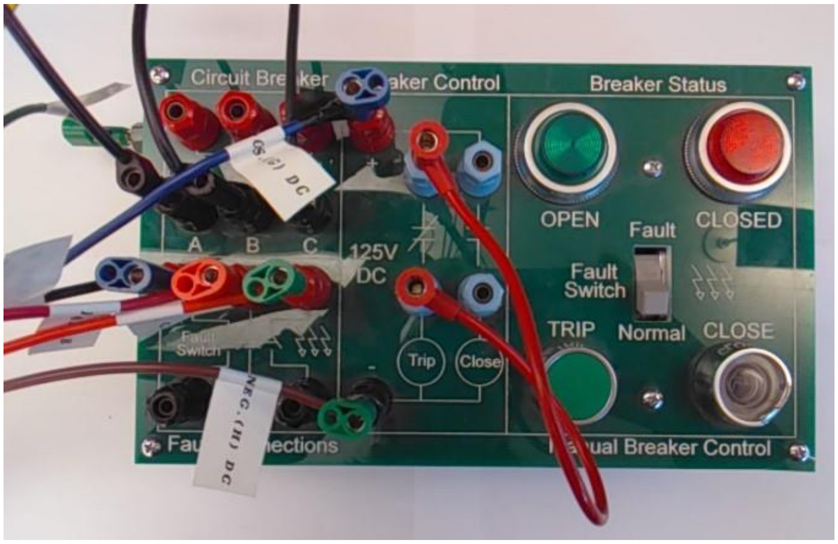


Figure 14. Circuit Breaker G Connections [30]

Figure 15 shows the 3-phase/3-wire current, voltage, and power measurements taken from the microinverter testing through the Yokogawa power meter display. The system is measured to have line-to-line voltage of 207.9 V, 445.8 mA current, and 159.3 W power.

Figure 15. Power, Current, and Voltage Measurements from the Yokogawa Power Meter

Figure 16 shows the ECU measurements of the power and energy generated by the solar panels through communicating with the microinverter. It reads 162 W and 0.08 kWh. The power reading on the ECU display yields a 1.667% relative change when compared to the power measurement on the Yokogawa display. It indicates that there is power loss in the transmission AC line (about 20-feet long) and other connections from the DC side to the AC side of the system.

Figure 16. Power and Energy Reading from the ECU Display

Chapter 7: Conclusion and Recommendations

This chapter draws conclusions about the grid-tied solar system test results, and key challenges faced previously, and makes recommendations to help continue the integration of the system into the Microgrid Lab.

7.1 Conclusion

This project proposes the integration of a grid-connected solar system to the Cal Poly Microgrid Lab. The solar system design is based on the identified customer needs, marketing requirements, and engineering specifications in the definition and planning stage. Two Kyocera KC120-1 solar panels, which output a maximum of 240 Watts power, are connected in series to meet the startup voltage requirement of the APsystems YC1000-3-208 microinverter. A three-phase Y-connected resistive load is connected to the system to balance the power produced from the PV. The load is calculated and measured to have about 216 Ω resistance per phase. The APsystems ECU-3Z is used to communicate with the microinverter through Zigbee communication protocol and send real-time reports to the EMA. The voltage, frequency, and power measurements on the Yokogawa power meter during tests matched theory and the reported values from the ECU with a 5% maximum relative difference.

The satisfactory outcomes of the initial solar system performance test indicate the success of the grid-tied solar system development and integration. The system is able to absorb sunlight, apply DC-to-AC energy conversion, and push the AC electricity to the utility grid. Meanwhile, the developed system is relatively cost-effective since it costs nearly half of the estimated budget.

7.2 Challenges Encountered

There have been many challenges encountered during the testing and analysis stage. Although the PV system testing was successful, it was very inconsistent at first because the microinverter was damaged. Until a replacement inverter was received and utilized in the tests, the element of the unsuccessful or inconsistent test outcomes was unknown. Hence, it took a long time looking for the issue of the system.

The first testing of the microinverter system used four KC120-1 solar panels instead of two. It was not successful because the load was insufficient for the source, which was about 480 W maximum power output from all four solar panels. The initial test was run many times with the same setup and two solar panels, but only a few tests had good results. The Yokogawa power meter and the ECU could not measure any power from the solar panels. The microinverter LED also kept blinking red, which indicated no power was produced. Various methods were used to troubleshoot the system since the reason(s) of the undesired results was unknown.

First, the KC120-1 solar panel cart was replaced with a BP SX 150 solar panel, which provides maximum power of 150 W and open-circuit voltage of 43.5 V. The alternative solar panel did not change the test outcome. The microinverter still did not sense any AC power. Then, the AC transmission line was replaced with simply DC cables, which connected the output of the solar panels to the microinverter. The microinverter was detached from the solar panel frame and relocated inside the Microgrid Lab. It was tested with the exact same setup, with the system connected straight to the infinite bus, isolated from the infinite bus, and with different procedure orders.

