Apollo Photovoltaic Overview and Assessment

A Senior Project
presented to
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California Polytechnic State University - San Luis Obispo

In Partial Fulfillment
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Bachelor of Science in Electrical Engineering

by

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Abstract

This senior project aims to take the various data sheets provided to us by PIVVIR Solar, the organization in charge of Apollo photovoltaic power plant, and perform an overall assessment as well as condensing the information into a more digestible and concise document. Currently, the documents provided to us by PIVVIR Solar are scattered and disorganized. Our goal is to take what we understand about photovoltaic power plants and combine it with the Apollo plant's datasheets and summarize everything into one focused document that more readers can understand.

Introduction

Solar energy represents a virtually unlimited source of power; as long as the sun shines on the Earth, its energy can be used to power our homes and machinery. Harnessing solar energy is possible through the use of solar cells. These devices utilize light-sensitive semiconductor material to convert light energy into electric potential energy, roughly around 0.6 volts [1]. Solar cells can be connected together into panels to produce larger voltages capable of powering electrical systems and other high power applications.

Although the efficiencies of solar energy vary, in 2019 the most efficient solar panel had an efficiency rating of 22%. Although the initial cost of implementing solar energy is significant, not only do the savings make up for it but as the installation process becomes more straightforward these cost will go down in the future. Since the year 2000, the Senate Bill 1345 "directed the Energy Commission to develop and administer a grant program to support the purchase and installation of solar energy and selected small distributed generation systems” [2]

Photovoltaic (PV) systems are a popular renewable energy option due to its ability to convert solar energy into electric power. This particular plant generates power directly to a Pacific Gas & Electric (PG&E) substation, making it a grid-tie photovoltaic system. The substation acts as the storage battery as the plant generates solar power. Since the solar panels generate DC power, it must be converted into AC power using a grid-tie inverter before it is stored in the grid. However, photovoltaic systems can also directly power the desired load, such as a residential house, based on demand.

The Apollo Photovoltaic plant was completed in 2018 by the PIVVIR company, with the twofold purpose of providing 4.5 megawatts of renewable energy and serving as an educational tool for students and faculty at California’s universities. Technical documents and record drawings, as well as opportunities for site visits, were made available to students pursuing advanced education and projects relating to the topic of photovoltaic systems.

Our senior project’s objective is to interpret the many different components that went into designing this solar power plant, and to create a straightforward and understandable document to aid future students in their work with the Apollo power plant. This process includes individual research into a database of documents on the design and construction of the Apollo plant, as well as analysis of the factors that impacted PIVVIR’s design of the plant.

Background

In early 2018, a ceremony celebrating the completion of the 18.5 acre AC Solar Farm. This farm was an effect to aid the cause of the California's Global Warming Solutions Act of 2006 goal of reducing the states greenhouse emission by 80% by 2020. Generating more than 11 million kWh per year, this power plant will be able to provide a significant amount of a facilities energy usage and is absolutely a step in the right direction for a cleaner, greener future.

In previous years as a start to a path to alternative energy, Cal Poly actually implemented a 135 kW solar array above the Engineering West building. Through a similar process in terms of how Cal Poly's relationship with Apollo, the University agreed to have SunEdison handle a significant amount of the design process from start to finish, however the agreement was slightly altered in that the university would be buying the energy produced from their grid. Although saving over thousands of dollars in terms of energy, this was still energy that was indirectly towards the end goal that Apollo accomplishes.

This project was also possible due to the collaboration with a provider of solar energy within the public, utility-scale, and public sector. This company has aided the entire development process of these projects from engineering, maintenance, financing, and design independently which provides a direct line to support and efficient quality within this process.

A significant audience for this solar farm would actually be students. As both Electrical Engineering Students and Faculty will be able to apply experiments or test their designs and understand how a real life application of a photovoltaic system would perform.

Not only is the objective of this report to set the initial stepping stones of introducing the project to future students within Cal Poly, but to offer a foundation of further understanding of photovoltaic systems towards the current available curriculum. Currently, helpful classes to supplement any further research towards these classes would be Sustainable Electric Energy Conversion and Advanced Solar-Photovoltaic Systems Design to have a background understanding regarding solar energy and its theoretical implementation.

