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# Designing Large scale Photovoltaic Systems

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**Abstract.** This paper presents a plan and procedure for the design and performance analysis of large-scale grid-connected solar Photovoltaic (PV) systems. A 1MW grid-connected PV system was designed and its performance was analyzed over the guaranteed life of the system using a photovoltaic system performance analysis program. In the system designed and analyzed in this paper, half of the produced electricity is fed to the load and the other half is stored to the grid. If the solar system cannot produce electricity for the load, then the load will use power from the grid.

A photovoltaic system is a power system designed to supply usable solar power by means of photovoltaic panels. It consists of an arrangement of several components, including solar panels to absorb and convert sunlight into electricity, a solar inverter to change the electric current from DC to AC, as well as mounting, cabling, and other electrical accessories to set up a working system.

## Key words

Photovoltaic Power System, Stand-alone PV system, and Grid Connected PV System.

## 1. Introduction

PV systems range from small, rooftop-mounted or building-integrated systems with capacities from a few to several tens of kilowatts to large utility-scale power stations of hundreds of megawatts. Currently, most PV systems are grid-connected, while off-grid or stand-alone systems only account for a small portion of the market.

Grid connected PV systems are becoming wide spread day by day. To design the power system with a grid connected PV system, we work on the design and simulation side in order to use the method more efficiently. Solar energy helps in reducing air and water pollution. Solar panels also help in reducing hazardous waste, resource mining which help chemical industries and lower the amount of waste that coal, and oil-based energy plants produce.

A flat panel PV system generates DC electricity in direct proportion to the amount of surface area that is exposed to sunlight. Modules are designed to supply this electricity at a certain voltage.

## 2. Stand Alone PV Systems

Stand-alone PV systems are designed to operate independently from the electric utility grid and are generally designed and sized to supply certain DC or AC electrical loads. These types of systems may be powered by a PV array only, or may use wind, an engine-generator, or utility power as an auxiliary power source in what is called a PV-hybrid system. The simplest type of stand-alone PV system is a direct-coupled system, where the DC output of a PV module or array is directly connected to a DC load. Since there is no electrical energy storage (batteries) in direct-coupled systems, the load only operates during sunlight hours, making these designs suitable for common applications such as ventilation fans, water pumps, and small circulation pumps for solar thermal water heating systems.

## 3. Grid Connected PV Systems

Simple grid connected solar power systems without batteries have many advantages. Firstly, it is economical. Since grid connected solar power system do not need batteries, this type of system is at least thirty percent less to install versus a battery-based systems. Typically, simple grid connected systems are ninety percent to ninety-five percent efficient, which makes the rate of return more attractive since batteries are less efficient overall. Moreover, its lower upfront cost, battery-less grid connected solar power systems avoid costs for batteries charge controllers, control panels, and a backup generator, thus reducing the upfront cost of going solar significantly. Grid connected solar power systems are expandable, meaning we can start with a small solar array and build your way up to a larger system.

Also, it is reliable. Maintenance is required with a battery-based system and if they are not properly maintained then the life of the battery will rapidly diminish. Grid connected solar power systems are more reliable since we don't have to worry about maintaining a battery pack. Apart from this, it is flexible. When it comes to designing a grid connected solar power system, it can be designed to our budget and desires of how much utility dependence, we want to offset with our grid connected solar power systems. Grid connected solar power systems get rid of a lot of parts, therefore they are easier to manage. These days many grid connected inverters include remote monitoring software which allows us to view the output, data and health of the overall grid connected solar power systems through an internet browser. Large-scale Grid connected PV systems consist of the following element components that are needed for all grid connected systems:

A- PV module

Solar PV Technology converts the sun's natural energy to useful electrical energy. Photo Voltaic modules are made of mono-crystalline or polycrystalline solar cells connected in series and parallel modes. The type of solar panel used in this project is mono crystalline. Mono-crystalline solar panels are the most efficient type of solar panels, but are also the most expensive. Flat panel systems account for the majority of renewable energy installations in the United States. At any given location on a clear day, the amount of sunlight striking the earth's surface is equivalent to approximately 1k watt / $ft^2$ [1].

B- Inverter

An inverter is a critical interface component that deploys feed-in function and converts direct current (DC) from the PV array into alternate current (AC) for the system output to be compatible with a local utility grid in terms of voltage and frequency values (mostly 50 Hz and 60 Hz in the USA). Inverters function as a control and optimization device [2].