After failing to successfully run the tests various times, a method involving the utilization of a DC source for solar simulation was brought up. A Rigol DC power supply DP832 was connected to the microinverter to test if it was functioning. Channels 1 and 2 can output 30 V maximum and 3 A maximum, which gives 180 W if both channels are run. The microinverter responded but the voltages on both channels of the power supply were fluctuating a lot and kept changing between constant current and constant voltage modes, even after the current limit was adjusted. The reason for this was suspected to be because the MPPT of the microinverter was trying to match the internal impedance of the power supply. The first few tests with the DC power supply did push about 70 W to the grid, but it dissipated within less than a second.

An alternative way to simulate the PV was to use sources G and H from the test panel as a DC source with a power rheostat to adjust its voltage. However, the microinverter LED stayed red, indicating that there was an electrode assembly ground fault.

There also have been challenges planning the meeting time due to the time conflicts of the students and faculty, and the lab availability. Other factors such as weather conditions, shade, and location are also constraints on the success of testing.

7.3 Recommendations for Future Projects

Troubleshooting the PV system took most of the project time in the last quarter. Due to inadequate planning and lack of technical experiences, the system with the SEL equipment did not have enough time to be implemented and tested unfortunately. This gives future students the opportunity to continue this project by integrating the grid-tied solar system to the Microgrid with SEL-735 and SEL-751. Since the basic framework has been built, studies on fault detection and protection can be done by simulating the system in ETAP and MATLAB, implementing the simulations with various experiment setups, and comparing the actual measurements with the simulated results.

A modern microgrid should be able to operate either connected or disconnected from the main grid; it should have two major modes: grid-connected mode and island mode. In grid-connected mode, the system is a lot easier to control and protect since it’s relatively small in terms of scale. Critical demand-supply balance becomes a challenge of operating the Microgrid in island mode since the voltage and frequency of the system must be maintained at 208 V and 60 Hz. Hence, it requires an elegant approach to run the solar system tests with it isolated from the infinite bus. Figure 17 shows the wiring diagram to test the system with a synchronous generator. It consists of a DC motor starter, a DC motor, a synchronous generator, power rheostat, a Yokogawa power meter, 2 circuit breaker modules, a 3-phase Wye-connected resistive load, and a microinverter. The DC motor starter is needed to protect the DC motor from potential damage caused by ultra-high current and torque during starting. DC motor is coupled to the synchronous generator as a prime mover to run the synchronous generator. The rheostat is used to adjust the field current. The circuit breaker allows isolation between the microinverter and the rest of the circuit. The Yokogawa then displays the voltage, current, frequency, and power measurements.