Overview

In this report, we will focus on the design and implementation of the Apollo photovoltaic system through the analysis of the key components of the system. The following sections will provide explanations and analysis of the Racking, Panelboards, Modules, Grounding, Inverters, Switchgear and Switchboards, Transformer, and Monitoring subsystems.

Racking

Racking is the initial component that is decided within a PV System design, with single vs dual systems having different pros and cons; and depending on the specific project requirements a certain type of system is more applicable than others. With the Apollo plant, the expectation was to provide a financial return within a ten year period of the initial installation, thus allowing PIVVIR to follow Duratracks Solar Tracker design.

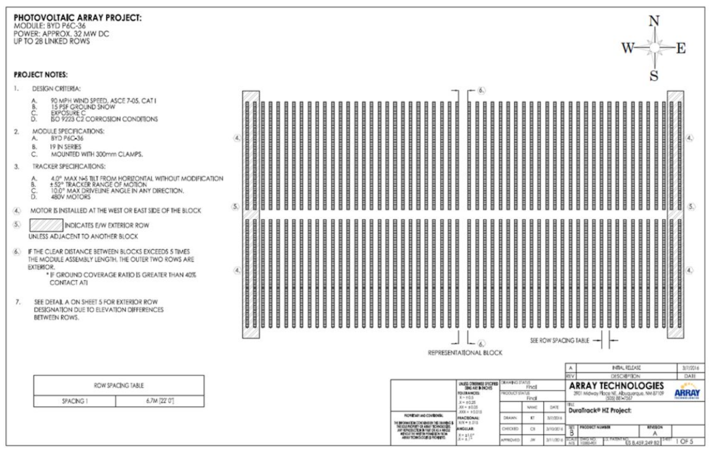

Figure 1: Racking Document Showing Duratrack’s Design

Having a horizontal single axis allows the site receive an optimal amount of energy not only by following the sunlight throughout the day, but also by backtracking and avoiding the shade created by other panels. Connected by a 3-Phase Motor, the figure below exhibits the a system which has proven to maintain its durability for thirty years, regardless of harsh natural conditions.

Panelboards

Panelboards also are varied based on system specifications. The Modelo plant guide involves not only numerous helpful one line diagrams and panel placement drawings but also relevant measurements of inverters. The implemented Transformer leading into these panelboards is the PVI 50/60 TL, a transformerless three-phase inverter that not only logs internal data, but also is capable of remote firmware upgrades and diagnostic reviews.

For this specific section however, the Tallmax Plus is also referenced.As a ground-mount installation, it is a monocrystalline module that is consistently utilized for large scale PV systems to interface between panelboards and further modules below. When dealing with PV systems in industry, it is significant to accommodate 120% of the estimated amperage fed to the loads, to prevent creating a panelboard receiving more energy than it can handle, negatively leading to fires of system failures. This can be achieved either by downsizing a main breaker or also installing a PV breaker to the inverter system before the panel reaches the main board.

Modules

A solar module is composed of several solar cells, which are typically arranged in a 6x10 formation. These cells harness energy from the sun to generate electricity. Depending on the efficiency and power output of the module, a module can produce 100-365 watts of DC electricity.

There are three main types of solar cells: monocrystalline, polycrystalline, and thin-film cells. This solar plant utilizes modules outfitted with polycrystalline cells. Polycrystalline, also known as multicrystalline, cells are easier to manufacture versus monocrystalline cells and also waste less silicon during the production process. As a result, polycrystalline modules cost less. Instead of using a single silicon crystal, cell manufacturers melt several fragments of silicon together to form the module wafers. Since each cell contains several crystals, electrons have less room to move. This causes the polycrystalline cells to have an efficiency of 13-16%, which is lower than monocrystalline cells, which have an efficiency of 15-20% [3]. However, cells that are more efficient also cost more. Another advantage that polycrystalline cells have over monocrystalline cells is that polycrystalline cells have a slightly lower heat tolerance. This means that polycrystalline modules have a slightly higher temperature coefficient than monocrystalline panels. Thus, as the temperature increases, the power output of the cells will not decrease as drastically [4].