The primary component in grid-connected PV systems is the inverter, or Power Conditioning Unit (PCU). The PCU converts the DC power produced by the PV array into AC power consistent with the voltage and power quality requirements of the utility grid, and automatically stops supplying power to the grid when the utility grid is not energized. A bi-directional interface is made between the PV system AC output circuits and the electric utility network, typically at an on-site distribution panel or service entrance. This allows the AC power produced by the PV system to either supply on-site electrical loads, or to back-feed the grid when the PV system output is greater than the on-site load demand. At night and during other periods when the electrical loads are greater than the PV system output, the balance of power required by the loads is received from the electric utility [3]. This safety feature is required in all grid-connected PV systems, and ensures that the PV system will not continue to operate and feed back into the utility grid when the grid is down for service or repair.

C- Transformer

The transformer transfers the electrical energy between two or more circuits through electromagnetic induction. Electromagnetic induction produces an electromotive force within a conductor which is exposed to time varying magnetic fields. Transformers are used to increase or decrease the alternating voltages in electric power systems.

D- Combiner Box

Wires from the individual PV modules or strings are run to the combiner box, typically located on the roof. These wires may be single conductor pigtails with connecters that are pre-wired onto the PV modules. A combiner box typically includes a safety fuse for each string and may include a surge protector.

## 4. DC Side Analysis of PV Systems

The solar panels side, DC side, of the 1 MW design is presented in this section. The number of panels needed for the system can be obtained by dividing the total system power (1MW) by the panel power

(380W) which results in 2631.6. This means that we need to use at least 2632 PV panels to get the needed power of 1MW. Where the numerator is the total PV system power and the denominator is the panel power in Wall. So 2632 solar panels are needed for the system to reach the system design goal.

The calculation of PV module and inverter are presented in Table 1 where the power of each PV panel is 380W and the three-phase inverter has three MPPTs and each MPPT has three strings input. From the PV array sizing chart, we can see that the number of panels per string is 20 and the lowest number of panels per string is 18. This is determined by using the PV module open circuit voltage, and the extreme lowest temperature for the site. The first value we find is the maximum number of panels that can be connected per string. This indicates that we cannot exceed 20.92 panels or else we will exceed the maximum voltage that the inverter is specified for. Therefore, we round the number down to 20. The second value is the minimum number of panels that can be connected in series to the inverter.

When the temperature reaches its minimum, the voltage will be increased above the nominal panel voltage. We can find the effect that the temperature has on the panels by utilizing the delta t and multiplying it by the extreme lowest temperature based upon tested conditions. The minimum number of panels is then found from.

## 5. AC Side Analysis of PV Systems

For the AC side of the system design, we need to determine the system connections from the inverter all the way to the utility grid connection. The inverter has a three-phase output of 60 kW at 480V. The three-phase current output of each inverter converts 60KW / (480V*1.73) which is equals to 72.2 A.

Due to the large scale of the designed system, we divide the inverters into two groups of eight with each group of eight connected within a combiner panel board. It is important to note that the National Electric Code (NEC) does not allow for any outside loads other than the inverters to be connected within these combiner panel boards.

As each inverter has an output of 72.2 A, the combiner panel board will be connected within an 800A combiner panel board (72.2 * 8 = 577.6 A * 125% = 722 A). The circuit breaker that connects the inverter into the combiner panel board will be sized at 100A. This is calculated by considering that most circuit breakers in use are only rated for a continuous load at 80% of their rating. The NEC defines PV systems as a continuous load, which is defined as a load that is active for three hours or more at one time. The inverse of 0.8 (80%) is equal to 1.25 so to size a circuit breaker, we need to take the inverter output and multiply it by 1.25. In this case, it is equal to 72.2 A * 1.25 = 90.25 A. The NEC allows us to round up this number to the next standard circuit breaker rating which happens to equal 100 A in this case. The conductors should be sized to carry the full continuous current and sized per the NEC.

From each combiner panel, a feeder is routed from the combiner panel to another piece of combiner equipment, a 1600 A switchboard. The 800A feeders will consist of two parallel sets of four #500kcmil conductors with each set containing a #1/0 ground conductor within 4” conduit. They will have to be switchboard constructed as typically, manufacturers do not make panel boards that will have ratings that are more than 1200 Amps. The switchgear will have two 800A circuit breakers that have input feeds from the combiner panel boards and one 1600A circuit breaker that will exit the switchboard to a fusible-disconnect switch.