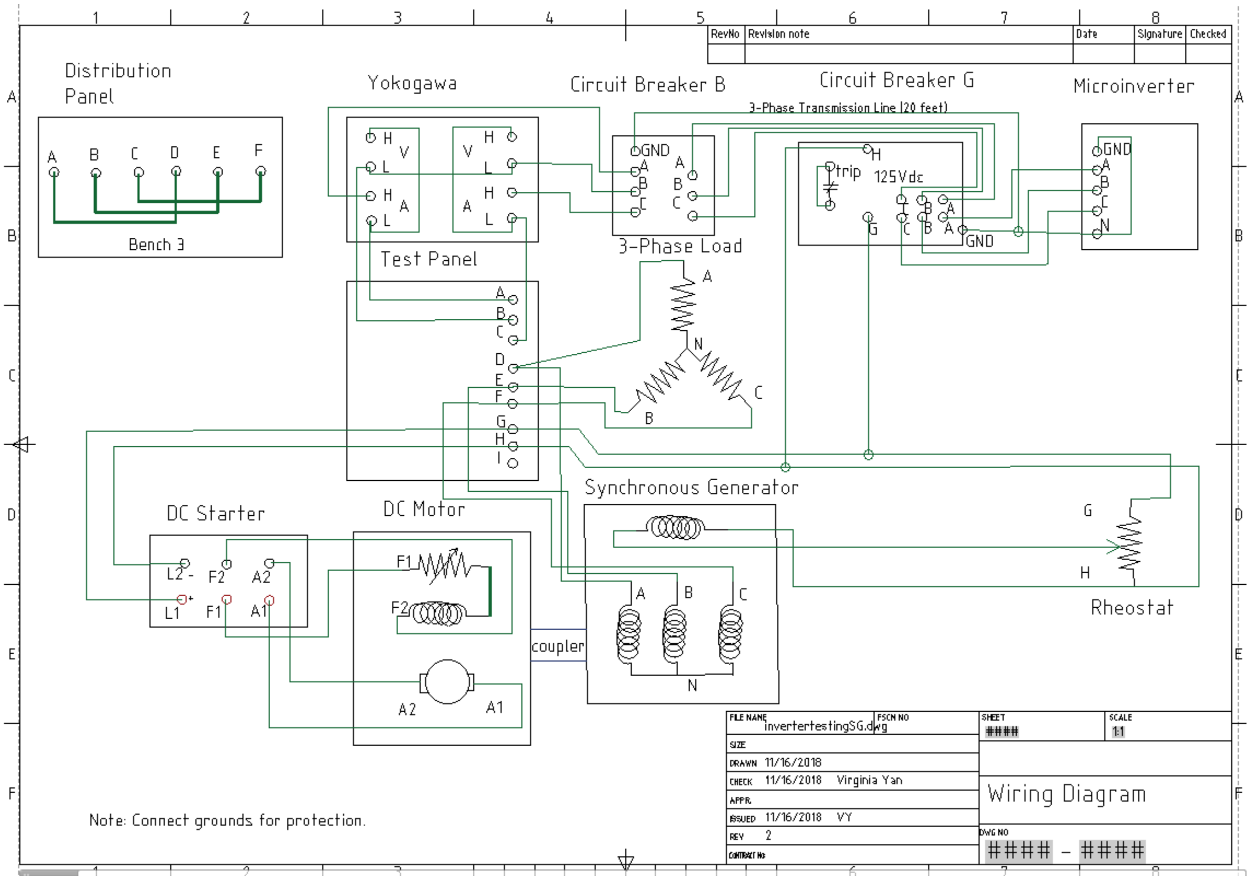


Figure 17. Wiring Diagram for Microinverter Testing with Synchronous Generator

To eliminate more limitations such as weather, temperature, sun exposure, and time which can affect the solar system test results, a photovoltaic emulator is preferred to simulate the solar panels since they have similar electrical characteristics and the output power is controllable. High power programmable DC power supplies such as B&K Precision power supplies PVS10005, PVS60085, and PVS60085MR have built-in Solar Array Simulation (SAS) function, which can simulate the output of a solar array and changes in irradiance conditions [32].

Overall system testing with the SEL relays will be performed and studied after the microinverter testing. The SEL relays will be tested with the factory default settings. The objective of the testing is to ensure the overall system is implemented successfully with all the equipment and devices working together.

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Appendix A - Bill of Materials

Table VI shows the grid-tied solar system Implementation bill of materials. Some equipment and components are donated and previously used. The running total is about $1,241.15, which is below the most likely parts cost of $2,029 and more than the most optimistic cost of $986 calculated from Equation (1).

Table VI. Grid-Tied Solar System Implementation Bill of Materials

Senior Project					TOTAL	$1,241.15		
Part Name (link)	**Host Site**	**Part Number**	**Unit Price**	**Amount**	**Price (set)**	**Shipping/Tax**	**Remarks**
Solar Integration to Grid							
BOUGHT PER UNIT							
KC120-1 Solar Panel	eMarine	ZOK50120	$585.00	4	$0.00	$0.00	donation
APsystems ECU-3Z	www.thepowerstore.com	APS YC1000 ECU	$293.33	1	$293.33	$0.00	
APsystems 1000W YC1000 3-Phase Microinverter	www.thepowerstore.com	APS YC1000	$266.67	1	$266.67	$0.00	
SEL-751 Feeder Protection	selinc.com		$950.00	1	$0.00	$0.00	donation
SEL-735 Power Quality and Revenue Meter	selinc.com		$1,500.00	1	$0.00	$0.00	donation
Single Axis Solar Tracker	amazon.com		$115.00	1	$115.00	$0.00	
UL IP66 Enclosure	amazon.com		$133.86	1	$0.00	$0.00	Paid by Dept
DC Disconnect Switch	https://lshoping.com/		$5.46	1	$0.00	$0.00	used
AC Disconnect Switch			$0.00	1	$0.00	$0.00	self-made
MC4 Cable Connector	Amazon		*$15.99*	1	*$15.99*	$0.00	
Single Axis Solar Tracker Kit	Amazon		*$115.00*	1	*$115.00*	$0.00	
Caster 4in Stem Swivel with Brake	Harbor Freight		$7.99	4	$31.96	$0.00	
Caster 4in Stem Swivel	Harbor Freight		$6.99	4	$27.96	$4.74	
12-gauge silver electro-galvanized slotted strut channel 10ft	Home Depot	ZA12HS10EG	$20.50	2	$0.00	$0.00	Paid by Dept
14-gauge silver electro-galvanized slotted strut channel, 10ft	Home Depot	ZB14HS10EG	$17.86	4	$0.00	$0.00	Paid by Dept
1" rigid conduit 10' long	Home Depot	544010000	$25.00	1	$0.00	$0.00	Paid by Dept
steel base plates 36x3x3/16	Home Depot	8.8748E+11	$17.64	2	$35.28	$0.00	
machine screw 5/16x 3/4" long zinc coarse	Miners Ace	H190084	$11.49	1	$11.49	$0.00	100 bolts in a box

