Senior Project

Sponsored by EPRI GridEd

Battery Energy Storage System

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ELECTRICAL ENGINEERING DEPARTMENT

California Polytechnic State University

San Luis Obispo

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Statement of Disclaimer

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Acknowledgment

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Project Abstract

The project continues part 1 of the "Reliability Measurement for Grid-Connected Solar System" project. The goal is to continue where the previous design ended. This project configures an ITECH IT-6000C and Tabuchi Battery Energy Storage System (BESS) to the small-scale microgrid at the Cal Poly, San Luis Obispo EE Department. Initially, a system was designed to connect an ITECH IT-M3633 as a PV solar source emulator to the Tabuchi BESS within a grid-connected microgrid system in Room 20-102 at Cal Poly. A photovoltaic Thevenin equivalent model was developed for the ITECH IT-M3633, which emulates 800 Watts, equal to two solar panels of average size. In this project, we expand the solar power emulator to 4000 Watts, equal to ten solar panels.

1 Introduction

Solar panels are becoming increasingly common in small-scale applications, such as residences. They allow households to become more environmentally friendly and reduce their electric bills. However, a problem with solar energy is that as more are added to the power grid, they can sometimes produce excess energy and are not used to their full potential.

Net load is the load on the system, subtracting the load that is met by energy sources implemented after the transmission stage of the power system. Solar panels are commonly installed in residences and manufacturing buildings, significantly impacting the power system after the transmission stage. Because of this, the net load is lowest when the sun is highest. Also, the load peaks around 7 am and 8 pm when most people are home from work, and more applications are used than in other parts of the day [1]. However, solar power generation decreases at these times of day, as the sun is low. This creates a duck curve, as shown below in Figure 1 [1].

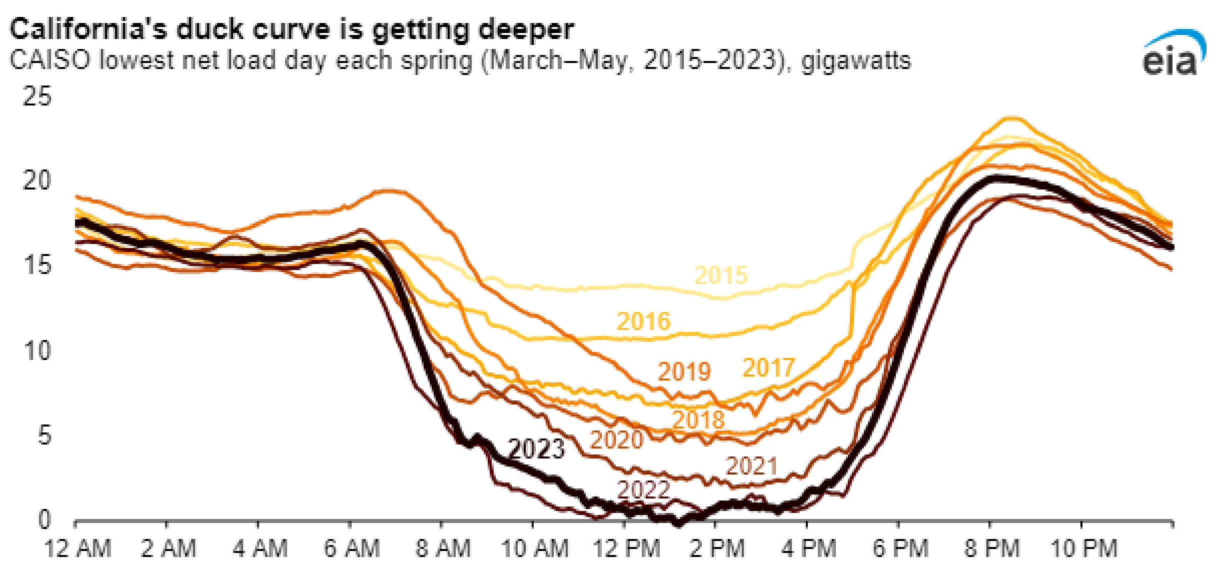

Figure 1:This curve shows the lowest net load day during springtime in California. [1]

Every year, the duck curve gets more and more extreme. The load during midday has decreased drastically from 2015-2022, yet the load at its peaks has not changed much. This is because more and more solar panels are being added to the system every year. In recent years, the net load has been approaching, and sometimes crossing, the zero gigawatt threshold. When the load crosses zero, renewable energy sources produce more power than is used. In these cases, power companies have to dissipate this excess power to prevent damaging the system. Also, the steep increase in power needed from non-renewable sources to meet the increased load puts stress on power plants and the system [1].

As solar panel output continues to increase, so does the need for energy storage. Energy storage allows excess solar energy to be generated during times of high sunlight and low load and used when the load increases and solar energy generation decreases. It can make the system more efficient by eliminating the need to waste excess power. It can also be used during peak load times to lessen the stress and load on the grid [1]. It is also more beneficial for the consumer, as they can use grid power during low-load times when the price of electricity is low and use their own stored power during high-load times when electricity is more expensive. The ultimate goal for battery storage is to flatten out the duck curve, lessen the load during peak load, eliminate the need to waste excess solar power and add incentives for renewable energy usage.

However, interfacing batteries with solar panels and connecting them to the grid creates a system that requires system protection. Systems are liable to faults, shorts, and arcs, which can damage the system or cause a hazard. System protection is measures taken in the design process to prevent these problems or mitigate their impacts. Therefore, there is a need for energy storage and system protection design with it.

2 Background

This project creates a BESS alongside solar panels to create energy storage capabilities. This maximizes the capabilities of solar panels by preventing the need for excess solar energy to be discarded and allowing solar energy to be used during hours when solar panels are not producing enough energy to match the household's demands.

However, this requires system protection to interface the battery and solar panels and ensure the system is safe and works correctly. System protection also allows the system to be grid-connected and prevent electrical overcurrent and ground faults. Other types of faults can't be protected, such as arc flashes or transient overvoltage, but they require higher voltages than what is used in the BESS, so protection against these types of faults is unnecessary.

One liability that the system needs protection from is overcurrent. Overcurrent is excess current in the system [2]. This can be caused by faults or overload. Overcurrent is prevented through the use of fuses and disconnect switches. A fuse is a safety divide that destroys itself when too much current flows through it, creating an open circuit [2]. Disconnect switches can also disconnect the load when the current is too high. Switches combined with fuses allow the user to open and close the circuit while the fuse prevents too high of current from passing [3].

Another way to use fuses is through a Variac. The Variac is a variable autotransformer with fuses implemented to limit the current flow. Variac, by nature, limits inrush current by slowing transformers' time to reach full power. Inrush current is an overcurrent that occurs when a device is first turned on. This is because the internal capacitors and inductors are discharged and draw a high amount of current very quickly to charge [4]. A Variac can protect by having fuses, thus preventing transient overcurrent and slowly bringing a system to full power, thus avoiding inrush current.

For this project, our main concern for our protection systems is to avoid over currents from the grid and our PV emulator and avoid over currents entering the DC supply from our supply voltage faulting or high inrush currents. Protecting the BESS from the grid and PV input was already built by a previous team, and protecting our supply can be achieved through a Variac.

This project is a continuation of a previous project that was unsuccessful in completing its goal. The previous team attempted to emulate PV cells through an ITECH IT-M3633 and used a DC disconnect switch with Bussmann Fusetron FRS-R-15 Fuses [5]. The ITECH IT-M3633 is a bidirectional DC power supply that acts as a directional power supply and regenerative electronic load [6]. The device can emulate a battery charger or a solar photovoltaic source.

It is also an electronic load and a digital multimeter. The electronic load can act like a variable resistor with an oscilloscope, multimeter, or battery by drawing a constant current.

Unlike a typical electric load, ITECH does not generate heat, which takes that power and gives it back to the AC network. It can be programmed for variable loading cycles as well [6]. ITECH can easily set either source mode or load mode while digitally setting voltage, current, and power while protecting over/under voltage, current, and power [6]. However, in the previous project, the ITECH IT-M3633 did not produce enough current to turn on the inverter, which prevented the system from functioning correctly [5]. This project replace the PV emulator with one that can produce a high enough current output to get the system to work correctly.