The fusible-disconnect switch will contain a 1600A fuse and be a visible break device that allows a worker to verify that the connection has been broken before work is performed within the device. All of the 1600A feeder will consist of five sets of #500kcmil conductors and #4/0 ground conductors within 4” conduit. The power disconnect should be located on the secondary side of a 1000kVA transformer. After that it will connect to a switch-board and from that switchboard half of the power will go to load and half of the power will go to utility.

Table1: Calculations for PV modules power (W) per inverter and the required number of panels per string.

| # Panels / String | String Power | Power / MPPT | Inverter Power | Total Power | Total # panels |
|---|---|---|---|---|---|
| 18 | 6840 | 20520 | 61560 | 984960 | 2592 |
| 19 | 7220 | 21660 | 64980 | 1039680 | 2736 |
| 20 | 6700 | 22800 | 68400 | 1094400 | 2880 |

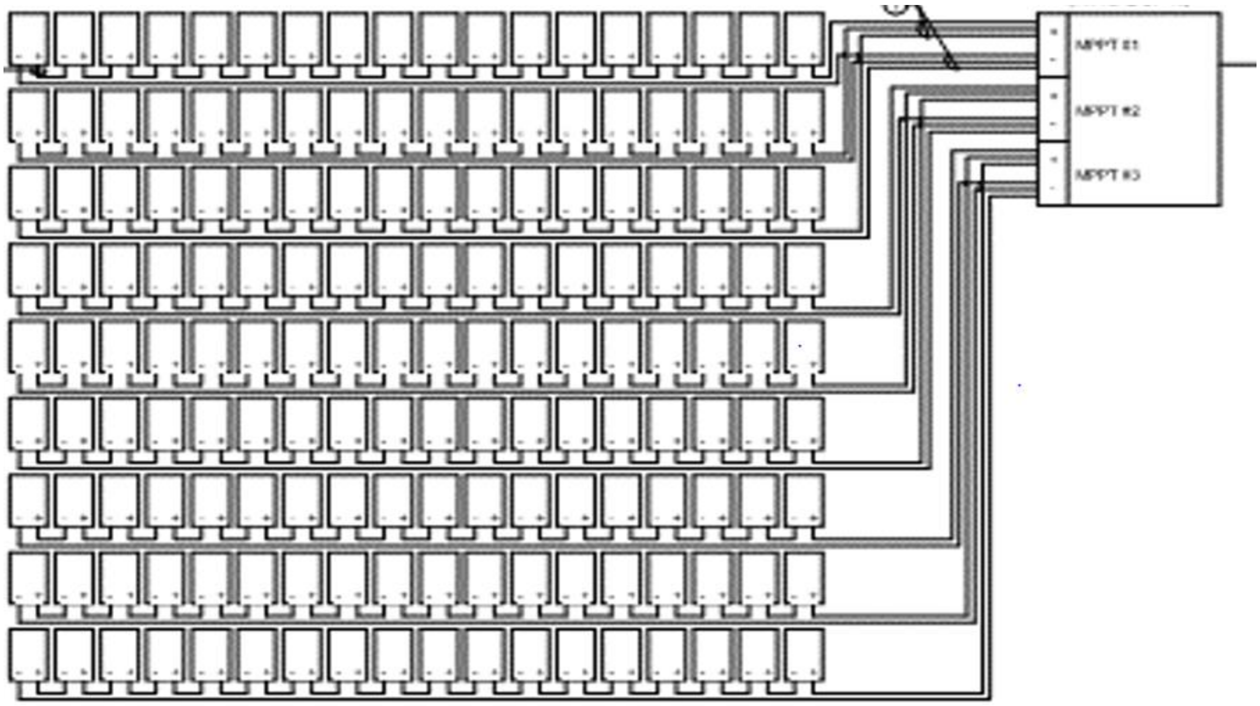


Fig. 1. 1 MW PV System DC side single line diagram Per Inverter

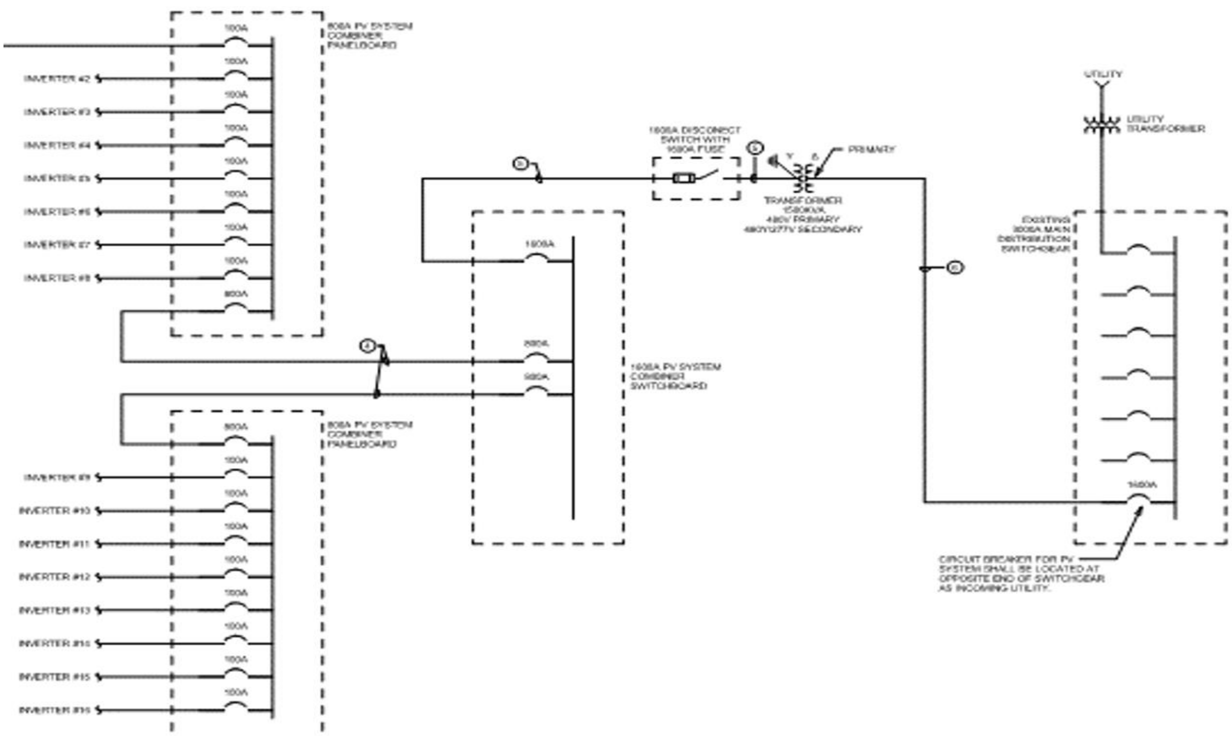


Fig. 2. 1 MW PV System AC side single line diagram for 16 Inverters