washer for 5-16" screw, 0.875" OD	Miners Ace	H290024	$11.49	1	$11.49	$0.00	100 washers in a box
high-strength steel hex nut, 5/16"	Miners Ace	H150006	$5.29	1	$5.29	$0.00	100 nuts in a box
hex head screw 5/16", 1.5" long, partially threaded	Miners Ace	56	$0.27	20	$5.40	$2.61	
metal rod 1" diameter	Home Depot	800487	$13.67	1	$0.00	$0.00	Paid by Dept
Clamp connector 3/8"	Home Depot	51411205119	$1.72	2	$3.44	$0.00	
Universal Clamp Pipe Clamp Strut Silver 1"	Home Depot	6.16013E+11	$1.84	4	$7.36	$0.00	need to purchase 2 more
Hex Nut 1/2-20	McMaster-Carr	93827A249	$8.76	1	$8.76		tax & shipping will be added; 25 hex nuts in a box
Grade 8 Steel Washer 1/2-20	McMaster-Carr	98026A033	$9.20	1	$9.20		25 washers in a box
3in.x 36in. Plain Steel Flat Bar	Home Depot	8.8748E+11	$17.64	2	$35.28		
1/2"-13 Hex Nuts	Miners Ace		$0.30	12	$3.60		
1/2" Washers	Miners Ace		$0.30	24	$7.20		
1/2"-13 Bolts, 2.5in. long	Miners Ace		$0.95	12	$11.40	$1.66	
12-gauge silver electro-galvanized slotted strut channel 10ft	Home Depot	ZA12HS10EG	$20.50	1	$20.50	$1.59	
1-3/8" Four Bolt Flange Bearing UCF207-22	The Big Bearing Store	UCF207-22	$11.29	4	$65.63		
#VALUE!	Amazon		$15.99	1	$14.52	$0.00	
Ratcheting Crimping Tool	Harbor Freight	97420	$14.99	1	$14.99	$1.16	
9PC Heat Shrink Tubing	Harbor Freight	96024	$0.99	1	$0.99		
14-16G HS Butt Connectors	Harbor Freight	66596	$2.89	1	$2.89	$0.30	
Fasteners	Miners Ace		$0.79	8	$6.32		
Fasteners	Miners Ace		$0.12	9	$1.08		
Fasteners	Miners Ace		$0.15	9	$1.35		
Fasteners	Miners Ace		$0.45	8	$3.60		
Fasteners	Miners Ace		$0.69	4	$2.76	$1.17	
Fin Hex Nut SAE 7/16-20	Miners Ace	H150009	$7.99	1	$7.99		100/box
C-PAK USS Flat Washer 3/8	Miners Ace	H270061	$6.79	1	$6.79		100/box
Fasteners	Miners Ace		$0.65	8	$5.20		
Fasteners	Miners Ace		$0.79	8	$6.32		
Fasteners	Miners Ace		$0.55	48	$15.34		
Fasteners	Miners Ace		$0.85	2	$1.70		
Fasteners	Miners Ace		$0.23	4	$0.92	$3.43	-$11.06 discount
Fasteners	Miners Ace		$0.55	20	$11.00		
Fasteners	Miners Ace		$0.65	10	$6.50	$1.36	
Fasteners	Miners Ace		$0.15	32	$4.80	$0.84	

Appendix B - Solar Microinverter Initial Test Start Program

Solar Microinverter Initial Test Start Program

By Virginia Yan, Do Vo
Updated Time: 11/29/2018

This start program is meant for the testing of YC1000-3-208 microinverter to the Cal Poly Microgrid Lab.

Note: 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.