3 Functional Decomposition

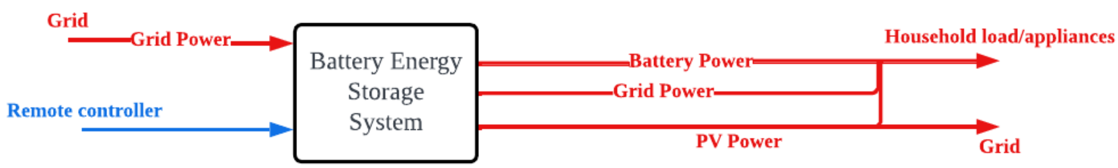

Figure 2:Level 0 Functional Decomposition

The above functional decomposition shows the system's flow of power and data. The blue indicates a data input, which in this case is a signal from the remote controller that allows the user to give instructions to the system, such as to switch between power sources applied to the household load. The remote controller allows the user to override the system's function, but the system works appropriately without user input. The red arrows indicate the flow of energy, which in this system is power from the grid, batteries, and solar panels. The system takes an input of power from the grid and decides when to use this power or the solar cell power or battery stored power. The system allows grid power to completely pass through to the household load when the solar cells have no energy output and the batteries have no energy stored. When the battery energy is stored, and the system detects that the price of grid power has surpassed a certain threshold, the system chooses to use the battery power on the household load instead of the grid power to save the customer money.

Also, depending on when it is economical to do so, the system outputs PV power to the household load and/or the grid. In summary, power sources flow both to the household load and the grid, and the power flow is determined by the system in order to save as much money as possible. The one direction of power flow that the system does not allow, however, is for the battery energy to flow to the grid, as it prioritizes saving the energy for the household to use.

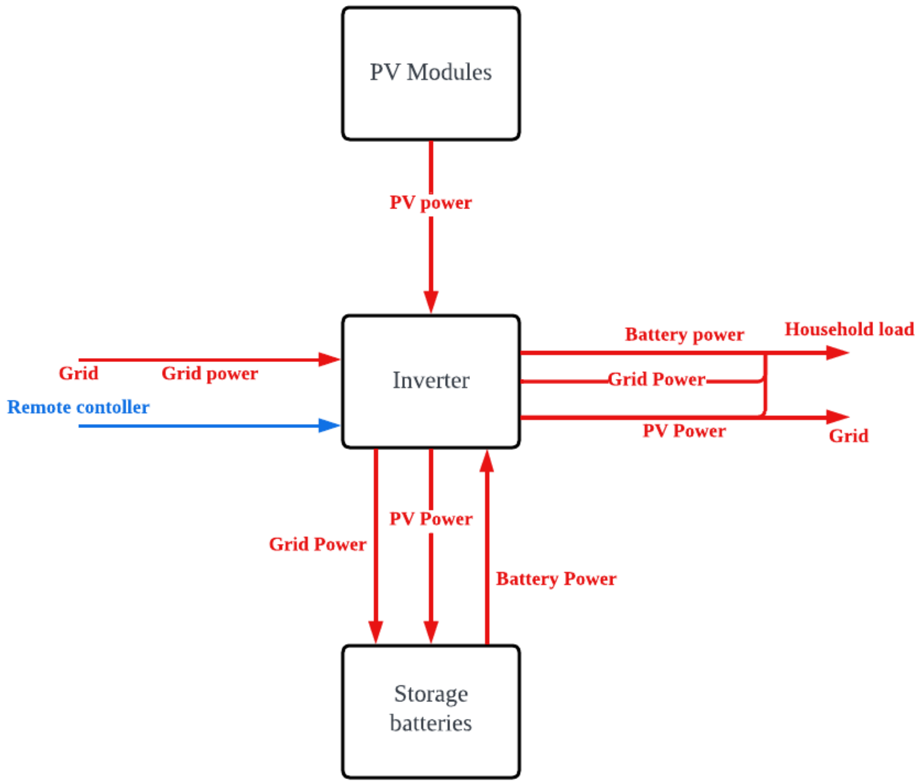

Figure 3: Level 1 Functional Decomposition

The Level 1 block diagram shows that the system has the same overall inputs and outputs as in Level 0, but it also shows the flow of power within the system. The system consists of the inverter, which converts DC power to AC and controls the flow of power to be as cost-effective as possible; the PV modules, which supply renewable energy; and the storage batteries, which allow for power to be stored. The inverter controls the flow of power between the grid, PV modules, storage batteries, and household load. The PV Modules do not take any power inputs and outputs its power to the inverter. The inverter then stores this power in the storage batteries and allows excess PV power to flow to the household load when the batteries are full.

If the batteries are full and the PV power exceeds the household load needs, the inverter directs some PV power back to the grid. In most instances, however, as the PV power infrequently meets the household load, the inverter uses a combination of PV power and grid power to supply the household with its power needs.

The inverter also controls the power flow through the batteries so that the system is as cost-effective as possible. The batteries store power from the PV modules, as well as from the grid, if the inverter determines that the grid power is cheap enough and the battery is at low enough capacity that it would be profitable to store this energy to later be used when the grid power is more expensive. The battery power can only be used when the inverter detects that the grid power price has reached a certain threshold, and battery power can never be outputted to the grid; both these restrictions are to ensure that the system is as cost-effective as possible by saving the battery power for peak load times.

4 Requirements and Specifications

Table 1: Requirements, Specs, and Justification

Requirements	Engineering Specifications	Justification
3,4	1. Solar panels are placed in areas with high amounts of sunlight and minimal shade cover.	Maximizing the sunlight the solar panels are exposed to maximizes the amount of energy they are able to produce. This makes the system more efficient and cost-effective.
1, 2, 3, 4	2. Use a PV emulator to replace solar panels for testing purposes	A PV emulator replaces solar panels so that testing and proper design can take place before the system

		is implemented with solar panels. This ensures that it works properly and meets the desired requirements.
1,2	3. Fused DC breaker between PV modules or PV emulator and inverter. This is created using a disconnect switch with fuses inserted [5].	A fused breaker prevents a current that is too high from flowing between devices. This prevents damage to the system and components as a form of system protection. Also, this keeps it safe and within power levels and allows it to be connected to the grid.
1,2	4. Implement fuses between inverter and batteries [5].	Fuses between the inverter and batteries protect the devices and system from too high of current. This is a form of system protection that makes the system function properly, safe, and able to be grid connected.
1	5. An inverter is placed between PV modules or emulator and the rest of the system.	The inverter converts solar DC power to AC power that is compatible with the other components in the system and the grid, allowing the system to work properly

		and be grid-connected.
1,2	6. Implement additional forms of system protection as needed	Testing with the PV emulator implemented reveal any possible locations of faults or overcurrent. Adding more measures of system protection as needed keep the system safe and able to be grid-connected.
3,4	7. Maximize power transfer to batteries.	Maximum power transfer ensures that despite internal impedance from the voltage source dissipating some power, the maximum power possible is delivered to the battery. In a circuit with a constant internal impedance, this is achieved by matching the load voltage to the source's internal impedance. However, with solar panels as the voltage source, this internal impedance is not constant or linear. This require some analysis of the photovoltaic emulator software.