## 6. PV System Simulation

When simulating a flat panel photovoltaic system, it is important to first understand the theory. In particular, the PV modules' equivalent circuit design, open-circuit voltage, and power and I-V curves under specified standard test conditions (STC). STC for a typical PV module is generally taken as 1000 W/m$^2$ irradiance, 25˚C temperature, and 1.5AM air mass. The equivalent circuit for a standard PV module, see Figure 3, is derived from the physics of current generation, but for the purposes of this simulation, it is important to consider the electrical calculations relating to the actual application in real systems. The use of computer simulation for the design and analysis of PV systems is presented in [1] where the authors recommend the use of MATLAB/SIMULINK for the design and analysis of PV systems.

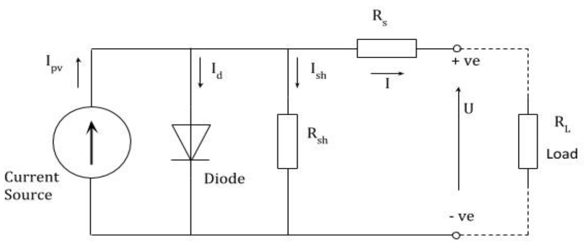


Fig. 3. PV Module Equivalent Circuit

As a sample for the use of MATLAB/SIMULINK, a full bridge inverter is shown in Figure 4.

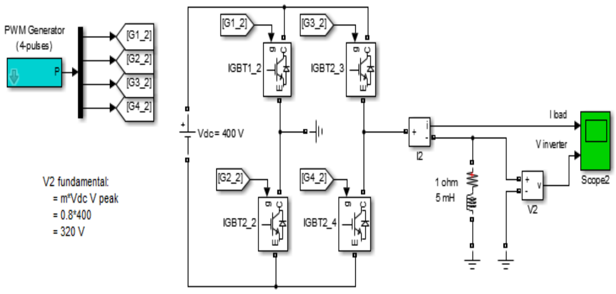


Fig. 4. Simulink Model of Full-Bridge Inverter

This inverter takes in a constant DC signal and generates an oscillating AC signal that is filtered to obtain a pure sinusoidal output, which is shown in Figure 5.