<u>Preparation Procedure:</u>

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

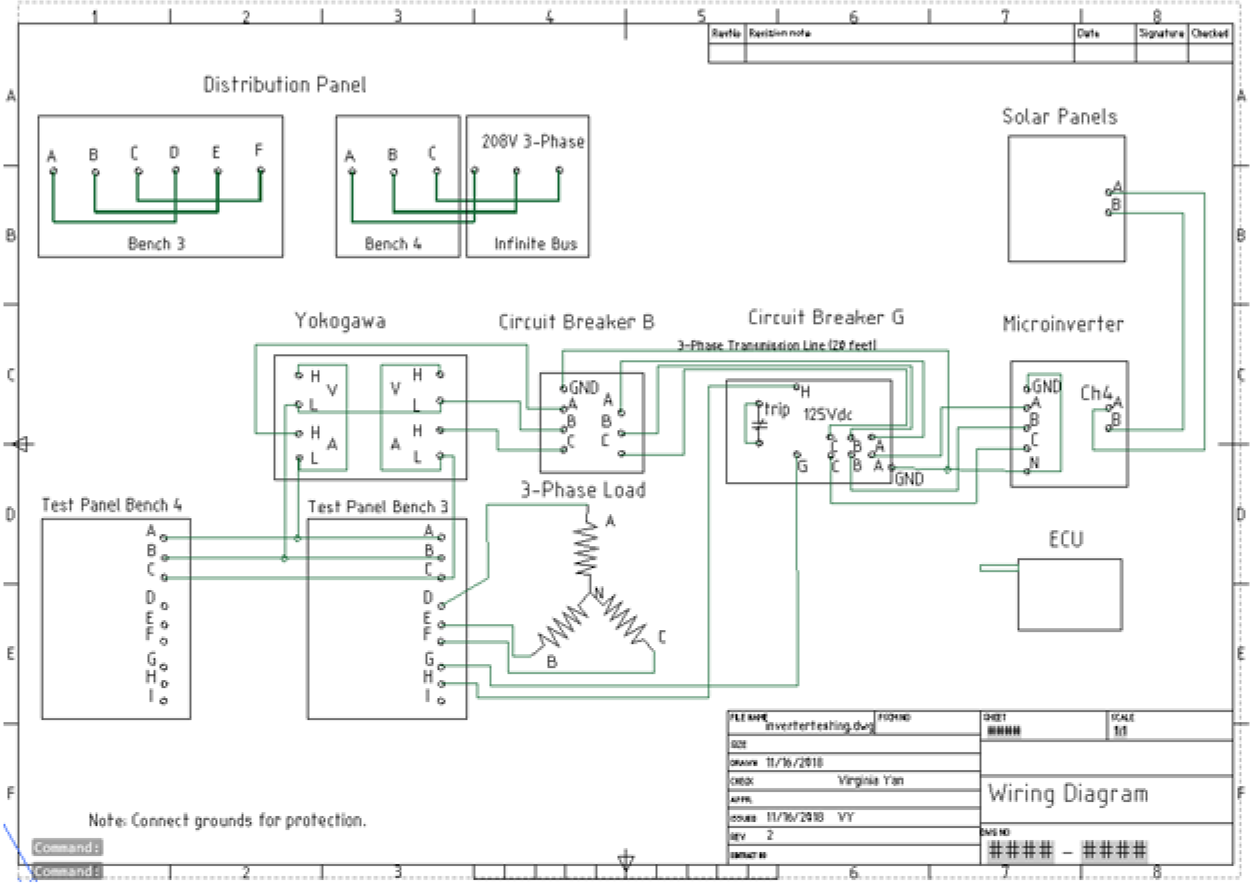
☐Step 2: Verify open-circuit voltage (about 40 V for two panels).

V_{OC} = _______________ V

☐Step 3: Lay the 3-phase transmission line along the pavement from PVs to the Microgrid Lab.

☐Step 4: Connect the solar tracker controller to a 12-V battery and turn on the power; make sure it is in automatic mode by pressing the “Set” button on the remote.

☐Step 5: Plug the AC cable (Microgrid side) into the Yokogawa Power Meter with the following setup:



Note: Connect grounds for protection.

☐Step 6: Connect the 3-phase transmission line from the Yokogawa Power Meter to the Microgrid; make sure the fuse in the Yokogawa is in good condition.

☐Step 7: Plug the AC cable (PV's side) to the circuit breaker G.

☐Step 8: Connect the MP4 connectors together.

Test Procedure:

☐Step 9: Turn on the DC source on the distribution panel.

☐Step 10: Turn on ABC, DEF, and GHI on the distribution panel.

☐Step 11: Turn on ABC, DEF, and GHI on the test panel.

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

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

☐Step 14: Verify approximately 0 W reading from the designated Yokogawa display.

☐Step 15: CHECK circuit breaker B OPEN.

☐Step 16: CLOSE circuit breaker B.

☐Step 17: Check the line voltages on the primary side of the green circuit breaker (from the

Microgrid Lab).

V_{AB} = __________V, V_{BC} = ___________V , V_{CA}= ___________V

☐Step 18: CHECK circuit breaker G OPEN.

☐Step 19: Connect Troy to channel 4 of the microinverter (nearest the antenna mounting thread).

☐Step 20: CLOSE the DC disconnect switch.

☐Step 21: Verify 3 short green blinks.

☐Step 22: CLOSE circuit breaker G.

☐Step 23: Wait for 5 minutes of the safety delay.

Start time: ___________ End time: ___________

☐Step 24: CHECK line voltages on the secondary side (from PV).

V'_{AB} = __________V, V'_{BC} = ___________V, V'_{CA}= ___________V

☐Step 25: Verify flashing fast green lights (2-sec gap).
(It indicates that microinverter is producing power with no ECU)

☐Step 26: Record voltage, current, and power measurements from the Yokogawa.

☐Step 27: Record ECU readings; check EMA report to verify power measurements.

☐Step 28: TRIP circuit breaker G.

☐Step 29: TRIP DC disconnect switch.