This solar plant uses the REC TwinPeak 2S 72 series solar panels. These panels are polycrystalline yet have up to 17.4% efficiency, which is higher than typical polycrystalline panels. The panels are made of 0.13” solar glass with anti-reflection surface treatment, the back sheet is composed of highly resistant polyester, the frame and support bars are made of anodized aluminum. At standard temperature and conditions, the panel's nominal power is 350 Wp, the nominal power voltage is 38.9 V, the nominal power current is 9 A, the open circuit voltage is 46.7 V, and the short circuit current is 9.4 A. The dimensions of the panel are 78.9"x39.4"x1.2" and weighs 48.5 lbs [5].

Grounding

Every single non-current-carrying metallic part of the PV power plant must be grounded. This includes components such as array mounts, PV module frames, equipment enclosures, junction boxes, and conduit. There are 2 types of grounding in PV systems, *equipment grounding* and *system grounding*. Equipment grounding electrically connects all exposed non-current carrying metal parts of the electrical system together and connects these metal parts to the Earth or *ground*. The purpose of equipment grounding is to prevent electrical shock and fire hazards in metal components such as in the PV modules [5]. In system grounding, one of the current-carrying conductors is connected to the equipment grounded system and the rest is connected to Earth. The current-carrying conductor that is connected to the equipment grounded system is known as the *grounded conductor* or *grounding conductor.* The connection between the grounded conductor and the equipment grounding system is known as the *system bonding jumper* in the NEC. Only one system bonding jumper is allowed in each separate electrical system in which the system grounded conductor is isolated from the grounded conductors of the source or other systems.

The National Electric Code (NEC) enforces specific sized conductors and types of connectors that must be used for grounding equipment. [6] These components are specifically called grounding conductors and grounding connectors. Because the grounding conductor is only connected to the ground at one point, current will flow in the grounded conductor but will not flow in any other grounding conductor since there is no other closed circuit where the current can flow.

“Using approved mechanical connectors and bonding washers are two popular bonding and grounding methods. Mechanical connectors can be mounted to a module or racking frame with lay-in features which accept a copper wire that bonds and grounds components. Bonding washers are used in conjunction with hold-down clamps and bolted joints on the racking system. The washer fits over the bolt, and when tightened to the prescribed torque value, pierces through oxidized or coated surfaces, providing a solid bond between metal parts.” [5]

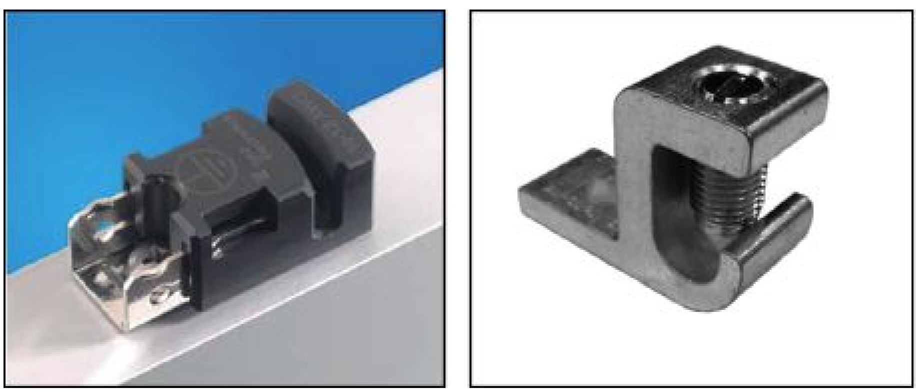

Figure 2: Standard grounding lug examples.

Since each module has a different manufacturer with various sizes, every different frame and clamp used for grounding is different depending on the module.