Requirements 1. Grid-connectable 2. Safe 3. Saves money in operation 4. Efficiently stores and uses renewable energy

Table 2: Engineering Specifications Table

Spec. #	Parameter Description	Requirement or Target	Tolerance	Risk
1	Solar power emulator output	6kW 40A	Rated	Low
3	Output power	5500W	Rated	High
4	Output current	22.9 A	Max	Medium
5	Efficiency storing solar power	95%	Max	Low

6	Grid frequency	56 Hz	Min	Low
7	Grid frequency	64 Hz	Max	Low
8	Battery charge power	3 kW	Max	Low
9	Battery discharge power	4 kW	Max	Low
10	Input power per solar panel string	2500 W	Max	Medium
11	Input operating current per string	12 A	Max	Low

4.1 Cost Estimates

4.1.1 Bill of Materials

Senior Project: PV Hybrid Inverter BESS
TEAM: Alec MacLean, Kaylen Schwartz, Kyle Begley
DATE/REV: DEC 5, 2023 VERSION V1.0

										USA	Foreign	
Sub	Sub	Sub	Sub	Description	Qty	P/N	Document	MFG	MFG P/N	1pcs Price (USD)	1pcs Price (Converted)	TEAM
Box Build - Model XYZ - Retail Configuration							Custom	Custom	--			1
1	Final Assy - Unit PV Hybrid Inverter BESS					1000	Custom	Custom	--			
	1	Main Mobile Storage Assy				1100	Custom	Custom	--			
		1	Tobuchi EIBS		1	1110	Spec	Tobuch	EIBS	$14,500.00	$16,900.00	
			1	Battery Units, 10kWh	2	1111	--	--	--			
			2	Hybrid Inverter	1	1112	--	--	--			
			3	Control Panel	1	1113	--	--	--			
			4	Polymer Mounting	4	1114	--	--	--			
		2	80/20 Framework Set		1	1120	Spec	80/20	TBD	$250.00	$300.00	
			1	Linear Railing, 4"x4"	50ft	1121	--	--	--			
			2	90 Degree	20	1122	--	--	--			
			3	Rivetting Connector	75	1123	--	--	--			
			4	Linear End Caps	10	1124	--	--	--			
		3	Castor Wheels, 6" DIA			1130	Spec	TBD	--			
	2	Rooftop PV System				2100	Custom	Custom	--			
		1	SunPower 4'x6' Solar Panles		7	2110	Spec	Sunpower	435	$300.00	$450.00	
		2	80/20 Framework Set		1	2120	Spec	80/20	TBD	$250.00	$300.00	
		3	3 AWG Wire		50	2130	Spec	TBD	TBD	$0.10	$0.11	
	3	DC Fusing				3100	--	Custom	--			2
		1	tric General Duty Safety Swit		1	3110	--	GE	--	$384.00		
		2	he Bussman Fusetron FRS-R-1		2	3120	--	Bussman	--	$12.02		
	4	ITECH Supplys				4100	--	ITECH	--			
		1	IT-M3633		1	4110	--	--	--			
		2	IT6000C		1	4120	--	--	--	$7,000.00		3
										$24,513.04	$20,655.50	

If made in the USA	0.5hrs x $40/hr	$20.00	$2.50
If made Foreign	0.5hrs x $5/hr		
Product Shipping Leadtime		1	8
		$24,533.04	$20,658.00

Figure 4: Bill of Materials

The following table is about the labor costs.

Table 3: Labor Costs

Team Member	Pay/Hour	Hours/Week	Weeks worked	Pay
Alec MacLean	$36.00	10	26	$9,360.00
Kaylen Schwart	$36.00	10	26	$9,360.00
Kyle Begley	$36.00	10	26	$9,360.00
			TOTAL:	$28,080.00

5 Gantt Chart

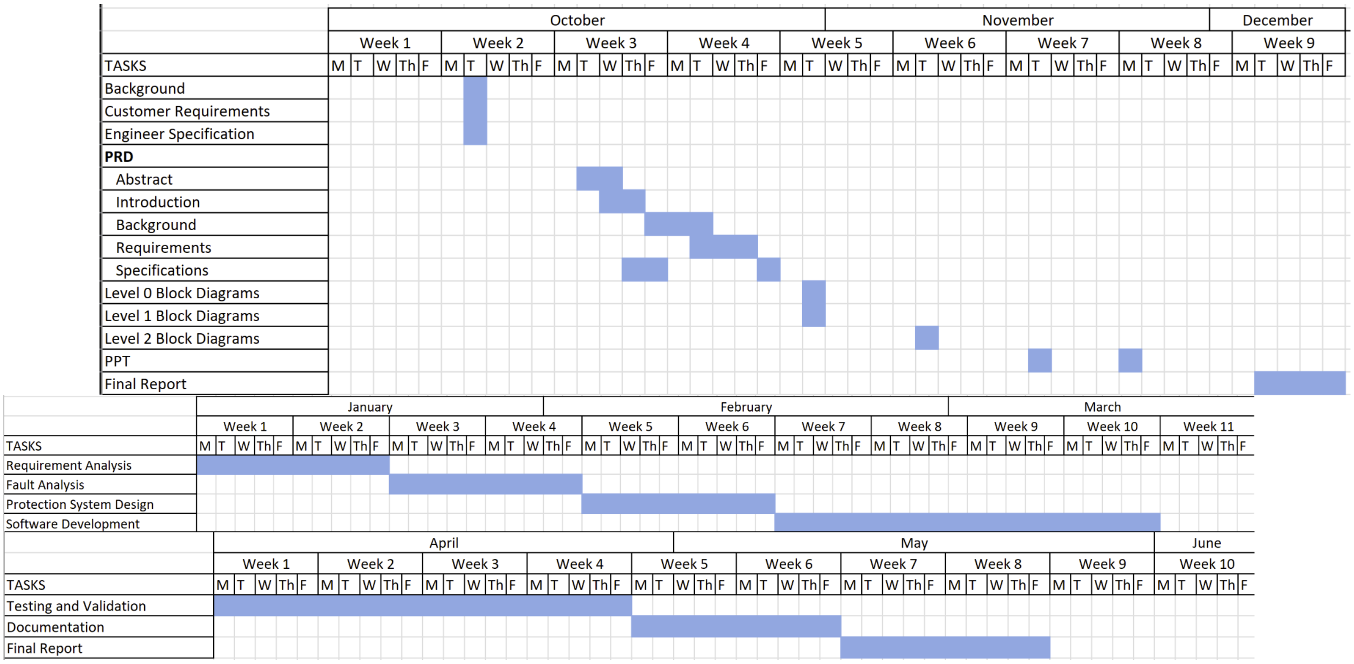

Figure 5: Gantt Chart

6 Project Execution

The original plan for this project was to implement a new power source in order to get the inverter to function properly and then design, simulate, implement, and test system protection for the BESS. However, once the power source was replaced, we saw that this was not possible. The problem turned out to be much bigger than an inadequate power source, so the project transitioned into troubleshooting and testing to determine the fault that the inverter was detecting to prevent it from working properly.

7 Design Overview

The following system diagram depicts the experiment in its final state. 240V 3 phase is sent through a Variac, which provides overcurrent protection and inrush current protection, to a 240-480V step-up transformer, which supplies the ITECH DC supply. The ITECH provides simulated PV voltage to the BESS, which consists of an inverter and subsystems.

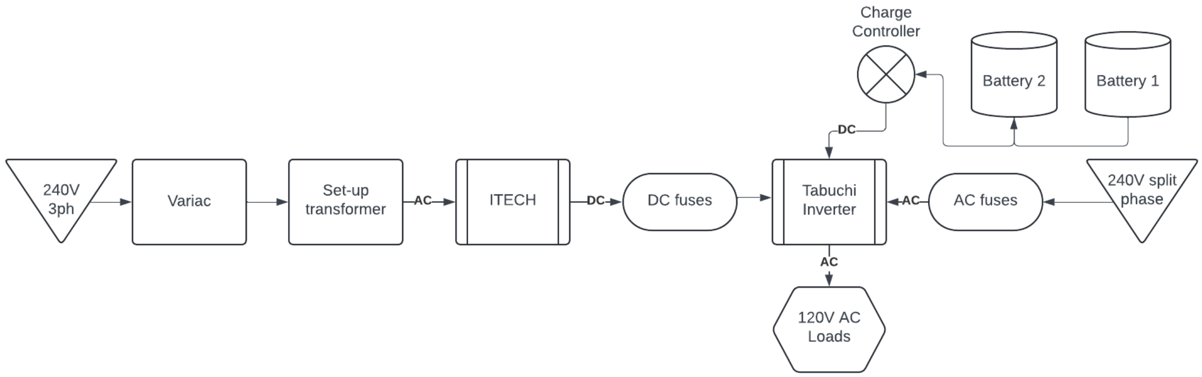

Figure 6: System Overview

8 Power Source Design

The first task of this project is to add a new power source, such as a PV emulator. The previous team was unable to get the inverter out of automatic stop mode, where the device senses a problem and does not function properly. It was determined that the power source that was used was not supplying high enough voltage to get the inverter to function properly. We implemented Itech Regenerative Bidirectional Programmable DC Power Supply as a DC power source that we can also program to use as a PV emulator. One issue with using this power source is that it requires a 3-phase 380 V AC input, and the highest voltage that was available in our lab is 3-phase 240 V AC. To remedy this, transformers were needed to step up the voltage. However, we also wanted to implement some protection between our system and the power source, so we implemented a Variac transformer with fuses inside it to add protection. This Variac regulates current flow during start-up to avoid the transformer's inrush current. The Variac is set to 24:19, and the transformer is set to 1:2 to step up the voltage from 240 V to 380 V. The power source setup is shown below.