☐Step 30: Disconnect MC4 connectors from the microinverter.

☐Step 31: Disconnect the AC cable connections.

☐Step 32: Turn off power in Microgrid Lab and disconnect all components.

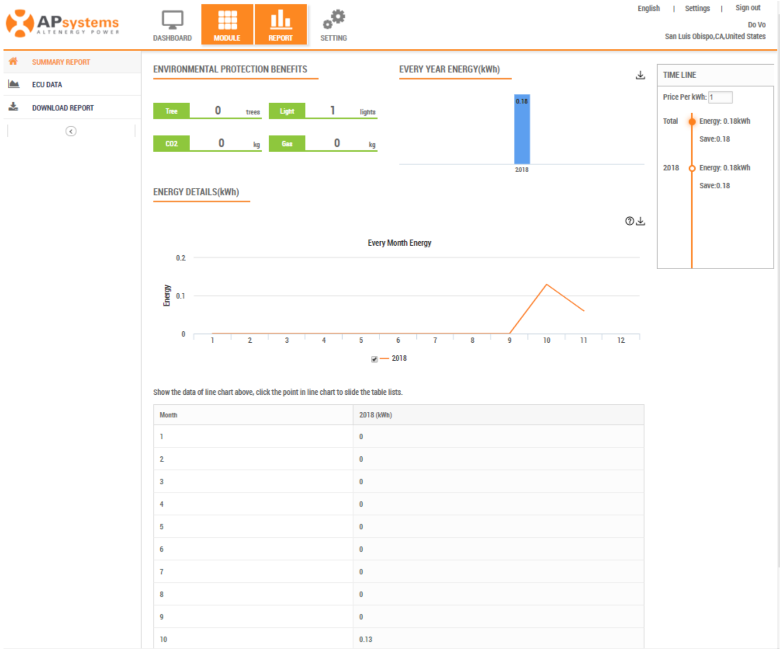
☐Step 33: Fold Troy and locate it to the PES room (R101).

Appendix C – Accessing the EMA Website and EMA App

Follow the below steps to quickly access the EMA website and the EMA app. User must register for an installer EMA account to have username and password information.

Accessing the EMA Website:

1. Go to apsystemsema.com and login with username and password.
2. Go to the “REPORT” page. It shows the monthly and yearly generated energy, environmental protection benefits, and timeline.



Do Vo
San Luis Obispo,CA,United States

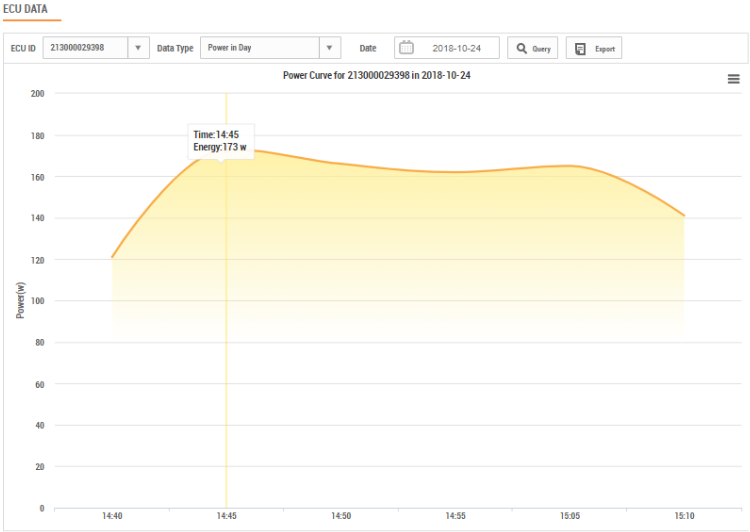
Tree 0 trees
Light 1 lights
CO2 0 kg
Gas 0 kg

Price Per kWh: 1
Total Energy: 0.18kWh Save:0.18
2018 Energy: 0.18kWh Save:0.18

Show the data of line chart above, click the point in line chart to slide the table lists.

Month	2018 (kWh)
1	0
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0
10	0.13

3. Click on ECU DATA. It displays the power curve in a day, energy curves, and allows users to export the report in Excel files.



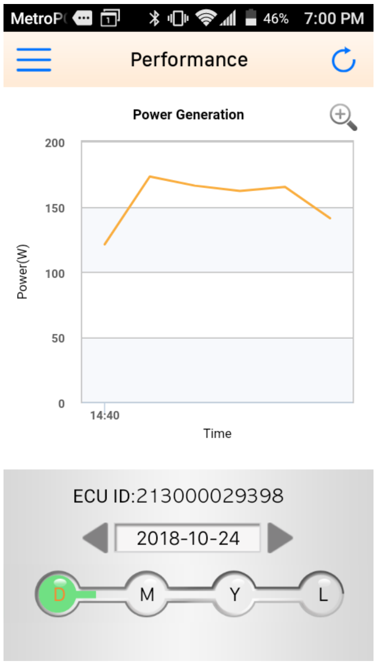
ECU ID 213000029398
Data Type Power in Day
Date 2018-10-24

Power Curve for 213000029398 in 2018-10-24

Accessing the EMA App:

1. Go to Play Store, and search for “APsystems EMA App”
2. Download the app and open it after installation.
3. Login by entering the correct username and password.
4. The home page displays the real-time output power, energy generated, and environmental benefits from the energy generated including the amount of gas, and number of trees saved, and Carbon Dioxide emissions.