Module Manufacturer	Model Numbers	Frame	Clamp
BYD	XXXP6C-36 Series -3BB	40mm	300mm 600mm
Canadian Solar	CS6X-xxxP F-Type Frame	40mm	300mm 600mm
Celestica	C72QxxxM Frame: FRA-1330-01 (Robin)	45mm	300mm 600mm
Celestica	C72QxxxM Frame: FRA-1256-01 (Jay) Frame: FRA-1051-01 (Magpie)	50mm	300mm 600mm
China Sunergy (CSUN)	CSUNxxx-72P	50mm	300mm
ET Solar	ET-P67231xxx	40mm	300mm
Hanwha Q CELLS	HSL60P6-PC-Y-zzz (Q) HSL72P6-PC-Y-zzz (Q)	40mm	300mm 600mm
Hanwha Q CELLS	Q-Pro L G3 / G3.1 310-315 Q-Pro L G2 305-310 (rev. 1)	40mm 42mm	300mm 300mm
Hyundai	HiS-MxxxTI HiS-SxxxTI	50mm 50mm	600mm 600mm
Jinko	JKMXXXX-60 Series JKMXXXX-72 Series	40mm	300mm 600mm
LG	LGxxxN2W-B3 LGxxxN1C-G4	46mm 40mm	300mm 600mm
REC	RECXXXPE72 Series	45mm	300mm 600mm
RECOM	Amur Leopard RCM-XXX-6PA Series	40mm	
Renesola	JCxxxM-24/Ab Series	40mm	300mm 600mm
SolarWorld	SWxxx XL Mono	33mm	300mm 600mm

Figure 3: Certain module manufacturers and their specific sizing specifications

Inverters

An inverter is a device that converts DC power into AC power. Inverters are essential for photovoltaic systems because the power generated from solar panels are DC, while residential and commercial buildings run on AC power. Thus, an inverter is used in between the solar panel and desired load so that the solar energy can be used. The two main types of inverters used are string inverters and microinverters. The type of inverters that this solar plant in particular uses are string inverters. This is because solar panels are typically installed in rows, called “strings”. A single inverter can be connected to multiple strings of modules. These strings carries the DC power generated from the modules to the inverter, where it is then converted to AC power to be used as electricity. String inverters are optimal for installations without shading issues and panels that are all facing the same way. This is because if a single module is shaded for a significant portion of the day, all of the other modules can only produce as much power as the lowest-producing panel. String inverters cannot adapt to shading issues, however, they are much less expensive than microinverters [7].

This solar plant utilizes the PVI 60TL three-phase transformerless string inverters from Yaskawa Solectria Solar. These inverters are grid-tied and come with AC and DC disconnects, three MPPTs, a 15-position string combiner, remote diagnostics, remote firmware upgrades, and various protection features. The Yaskawa inverters are also National Electric Code (NEC) 2014 compliant, which means that they are capable of sensing arc faults and can shut down rapidly, and can be installed in 0-90° orientation. The DC input of the inverters have an absolute maximum open circuit voltage of

100VDC, an operating voltage range of 200-950 VDC, a max power input voltage range of 540-850 VDC, a maximum operating input current of 38 A per MPPT, a maximum available PV current of 60 A per MPPT, a maximum PV power input of 90kW (30 kW per MPPT) and a start voltage of 330 V. The AC output of the inverters have a nominal output voltage of 480 VAC, a continuous output power of 60 kW, a maximum output current of 73 A, a maximum backfeed current of 0 A, a nominal output frequency of 60 Hz, an output frequency range of 57-63 Hw, and a power factor of 1. The panel has a peak efficiency of 99%, a CEC efficiency of 98.5%, and a tare loss of 2 W. The panel can operate at -22°F to 140°F, though derating occurs over 122°F, at relative humidities of 0-95%, and at altitudes of 13,123 ft, though derating occurs over 9,842.5 ft. While the inverter operates, it can produce up to 55dBa at 1 m at room temperature [8].

Switchgear and Switchboards

The majority of modern electric power systems rely on switchgear and switchboards. Both switchgear and switchboards monitor the state of the system, providing statistical and technical data about the system's operational status, as well as contain measures to protect the system from overloads and faults. They often consist of circuit breakers, current transformers, measuring equipment, and a protection relay. The main difference between switchgear and switchboards is that switchgear typically deal with voltages up to 350 kilovolts, and switchboards typically deal with voltages below 600 volts.

The Apollo system utilizes one 12kv switchgear and two solar AC switchboards. With the Apollo system divided into two subsystems, System A and System B, two switchboards are required to cover the entire system. Switchboard A receives AC current from Panelboards A1 through A7, and Switchboard B receives current from Panelboards B1 through B6. The switchboards monitors the system through these currents and, if a fault or surge has occurred, protects the subsystems from electrical damage and prevents faults from influencing other parts of the system. The currents are passed through the Solar Generator Disconnect Switches before reaching the New Solar Transformers. From there, both subsystems feed into the 12kv switchgear [9].