9 Tests and Development

9.1 Power Source Transformer Open Circuit and Load Test

The step-up transformer, with a ratio of 1:2, was previously donated to the Cal Poly EE Power Ground, but its functionality had not been checked. To determine if the transformer would operate under full load, we performed an open circuit test to determine its viability. To run this test, we Connected 120 V AC single phase to phases A and B of bench 3 in the EE department's power lab. We then ran the positive through the ammeter of bench 3 and connected the positive and neutral leads to phases D and E of bench 3. We then routed the D and E phases of bench 3 to the H1(A) and H2(B) phases of the power transformer primary on the lab's patch panel. We then connected the secondary A and B phases of the transformer to the A and B phases of bench 4 on the patch panel. We then ran bench 4's voltmeter across the benches A and B phases. Using bench 3's control switch, we closed the circuit and observed 49.5 V AC at bench 4. We opened the circuit and connected two 35-ohm resistors parallel across the A and B phases of bench 4 using the same setup. Closing the circuit, we observed 49.3 V AC and 2.15 A at the load and ammeter, respectively. These tests confirmed that the power transformer was in good health and could supply the ITECH supply properly.

Figure 7: Step-up transformer during open circuit test

9.2 Power Source - Variac Test

As stated previously, in order to provide protection to the power transformer and avoid its inrush current, we used a 7.0 KVA variable autotransformer. To test the Variac, we first removed its 50-amp fuses and tested their continuity. After confirming their functionality, we connected the primary A, B, and C phases of the Variac to 240 V 3-Φ AC on the lab's patch panel, and its neutral to ground. We then ran the secondary of the Variac to the primary of the step-up transformer and ran its secondary phases to bench 3. We then connected bench 3's voltmeter across the A and B phases of the bench and brought the Variac to 33% of the full load. At 33% full load, 200 V AC was measured at the bench. This test proved that the Variac was capable of supplying the ITECH and step-up transformer.

Figure 8: Power flow control Variac

10 ITECH Initialization Test

In order to connect the 480 V AC secondary of the step-up transformer to the ITECH input, we modified four Hampton plug connectors to have males on one end and SV 5-5.5 spade connectors on the other. After connecting L1-H1 (A), L2-H2 (B), L3-H3(C), and GND-H0 (N) with the modified plug connectors, we brought the Variac to 30% and turned on the ITECH. After confirming that it turned on and that it needed a higher supply voltage, we increased the Variac until 380 V AC L-L was measured on the secondary of the step-up transformer.

We then confirmed that the output of the ITECH matched what was displayed on the control panel.

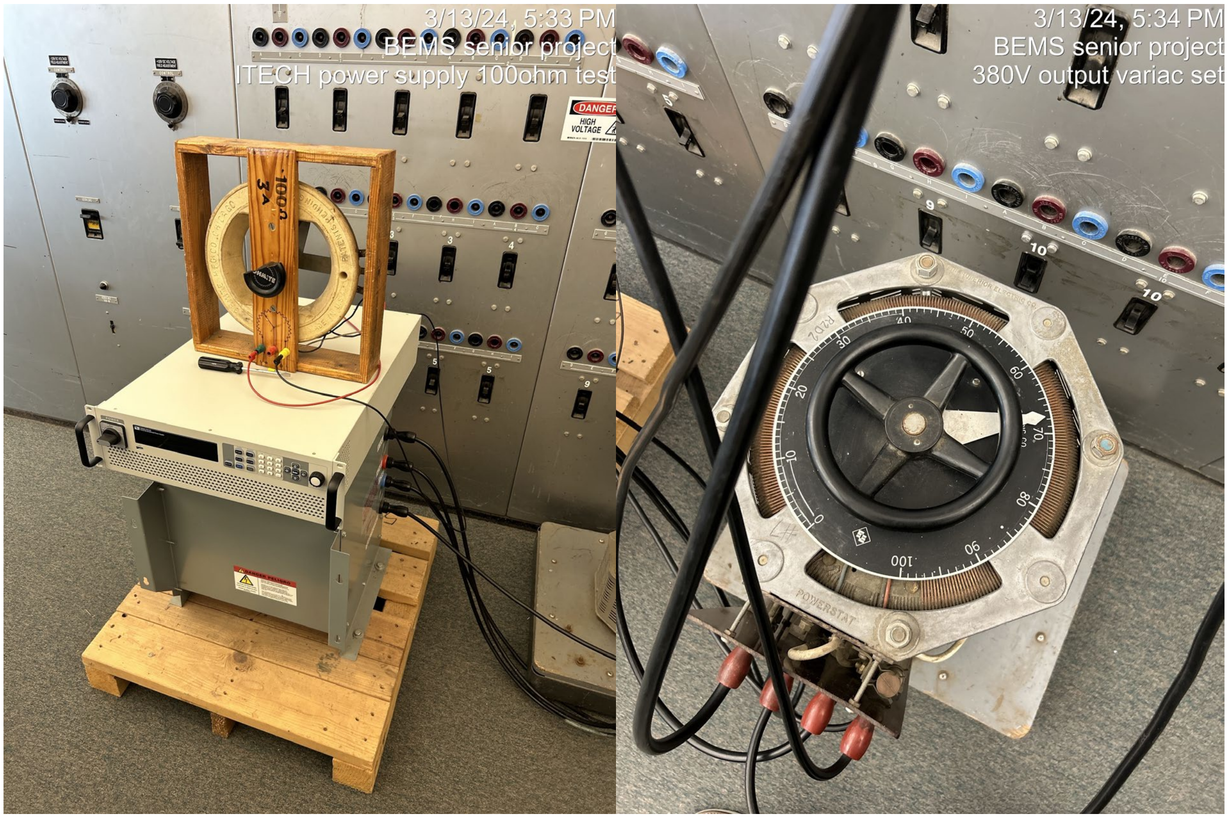

Figure 9: ITECH output test and Variac 380V output setting

10.1 ITECH Start and Run Procedure

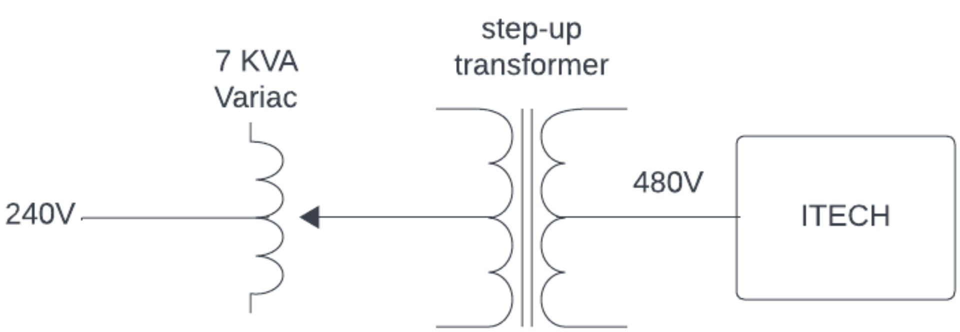

Figure 10: ITECH supply wiring diagram

To set up and run the ITECH, we designed and built the circuit above. 240V AC 3 Φ, connected to a 7KVA Variac, connected to a 240 delta to 480 wye transformer, and then connected to the ITECH's supply terminals. To turn on and run the ITECH, we do the following.

1) Connect the circuit to 240V AC 3 Φ.

2) Turn the Variac until a minimum of 380V L-L, or a maximum of 480V L-L, is measured at the input terminals of the ITECH. The minimum is achieved at about 70% on the Variac handle, as seen in *Figure 6*.

3) Once the minimum voltage is achieved, turn the power knob on the left side of the Variac to the on position, as shown below.

Figure 11: ITECH after start-up

From here, the ITECH acts as a conventional DC source. Its voltage, current, and power output can be set with the **V-set, I-set,** and **P-set** buttons.