5. Press the upper-left button to go to the performance page. The performance page shows the daily, monthly, yearly, and overall power generated by the solar panels.



ECU ID:213000029398

2018-10-24

Appendix D – Senior Project Analysis

Project Title: Grid-Tied Solar System
Student's Name: Virginia Yan
Student's Signature: Virginia Yan
Advisor's Name: Ali O. Shaban

1. Functional Requirements Summary

Distribution level solar energy generation has gained importance and popularity, because it helps create a sustainable electricity system while reducing the harmful environmental impacts our current power systems have. This project proposes an alternative energy source, a laboratory-scale grid-connected photovoltaic system. A KC120-1 solar panel produces approximately 120 Watts A grid-tied solar power inverter does DC-to-AC conversion and minimizes energy transfer losses. The inverter also has an anti-islanding feature, which senses a power outage and prevents back-feeding through isolating the circuit. The circuit breakers isolate electrical components and protect the circuit. Schweitzer Engineering Laboratories SEL-751 Feeder protection relay and SEL-735 power quality meter protect and monitor the feeder before joining the Microgrid Lab.

2. Primary Constraints

The most significant challenge involves the DC-to-AC inverter, which must output 208 V AC voltage to feed the electricity back to the utility grid. After intensive research, an alternative method includes a DC-to-AC single-phase inverter and an AC single-phase/three-phase inverter. However, the additional power losses become significant. Then purchasing a DC-to-AC three-phase grid-tied inverter, through research, costs $2,000 minimum because most are commercially rated. Therefore, they require commercially rated solar panels, which can output 225Vdc minimum. It changes the entire design topology and the equipment used.

Another difficulty encountered includes the synchronization between the solar panel and the utility grid. Lacking relevant knowledge makes it difficult to determine the most suitable solution. Most IEEE journals focus on the synchronization scheme for only single-phase grid-tied inverters.

Moreover, solutions involving eliminating harmonic distortion and grid disturbances also play a significant role. Many IEEE journals suggest using LCL filtering and some other alternative methods, but the final decision requires more research and discussion.

3. Economic

When considering human capital, students gain understanding in power systems fundamentals during the process, which increases their competitiveness in the job market. It can potentially boost their income and the Cal Poly electrical engineering program. Having uninterrupted electric power, students, staff, and faculty increase their productivity and work performance. The efficient use of manufactured capital helps the Microgrid Lab reduce resource use, enhance efficiency and sustainable development. Commoner's law of ecology suggests: "everything connects to everything else [11]." Re-using solar panels, SEL protective relays and power quality meters, and other loaner devices not only reduce manufacturing costs, but also positively impacts financial capital. The project uses sunlight as an alternative energy, which systematically reduces dependence on fossil fuels. The natural capital includes renewable energy, which reflects the zero-emissions production goal.

The project costs accrue when the first design-build-test cycle begins because purchasing parts and tools cost money. The labor costs also accrue because the entire process uses approximately 442 man-hours. Benefits accrue after the project ends and the design gets implemented and manufactured.

Pacific Gas and Electric (PG&E), Schweitzer Engineering Laboratories (SEL), other electrical manufacturers, and the Cal Poly electrical engineering department pay for the project. Table V gives the total project cost estimation. It estimates the project cost about $19,914.154 including labor costs and parts costs.

The college gains profit when a new power systems protection theory laboratory coursework becomes established and students can register for the course. This can potentially become a project-based laboratory course and let other tech companies donate more relevant lab equipment. Cal Poly electrical engineering department also profits if companies use the protection strategies or systems.

The products emerge after the final implementation and analysis process end. In Figure 3, the Gantt charts show that the project requires approximately 25 weeks, which allow adequate development time and different design approaches. Optimistically, the product designs estimate a 20-year lifetime, assuming minimum maintenance and upgrades occur when necessary. The maintenance costs exist when the overcurrent protection, overvoltage protection, and other fault detection fail to work.

4. If Commercially Manufactured:

An estimated 500 devices or systems are manufactured and sold per year at an estimated manufacturing cost of $4,000. A target purchase price ranges from $8,000 to $12,000, which means profits can reach $8,000 per year. Other companies can license successful protection methods and apply them to their product or services.