As the name implies, the 12kv Switchgear sees input voltages of 12,470 volts, and three phase input currents of 1200 A. Two 2500 KVA transformers feed approximately 12,470 volts into the switchgear, and are followed by general purpose fuses and load break switches rated for 15,000 volts. The currents from each transformer combine before feeding into the switchgear. A 600:5 current transformer passes a portion of this current to a Shark meter, a revenue and power quality metering device; two SEL relays feed this current back into the circuit breaker to open, close, or maintain the primary current. The remainder of the current passes through an AC circuit breaker (labeled “52” on the single line diagram [10]) rated for 15 kilovolts and 600 amps. A portion of the outgoing current travels through a current transformer, which passes 120 to 240 volts to the breaker control, battery charger, space heater, and interior lightning systems. From here, the circuit joins the PG&E grid.

Figure 4 : GE Spectra Series Switchboard [5]

PIVVIR employed GE brand Spectra Series Switchboards, a common variety for systems of this size. These switchboards utilize 800-4000A insulated case circuit breakers, 400-1200A molded case circuit breakers, 800-4000A high pressure contact switches, 400-1200A fusible switches, 800-4000A bolted pressure switches, and 800-5000A low voltage circuit breakers [5].

Transformers

Power systems of all varieties commonly employ two types of transformers: current transformers and step up voltage transformers. Current transformers are used in conjunction with relays to sample the output current and to provide overcurrent protection. The 600:5 current transformers utilized in the Apollo System's switchgear transform the input current of approximately 1200 amps into a current in the range of 10 amps; this current represents the normal current seen by the SEL relays of the switchgear, which trip when a current of approximately 750 amps is observed [11].

Figure 5 : CG Power Systems Power Transformer [9]

The primary function of the set up voltage transformers in this system is to convert the 240-480 volts generated by the solar arrays into a distribution voltage of 12,470 volts. The transformers used in this system were supplied by CG Power Systems USA, and were designed using the IEEE/ANSI design standard. The transformers feature a delta configuration on the 12,470 volts High Voltage winding, and a grounded wye configuration on the 480 volts Low Voltage winding. Two voltage transformers are used for the Apollo system: one for System A and one for System B. Both transformers are implemented before the switchgears of each system to provide the 12 kilovolts needed for the switchgears to operate.

Monitoring

A photovoltaic monitoring system collects and analyzes a number of parameters being measured in a photovoltaic plant to monitor and evaluate its performance. Also, the monitoring system keeps track on various electricity generation faults. The simplest monitoring of an inverter is done by reading values on display (usually LCD) and an integral part of every grid-connected inverter. Some common monitoring parameters include PV array power, AC grid power, and PV array current. More sophisticated monitoring parameters include environmental data such as module temperature, ambient temperature, solar radiation, and wind speed.

Apollo employs a variety of different monitoring devices. For their weather sensor, Apollo uses the LUFFT WS601-UMB Smart Weather Sensor. The LUFFT WS601-UMB is a weather sensor that can measure humidity, precipitation, air pressure, wind direction, and wind speed. Apollo uses the LUFFT WS601-UMB Weather Sensor due to its low power, maintenance-free operation, and open communication protocol as well as its aspirated radiation shield and heater.

Figure 6: LUFFT WS601-UMB Smart Weather Sensor

For their pyranometer, Apollo uses the EKO MS-80 Pyranometer. Apollo uses the EKO MS-80 Pyranometer because of its ultra low temperature dependency and exceptional non-linearity characteristics which guarantees optimal sensor performance under any environmental conditions.

Figure 7: EKO MS-80 Pyranometer

For their network camera, Apollo uses the AXIS M3027-PVE Network Camera. Apollo uses the AXIS M3027-PVE because of its day and night functionality, high image quality in day or night, and most importantly, it can track the flow of people and improve area management. The AXIS M3027-PVE allows users to digitally pan, tilt, and zoom in on areas of interest with a 360° overview.