It is important to note that using each of these buttons sets the supply as a constant voltage source, constant current source, or constant power source, respectively. Once adjustments are made, the On/Off button will be pressed to produce the selected parameters on the output terminals. The ITECH has many unique modes of operation, all of which can be found in its user manual. However, for our purposes, we only used its SAS photovoltaic emulator function. The steps we used to set and run the SAS are described below.

1) Press **Shift**, **I-set** (**Function**) to open the function selection menu

Figure 12: ITECH function select screen

2) Use the ↑/↓ **(up/down)** arrow keys to navigate to the SAS function and select it.

Figure 13: ITECH SAS function select screen

3) From here, the user can select *Static, Table, or Filter*. The table feature requires the software provided by ITECH to run, and the Filter feature reduces the input noise. For our testing, we chose to use the **static curve.**

4) Once *Static* has been selected, the user can select *Curve or User-defined.* The curve creates a fixed format PV curve, requiring input parameters Vmp, Pmp, and Solar panel material.

5) In order to have more control over our IV curve, we used the User-defined selection.

Figure 14: ITECH SAS User-define function select screen

6) From here, the user can select a saved curve from the *Open* menu.

7) Or, the user can edit the current selected curve using the *Edit* menu.

8) Once the desired curve is selected from the *Open* menu, the user selects the *Run* option.

9) The ITECH is now in SAS mode; pressing the **On/Off** button sets the output terminals to values determined by the imputed SAS settings.

Figure 15: ITECH in SAS User-defined mode

11 Stand-Alone Operation Test

The Tabuchi Installation manual instructs how to wire the system and what to do once construction is complete. Since previous teams had already wired the inverter, batteries, and fusing, we moved to the first test in the manual. The stand-alone operation test follows the following steps.

1. Check the wiring to solar panels.

    a. Confirm there is sufficient sunlight.

    b. Connect panels to the inverter.

    c. Confirm voltage is between 80-600V DC.

        i. During the initial test, we used the ITECH as a DC supply and would later switch to its SAS mode

2. Activate and check the power of the storage batteries

a. Confirm the [+] and [-] cables are not shorted and switch the battery breaker to the on position

b. Confirm that the operation lights on the batteries are green

c. Measure the voltage across the battery terminals inside the inverter to be within range

    i. 120VDC-200VDC for our model, the THD-S55P3BB-US

3. Start up the Inverter

    a. Set the DC disconnector switch to the ON position

4. Set remote control initial settings

    a. Set time and date

    b. Press save

    c. Return to home screen

5. Confirm communication between the storage battery and stand-alone operation.

    a. Check the remote-control display status for "manual grid stop."

    b. Press run stop

    c. Press the [RUN/STOP] button on the Remote controller.

        i. The button turns red.

The amount of solar power generated and the storage battery charge amount is displayed. The maximum rate of charge to the storage battery is 3.0 kW. (0 to 3.0 kW is shown depending on the amount of sunlight). If no load is connected to the inverter, a positive value shown under consumption represents the output power required to operate the inverter. When solar power is not being generated, power is discharged from the storage battery. On the storage battery, the MODE status indicator turns green when charging and orange when discharging. If the inverter does not start operation and any error message is displayed on the Remote Controller, turn off a DC-switch Disconnector of the inverter, a switch of the storage battery, and an AC breaker outside of the inverter. Then, wait for about 5 minutes until the remote controller's display turns off. Afterward, turn on the DC-switch disconnector of the inverter, the battery switch, and the AC breaker outside of the inverter. Resume steps 4 and 5.

6. Check voltage at stand-alone terminals
    a. 120V+/-6VAC for our model
7. Stop stand-alone operation test
    a. Press and hold the [RUN/STOP] button for 5 sec or longer to stop the operation. The status lamp goes out.
    b. Set the DC Switch-Disconnector on the inverter to the OFF position.
    c. Set the switch inside the storage battery to the OFF position and close the switch cover.

12 Grid Tied Operation Test

After the stand-alone operation test, we decided to move on to the Grid-tied test outlined in the installer's manual. We followed the following steps.

1. Confirm the current sensors are installed.
    a. Confirm that the grid-tied operation has been manually stopped.
    b. Press the [RUN/STOP] button on the Remote Controller to start the grid-tied operation. The status light turns green, and "GRID-TIED MODE" is displayed.

c. Confirm the storage battery charge on the Remote Controller. The value should be around 3.0 kW charging.

d. Press and hold the [RUN/STOP] button for 5 seconds or more to stop the grid-tied operation. "MANUAL GRID STOP" is displayed, and the status light turns off.

2. Check grid-tied operation.

a. Set the inverter DC Switch-Disconnectors in the ON position.

b. Set the grid-tied breakers to the ON position.

c. Press the [RUN/STOP] button to start the grid-tied operation. "GRID CONNECT→" appears for the duration configured by the setting value. Afterward, "GRID-TIED MODE" appears, and the status light turns green.

The initial operation is set as HOME BACKUP Mode. The battery is charged with about 3kW power until fully charged.

3. Check the Backup Load Panel connections.

a. Confirm that the breakers in the backup load panel are in the OFF position.

b. Confirm that the bus voltage in the backup load panel is at 120 V.

4. Confirm that the power recovery is active during a power outage.

a. Set both the main breaker and the grid-tied breaker in the Electrical Service Entrance to the OFF position.

The power outage error code should be displayed on the Remote Controller.

b. About 5 seconds after Step "a" is performed, a stand-alone operation starts.

"STAND-ALONE MODE" should be displayed, and the status light turns red.

c. Set both the main breaker and the grid-tied breaker in the Electrical Service Entrance to the ON position.

d. "GRID CONNECT→" should appear after step 3 has been performed. The display changes to "GRID TIED MODE" after the time configured by the setting value elapses.

e. Press and hold the [RUN/STOP] button of the Remote Controller for 5 sec or more to stop the grid-tied operation.

"MANUAL GRID STOP" should be displayed, and the status light should be turned off.

13 Tabuchi Operating Procedure

Tabuchi: Recommended setting internal DIP switches (SW1101) to "self-supply" (0001) configuration and to connect the resistive load to the stand-alone terminals.

Results: After setting switches and connecting 1.5K ohms to the load terminal, we observed 114VAC and 0.1A running through the load. We also learned to produce I-V curves manually through the ITECH control interface and contacted Tabuchi as well as Bright Power Incorporated in Vallejo for solar parameters. Tabuchi suggested using V= 300-400VDC, I = 6-8A, and FF = 0.8-0.9, and for the BPI we used Vmp=41.2V, Voc = 49.4V, Imp = 10.93A, Isc = 11.52A with four modules in series totaling Vmp = 164.8V, Voc = 197.6V, Imp = 10.93A, Isc = 11.52A.

14 Battery Test

The next test we decided to run was on the batteries. The lifespan of lithium-ion batteries is typically 2-3 years, so a test was necessary to see if they still functioned properly [7]. To test the batteries, we charged them for a while using the DC power supply, then attached a resistive load. We attached each battery to multiple resistive loads to ensure that the current stayed constant for a while. If the current through the load dropped off quickly, that would show that the batteries are unable to hold their charge properly. The test results are shown below.

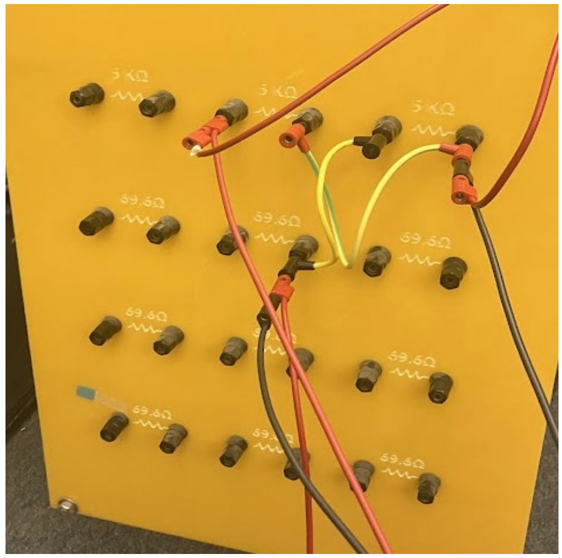

Figure 16: The load used for the battery test WITH two 5 kΩ resistors in parallel, a total load of 2.5 kΩ.