5. Environmental

Nobel Prize winner Milton Friedman defines externality as the effect between two individuals/corporations' transaction on third parties [12]. The project has positive external impacts on San Luis Obispo community and other communities because it uses renewable energy and does energy conversion. However, "there is no such thing as a free lunch [9]." The project connects to the entire proposed Microgrid Lab project, which uses transformers, generators, and motors. They all have emissions which can harm the environment. Additionally, the part transportation has indirect negative environmental effects.

The project uses PG&E electricity directly and the electricity converted from sunlight. The project improves PG&E services, because it uses renewable energy and provides uninterrupted electricity. Solar generation makes the main grid more efficient and durable. If successfully implemented, the project has a positive impact on other species because it improves sustainability by reducing ecological footprint.

6. Manufacturability

The main issue with manufacturing this product involves high initial manufacturing cost, which can bring less profits than expected. Due to the lack of DC-to-AC three-phase non-commercial inverters, technical difficulties arise. When lowering the inverter costs, power losses and harmonics become the tradeoffs. A more effective and efficient method requires more discussion and analysis.

A new grid-tied solar system requires the homeowners to have electrical permits or licensed electricians [13]. California state law also charges the agency for permit processing and inspection. This fee and labor costs must be considered when installing the system. Additionally, regulatory requirements and the permitting process involve strenuous effort because they require many paperwork.

7. Sustainability

The challenges include successfully synchronizing and feeding the current to the main grid. Significant power losses could occur during the process.

The project uses sunlight as an alternative energy, which improves sustainability. Re-using the equipment and devices for future projects and proper equipment disposal also help achieve sustainability. Over time, the power systems protection scheme may experience significant challenge because the equipment degrades. Hence, IEEE and/or NEC safety standards require regular and consistent maintenance.

8. Ethical

The project provides Cal Poly students a platform to develop their power systems knowledge. Thus, it serves the last IEEE Code of Ethics because it helps students “in their professional development” [14].

The system actively promotes utilitarianism, the greatest good for the greatest number via re-using solar panels, protection relays, and other electrical equipment [15]. It reduces the improper equipment disposal and help achieve a sustainable future. It also promotes beneficence, because it provides reliable and safe electric power. If the project documentation and strategies contribute to the potential power systems protection laboratory coursework, it also benefits future Cal Poly students.

To meet the non-maleficence framework, a cost-benefit analysis may be conducted because the design involves dangerous elements like high current and voltage above 120V. However, it becomes crucial when doing the cost-benefit analysis involving human lives, because the Ford Pinto tragedies should not get repeated [16]. The Ford Motor Company chose not to upgrade the Pinto’s fuel system design, which caused 180 deaths. All engineers should identify any immoral practices related to safety issues and enhance their ethical sensibilities. Reinforcing the IEEE Code of Ethics should provide a guideline and safety boundaries. This design contains safety features like overcurrent protection and overvoltage protection via circuit breakers and protection relays.

9. Health and Safety

One safety concern involves the implementation stage, because it deals with voltage above 120V and high current. Students should always take proper electrical safety precautions when implementing the design. They must follow Cal Poly’s laboratory safety guidelines and must have one other person in the lab.

Modern PV panels are mostly silicon-based, and they have been concluded to pose very little to no risk of toxicity to public health and safety [17]. However, some minor PV cells contain lead, which is very toxic and especially harmful to children. Some older PV panels still have solder that contains lead, but more modern PV panel manufacturers have changed to use lead-free solder.

10. Social and Political

In 2005, the Energy Policy Act established IEEE 1547 as the national standard for the interconnection of distributed resources in the United States. The latest standard updated allowed inverter manufacturers to provide certain capabilities like the anti-islanding feature. Interconnection requirements traditionally required the inverter to shut down during power outages for safety purposes [18]. However, the loss of solar generation greatly increased as more solar panels got installed. The costs became massive especially when the 2016 wildfire in Southern California prevented 1,200MW solar generation. The project implements solar inverter with anti-islanding feature, which can potentially impact the Cal Poly community during power outages. PG&E and its employees, Cal Poly, and Schweitzer Engineering Laboratories hold direct stakes because they receive financial benefits directly. Electrical manufacturers which donated the equipment and devices receive tax deductions. Cal Poly electrical engineering students also benefit directly, because the knowledge they gain can increase their future income and career. The San Luis Obispo community also indirectly benefit from solar generation because it creates clean, renewable energy and has positive impacts on the environment.

The project primarily provides electrical engineering students a platform to apply power systems protection theory and fundamentals. Such a small scale has little real benefit or profit except educational benefits. Students do not actually get paid during the process. Inequities may occur here. However, it is then paid off in their future careers.

11. Development

Through the literature search performed, basic comprehension of modelling electrical systems and fault detection were gained. Although most IEEE journals and conference papers did not provide solutions to implement DC-to-AC three-phase inverters, the resources help reduce harmonic distortion and power losses and improve power quality [19].