Figure 8: AXIS M3027-PVE Network Camera

Finally, for their power meter, Apollo uses the SATEC PM130 PLUS which is a compact, multi-function, three-phase AC powermeter specifically designed to meet the requirements of Apollo. The SATEC PM130 PLUS power meter can measure 3 voltage inputs and 3 current transformer-isolated AC inputs for direct connection to power line or via potential and current transformers. It can also measure parameters such as true RMS, volts, amps, power factor, V/I unbalance, and frequency. It also comes with 25/50/60/400 Hz measurement capabilities.

Figure 9: SATEC PM130 PLUS Powermeter

All of these different monitoring devices are connected through a software program called GreenPowerMonitor PV Portal monitoring solution. GreenPowerMonitor PV Portal monitoring solution is a piece of software that allows for people to supervise the operation of photovoltaic plants, analyze current and historical data from all the devices, manage and configure data, as well as many other features. Apollo has physical devices called *dataloggers* inside each facility which regularly sends over data to the GreenPowerMonitor server and then standardized, treated, and adapted to the needs of Apollo.

Conclusion

This project aims to not only be a comprehensive source of information about the Apollo Photovoltaic system, but to help guide future Cal Poly seniors who will base their senior projects on the plant. The diagrams and documentation given to us by PVIR resulted in an overview of the various aspects of the photovoltaic system. While this project touched on most of the aspects and components of the photovoltaic system, this guide can still be improved. Other topics that could be explored are the design of the photovoltaic system, finding ways to increase the efficiency of the plant, and how power is distributed to the grid, just to name a few.

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Appendix A: Senior Project Analysis

Project Title: Gold Tree Photovoltaic Power System Analysis

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Advisor: William Ahlgren

1. Summary of Functional Requirements
    a. This project will be able to educate students on the various components used in building the Apollo photovoltaic power plant. Also, the project will discuss the advantages and disadvantages of said components and their purposes.
2. Primary Constraints
    a. Challenges associated with the project include knowing and understanding the exact specifications of the equipment. Since the information we have is sensitive and confidential, we aren't given everything and have to draw conclusions ourselves. Also, the whole system is extremely complex so even with all the information, it can be difficult to comprehend everything solely by looking at datasheets and diagrams.

3. Economic
    a. What economic impacts result from the project?
        i. Human Capital: If our project produces beneficial results, our project can possibly introduce new jobs in building of solar photovoltaic plants.
        ii. Financial Capital: Our project may educate or optimize existing solar photovoltaic power plants thus saving money when it comes to choosing the right components.
        iii. Natural Capital: Our project is an educational document so natural capital is preserved.
        iv. Costs: Our document is free and meant to help future students so our project comes at no cost.
4. If manufactured on a commercial basis:
    a. The estimated downloads would include PIVVIR solar employees as well as future students interested in construction of solar photovoltaic plants.
5. Environmental
    a. Construction of solar photovoltaic plants do have some environmental liabilities due to taking up acres of land
    b. Components broken down and disposed may cause harm to nearby wildlife as well as humans.

6. Manufacturability
    a. As this project is entirely an educational document, no manufacturing is required.
7. Sustainability
    a. Since we're dealing with a solar photovoltaic power plant, our project naturally is sustainable when compared to other forms of energy like oil.
    b. In the future, this information can be outdated, so it is important to keep this educational resource updated.
8. Ethical Considerations
    a. A major issue comes from the integrity of our project, as incorrect information could cause possibly cause issues for PIVVIR's solar employees or future students. It is important and ethical of us as engineering students to report our shortcomings in order to prevent this.
9. Health and Safety
    a. A possible safety concern we should be aware of comes from the repercussions of incorrect information and how it could affect everyone reading this document.
10. Social and Political
    a. Alternative energy is a significant issue on the political platform. Just recently, there was a debate on the recent voting on Measure G passed in San Luis Obispo about groundwater and local environment. Luckily for us, solar energy is an accepted form of cleaner energy so we do not expect

any political conflicts. Rather, it will benefit the community by providing a renewable energy source.

11. Development:

    a. For the development of this project it was important to understand how solar photovoltaic power plants work.