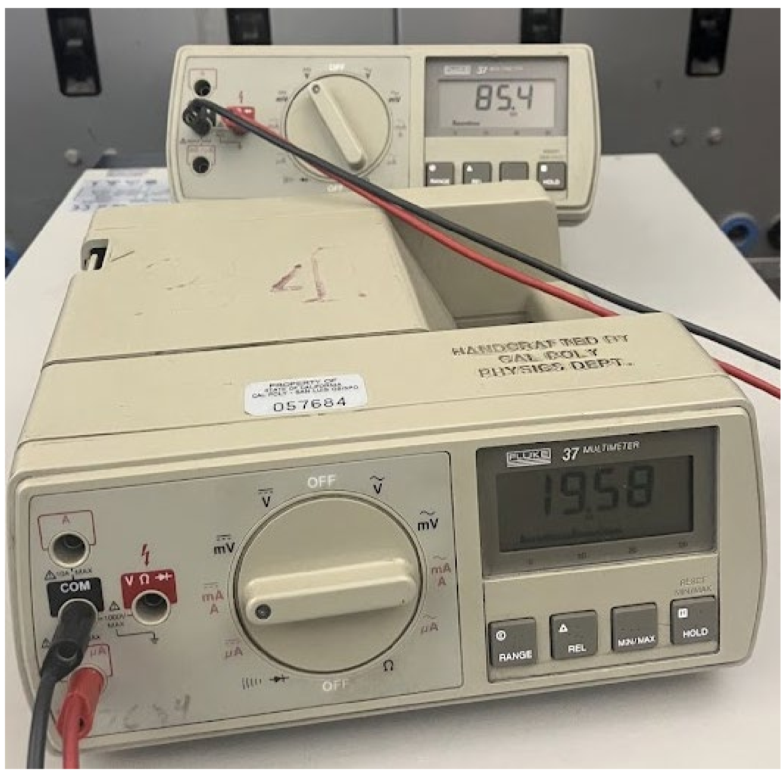

Figure 17: Voltage reading across battery 1 and current reading through the resistor when battery 1 is connected to the resistive load.

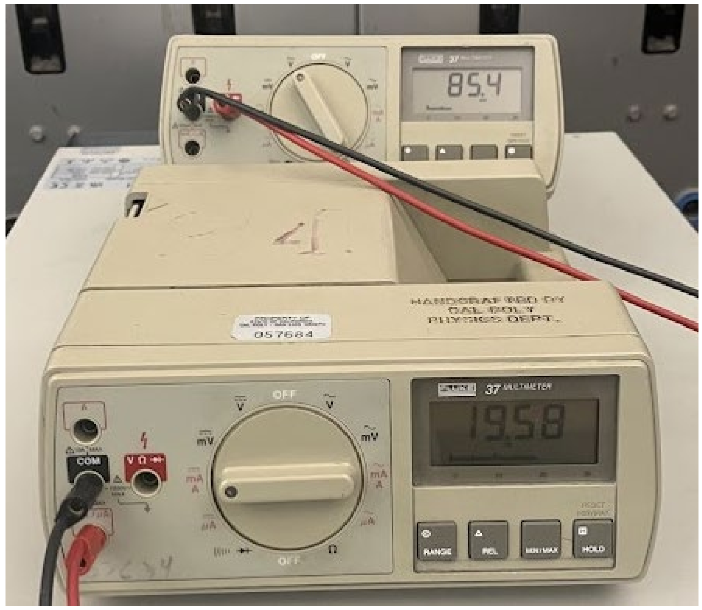

Figure 18: Voltage reading across battery-2 and current reading through the resistive load when battery-2 is connected to the load.

These results show that the batteries have similar voltages, and the same load resistance draws the same current from each of them. Also, these configurations were left to sit for a while, and it was shown that the current did not drop, which shows that the batteries were holding their charge properly. This test shows that the batteries were likely functioning properly, and more tests needed to be run to determine the fault.

15 Power Source Test

At this point, we were running out of things to test other than the inverter, so even though the power source was brand new, we decided to test it to make sure it ran properly. To do this, we created a simple circuit with the power source, resistor, and ammeter in series. The power source was set to 20 V, and three 69.6 ohm resistors were connected in parallel, creating a load of 23.2 ohms. With this configuration, the ammeter read .8 Amps, which matches the power source reading of .831 Amps and is similar to the expected value of .86 Amps. Then, when the voltage was dropped in half to 10 Volts, the ammeter reading and source reading for current both dropped in half as expected. The test setup and results are shown below.

Figure 19: Three parallel 69.6-Ohm resistors load configuration equal to 23.2 ohms.

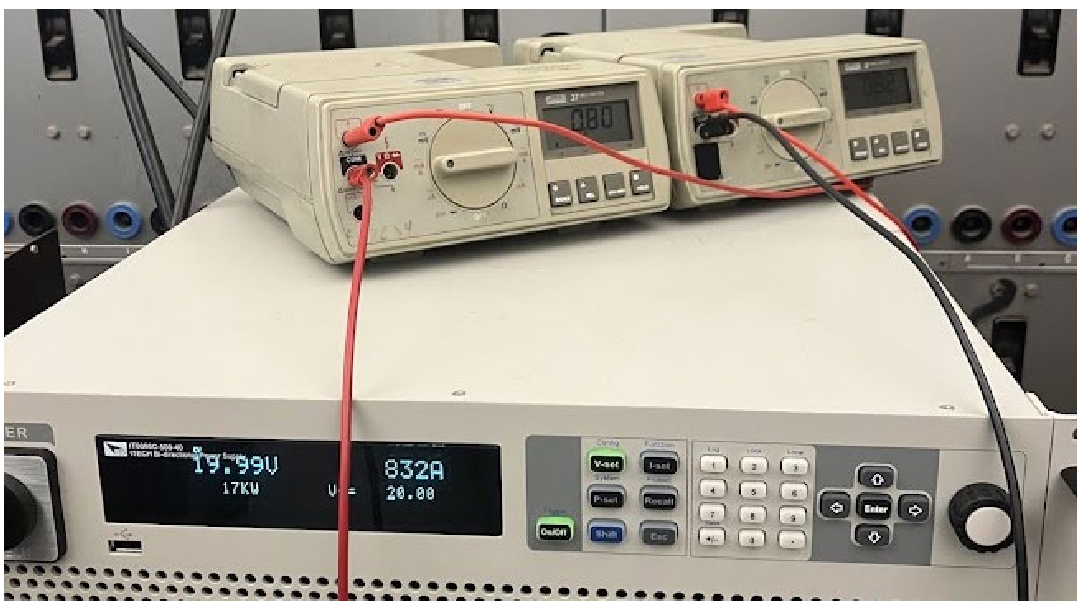

Figure 20: 20-Volt test. The ammeter and source current readings are consistent with the expected values.

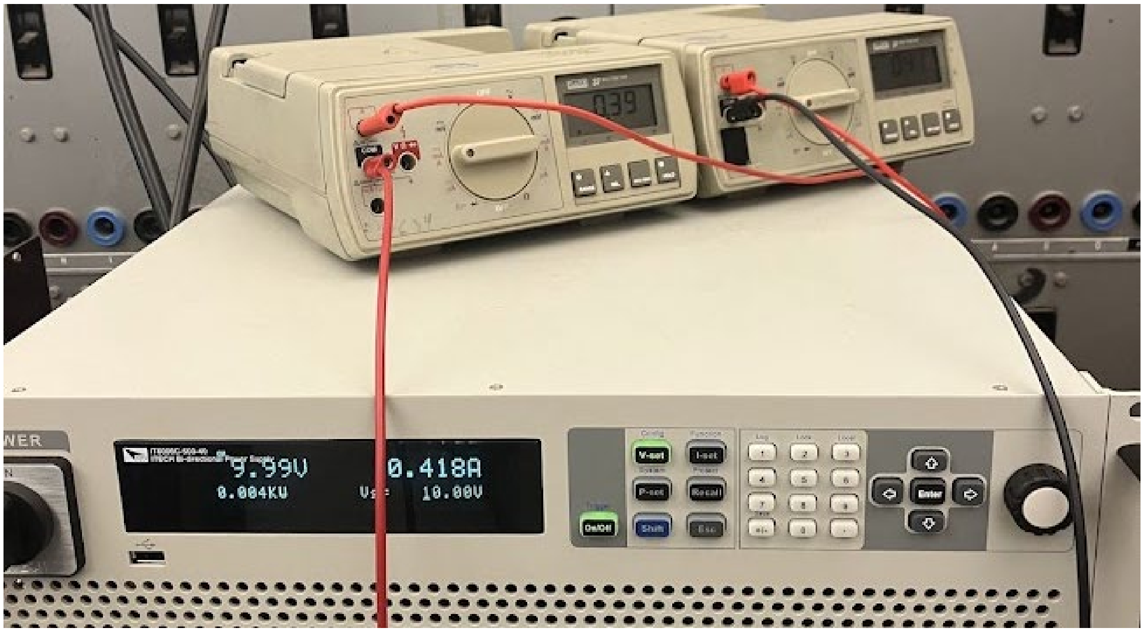

Figure 21:10-Volt test. Ammeter and source current readings: The current drops by ½ as expected.

This test did not serve to prove whether the power source functions properly as a PV emulator, but at this point, all that was needed was a simple DC source. This test did show that the power source functioned properly for this purpose, as it outputted the expected voltage and current. After testing the power source, Tabuchi asked for the IV curve we were using in order to determine what other tests to run. At this point, we had been using the ITECH power source as a simple DC power source and had not set it up as a PV emulator. Tabuchi recommended that we use V= 300-400VDC, I = 6-8A, and FF = 0.8-0.9 for the IV curve. Using these parameters, we set the ITECH supplies SAS to Vmp = 350 Imp = 7A, Voc = 400V, Ioc = 8A. Once we turned on the SAS with the new parameters, we saw no change. We also attempted to run the inverter with the SAS parameters sent by BPI (Vmp=164.8V, Voc=197.6V, Imp=10.93A, Isc=11.52A).

16 Remote Communication Cable

During troubleshooting, our team and the engineers at Tabuchi Electric narrowed our focus to the possibility that the cable remote controller and the inverter may have been damaged. To test the condition of the cable, we disconnected the remote controller from the cable and removed the inverters from the panel and protective cover, exposing the full run of the cable. Using a multimeter to test the continuity of each of the four communication lines, we found that each was intact and conducting.

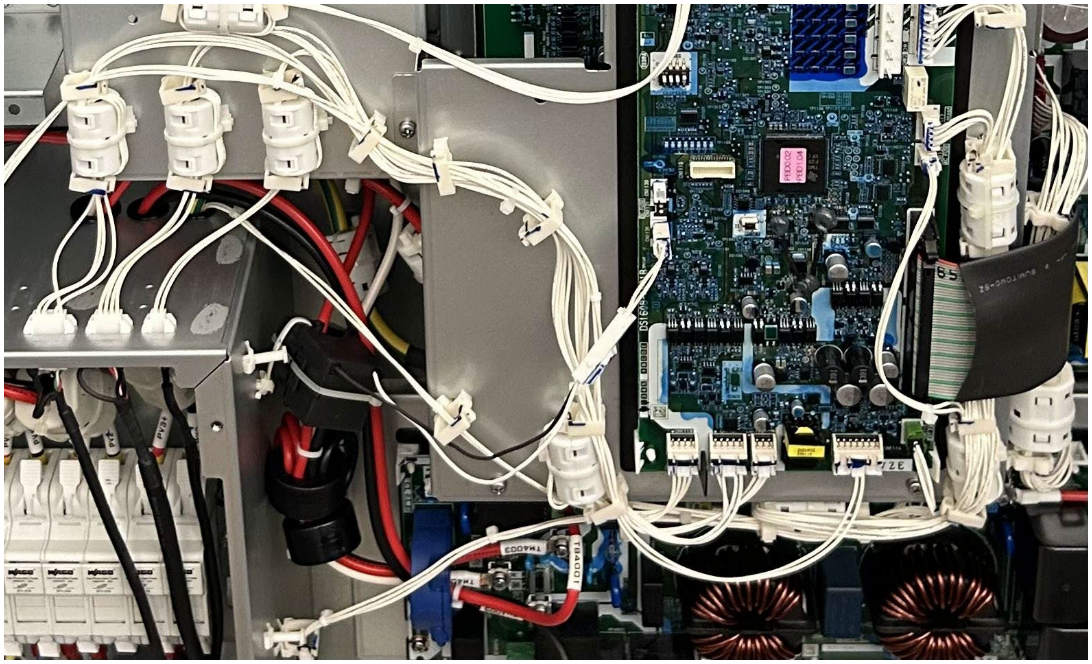

Figure 22: Remote control internal communication line overview

17 Specs

Product name: Storage Battery Unit

Rated Voltage: 86.4V

Rated Capacity: 9.89 kWh

Battery Type: Lithium Ion

Manufacturer: Tabuchi Electric Co.

Product name: Step-Up Transformer

Phase: 3

Rated Voltage input: 240V

Rated Voltage output: 480V

Rated power: 15kVA

Rated primary current: 36.1A

Configuration: Dy11

Percent Loss: 4.7%

Weight: 215 lbs.

Frequency: 60 Hz

Manufacturer: Hammond Power Solutions

Product name: Remote Controller

Rated Voltage: 15V

Rated Power Consumption: 3.1 W

Manufacturer: Tabuchi Electric Co.

Product: IT6006C-500-40

Efficiency: 92%

Working Temp: 0-50 degrees C

Input three-phase Voltage: 342-528 V

Input Current: L1 = 20A, L2 = 20A and L3 = 0A

Maximum Input Apparent Power: 6.6kVA

Frequency: 47Hz~63Hz

Output Voltage: 0 - 500 V

Output Current: -40 to 40 A

Output Power: -6 to 6 kW

Output Resistance 0 to 1 Ohms

Product name: Hybrid Solar Inverter

DC ratings for PV inputs (3 total)

Rated Input Voltage: DC 80-550 V

Rated Current: DC 12 A

Max input voltage: DC 600V

Max input current: 15A

AC ratings for the grid-tied:

AC voltage: 211.2-254V

Nominal Frequency: 60 Hz

Output voltage: 240V

Input current: 23.4A

Max output current: 22.9A

Max Power out 5500W

Stand-alone:

AC voltage: 114-126V

Nominal Frequency: 60 Hz

Output voltage: 120V

Max output current: 27.5A

Max Power out 3300VA

Charge controller:

Max continuous output current: DC 16.5A

Max Charge/discharge current: DC 26A

Output voltage: DC 178.2V

Charging output voltage range: DC 120-200V

Manufacturer: Tabuchi Electric Co.

Product name: FLIR C3-X

IR resolution: 128 x 96 pixels

Thermal Sensitivity: < 70 mK

FOV: 54 deg x 42 deg

IFOV: 7.9 mRad/pixel

Image Frequency: 8.7 Hz

Operating Voltage: 3.7 V

Battery Capacity: 1800 mAh

Operating Temperature Range: -10 to 50 degrees C

Manufacturer: FLIR

Product name: Connection Box Charge Controller

Input Voltage Range: 120-200 V

Maximum Current: 26 A

Operating temperature range: 0-40 degrees C

Manufacturer: Tabuchi Electric Co.

Product name: Variac Autotransformer

Rated Input Voltage per phase: 120 V

Rated Output Voltage per phase: 0-140V

Rated current per phase: 50A

Nominal Frequency: 50/60 Hz

Rated power: 7kVA

Manufacturer: The Superior Electric Co.

18 Conclusion

BESS systems store and provide renewable energy, offsetting the duck curve. Our system was meant to consume power from an emulated PV grid, store the energy, and expel it later as AC power.

19 Bibliography

[1] R. Bowers, E. Fasching, K. Antonio, "As solar capacity grows, duck curves are getting deeper in California," eia.gov, June 21, 2023. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=56880. (Accessed Oct. 10, 2023)

[2] L. Mari. "National Electrical Code Basics: Overcurrent Protection Part 1." eepower.com https://eepower.com/technical-articles/national-electrical-code-basics-overcurrent-protection-part-1/#:~:text=National%20Electrical%20Code%20(NEC)%20Article,damage%20to%20the%20electrical%20components (accessed Oct. 26, 2023)

[3] "What Is a Safety Switch (Disconnect Switch)." psicontrolsolutions.com https://www.psicontrolsolutions.com/blog/safety-switch-disconnect-switch/#:~:text=Fusible%20safety%20switches%20combine%20fuses,provide%20no%20circuit%20protection%20capability. (Accessed Oct. 26, 2023)

[4] "Inrush Current," *Sunpower Electronics UK*, Jul. 01, 2014. https://www.sunpower-uk.com/glossary/what-is-inrush-current/ (accessed Jun. 10, 2024).

[5] Y. N. Myint, M. Caraballo, C. Gonzalez, W. Hoang, P. Tafoya, "Reliability Measurement for Grid-Connected Solar System Part 1: Improve Grid-Connected Solar System By Adding Battery Energy Storage System (BESS)," California Polytechnic University, San Luis Obispo, February 2023.

[6] "IT6000C Series Bidirectional Programmable DC Power Supply," ITECH, New Taipei City, Taiwan.

[7] Tektronix, "Lithium-Ion Battery Maintenance Guidelines."

20 Appendix

A. Analysis of Senior Project Design for Battery Energy Storage System

Student's Name: Student's Signature:

Alec MacLean:

Kaylen Schwartz:

Kyle Begley:

Advisor's Name: Advisor's Initials: Date: Dr. Majid Poshtan: MP :6/12/2024

21 Summary of Functional Requirements

The Battery Energy Storage System (BESS) is a system that creates energy storage capabilities for small-scale solar panel installations, such as for households. The system is very liable to faults, shorts, and arcs, which need to be mitigated to ensure the system is safe, reduce damage to the system, and allow it to be grid-connected. The main aspect is integrating system protection to mitigate these risks.

22 Primary Constraints

Making the system grid connected adds many constraints to the design. Working with high-energy storage capabilities also adds constraints to the design to make the systems safe. To make the system grid-connected and safe, some system protection needs to be implemented.

22.1 Economic

Adding solar panels to homes allows homeowners to save money on their electricity bills. This BESS allows homeowners to save even more money by using their solar energy during peak load times, when electricity is more expensive, instead of only when the sun is out, which is when electricity is already cheaper. Although there is a high up-front cost, over time, this product saves the customer money. The original system cost $17576 and included labor, batteries, panels, a smart inverter, protections, and a rack. This price is comparable to systems with similar capacity on the market. Over its 3 to 10-year lifespan, Tabuchi claims that its batteries and smart inverter could save up to 55% on their customer's energy bills [1][6].

The system's batteries last up to 10 years and cost $2204.42 per battery to replace [7]. This project has been developed for the past year and is estimated to take another 6 months to complete. Once the project is completed, the system will be left in Cal Poly's power conversion lab, where it is ready to be connected to the grid.

22.2 Case of manufactured on a regular basis.

A device of this nature would not be manufactured on a regular basis. Although the concept would remain the same across each system manufactured, its specifications would fit each customer's needs. The Tabuchi Smart Inverter can handle a maximum input power of 2500 watts and can manage one to two 10 kWh batteries. Due to the variability in generation capacity and storage capacity, each one would need to be made to fit the customer's needs.

22.3 Environmental

The main environmental impact of this product is more positive than negative. The product makes solar energy more efficient than it usually is so that we are not wasting so much of it. The main natural resource used by our project is the sun. The project simply aims to make the sun a more efficient source of power than it already is. This is great since solar energy is an incredibly sustainable form of energy already, so relying on it more is quite a positive

22.4 Manufacturability

The batteries, smart inverter, and panels come prebuilt. Manufacturing the system would only require the assembly of these components by someone with enough electrical engineering knowledge to do so responsibly. The only foreseeable challenges in manufacturing systems like this would be the proper installation of the building and the grid. As well as installing the system in an aesthetically pleasing manner. For the time being, our system is only a prototype that has been assembled out of a 12-gauge galvanized strut channel and wood. A system ready for the market would have a cleaner look.

22.5 Sustainability

The system addresses issues with renewable solar energy by allowing it to be used on demand rather than only when the sun is out. At times, solar panels can produce an excess amount of power for the system, so this allows any excess to be stored and used later rather than having to be wasted.

This makes their implementation more energy efficient and able to replace more non-renewable energy sources. One issue, however, is that the system uses lithium-ion batteries. Lithium-ion is a non-renewable resource that requires mining, which has negative impacts on the environment and people around it. The mining process creates droughts, pollution, and ecological damage [5]. As well, forced labor and child labor are often used in lithium mining [5]. These batteries also have a lifespan of about 3 to 10 years, depending on their use [1]. Although lithium-ion batteries are recyclable, less than 5% of these batteries are recycled in the United States, as recycling plants have limited capabilities [2]. There are other options for energy storage, such as hydroelectric or mechanical, that don't require the use of lithium-ion, but these systems are on a much larger scale and would not work for single-household energy storage [3].

22.6 Ethical

The main ethical focus of the project is ensuring that it functions safely. This upholds the IEEE Code of Ethics code 1.1, "to hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, to protect the privacy of others, and to disclose promptly factors that might endanger the public or the environment" [4]. However, there are ethical concerns with the use of lithium-ion batteries, as lithium mining can often involve forced labor and child labor [5].

22.7 Health and Safety

The system protection aspect of the design mitigate any danger that the use of this product could pose. Without system protection, the high voltage and energy storage capabilities could pose a threat through electrocution, starting fires, or damaging the power system.

22.8 Social and Political

The product has the greatest impact on the customer, as they benefit the most from the cost reduction on their energy bill. However, if more BESS units are implemented for households that have solar panels, power companies and everyone will be impacted. Power companies are impacted because BESS units can reduce the stress on the system that ramping up to peak loads requires. Also, if more BESSs are used, renewable energy will be used more effectively and efficiently, and the use of solar panels will be more incentivized. This impacts everyone as it lessens the use of non-renewable energy sources and is better for the environment. However, this global impact can be small, as there are many other causes of climate change, and BESS will likely not have a large impact on climate change on its own.

It also has an impact on the people who live near lithium mining because as more BESS units with lithium-ion batteries are made, more ecological damage happens to these areas. For these people, this damage is more impactful than the environmental benefits that come from making this BESS.

22.9 Development

In this project, we learn more about power system protections and how to employ them on a grid-tied BESS. We study fault analysis and how to protect our system from multiple types of faults. We also learned about solar simulation, modeling solar panels in electric circuit analysis, and using simulation to determine the best placement for solar panels.

23 Engineering standards

During this project, we applied the IEEE standards and the National Electric Code.

24 References

1) Patrizio, "The environmental impact of lithium-ion batteries – how green are they really?" Data Center Knowledge | News and analysis for the data center industry, May 23, 2023. https://www.datacenterknowledge.com/hardware/environmental-impact-lithium-ion-batteries-how-green-are-they-really#%20A%20Ways%20to%20Go (accessed Dec. 08, 2023).

2) M. Jacoby, "It's time to recycle lithium-ion batteries," American Chemical Society. Accessed: Dec. 08, 2023. [Online]. Available: https://cen.acs.org/materials/energy-storage/time-serious-recycling-lithium/97/i28

3) "What is renewable energy storage?" National Grid Group. https://www.nationalgrid.com/stories/energy-explained/what-is-renewable-energy-storage (accessed Dec. 08, 2023).

4) "IEEE Code of Ethics," IEEE Code of Ethics. https://www.ieee.org/about/corporate/governance/p7-8.html (accessed Dec. 08, 2023).

5) "The Social and Environmental Impacts of Lithium Mining," Borrum Energy Solutions. https://borrumenergysolutions.ca/blogs/blog/the-social-and-environmental-impacts-of-lithium-mining (accessed Dec. 08, 2023).

6) T. Kenning, "Tabuchi's home energy storage can 'adapt' to changing policy landscapes," energy-storage. News, https://www.energy-storage.news/tabuchis-home-energy-storage-can-adapt-to-changing-policy-landscapes/ (accessed Dec. 8, 2023).

7) "Ecco 48v 206ah 9.89kWh lithium-ion battery," Solar Warehouse SA, https://solarwarehousesa.com/products/ecco-48v-206ah-9-89kwh-lithium-ion-battery (accessed Dec. 8, 2023).

8) C. IEEE Standard for General Requirements for Dry-Type Distribution and Power Transformers

9) https://drive.google.com/file/d/1O-mdY45f4jf4pAACubTF9f_1LNiKTJNj/view?usp=drive_link