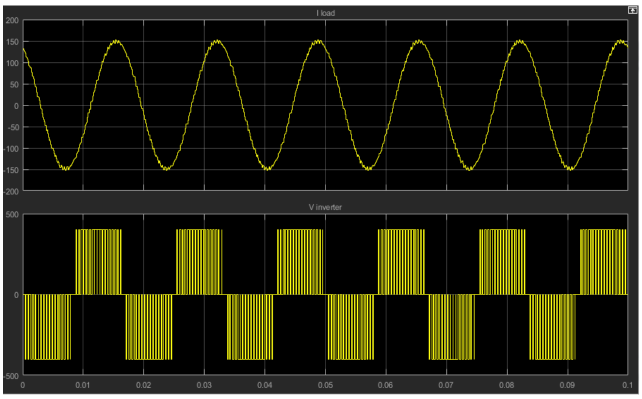


Fig. 5. Simulink Scope for Full-Bridge Inverter Output before and after the filter

For commercial applications, an AC oscillation frequency of 60-Hz is used, and the quality of an inverter is determined by the smoothness of its 60-Hz signal, with better quality inverters yielding smoother signals. The more noise that is present in an inverter's output signal, the less power transfer that inverter can achieve. In general, a full-bridge inverter will output a higher quality signal than a half-bridge inverter, which is why full-bridge inverters are preferred for renewable energy and power electronics applications. A complete MATLAB/SIMULINK model for a grid connected PV system is given in figure 6, and simulation for grid connected system is presented in [4]

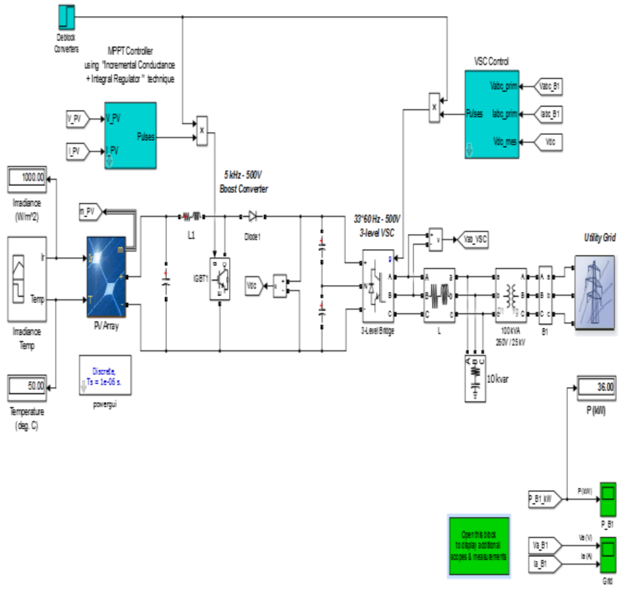


Fig. 6. Final 40-kW PV Array with 25-kV Grid Tie-In

When operating a PV system, there are times when more power is generated than what is needed to drive the load. In such a case, the extra power must either be fed into the main grid or captured and stored in a battery bank. Even in the case of a grid-connected system, a battery back-up is often preferred (in addition to the grid connection) because it allows the system to remain self-sufficient during non-operational hours.

One important consideration for the selection of a renewable system's battery is how much current the load will draw from the battery bank. The maximum current drawn cannot exceed what the battery is rated for, otherwise the chemical reactions that occur inside the battery will not be able to keep up with the current draw and the battery life will be greatly reduced [5].

Another consideration is determining at which point in the grid to insert the renewable-sourced power. If a large amount of power is being generated, then transmission line insertion is the best location because the voltage in those lines averages 500-kV, depending on where the transmission lines are located. If a small amount of power is being generated, then the distribution lines are the best place for insertion [6].

## 7. PV System Performance Analysis

The designed system is analyzed in this section using the trial version of PV SYST V6.77 simulation software. We start with the project design option from the main menu, then the location is set to Boston, which is located at latitude of 42.37N and longitude 71.06W, and the tilt angle is set to 37 degrees. The calculation variants were set as given in figure 7, and the PV module and inverter information [7] and [8] were set as given in figure 8.

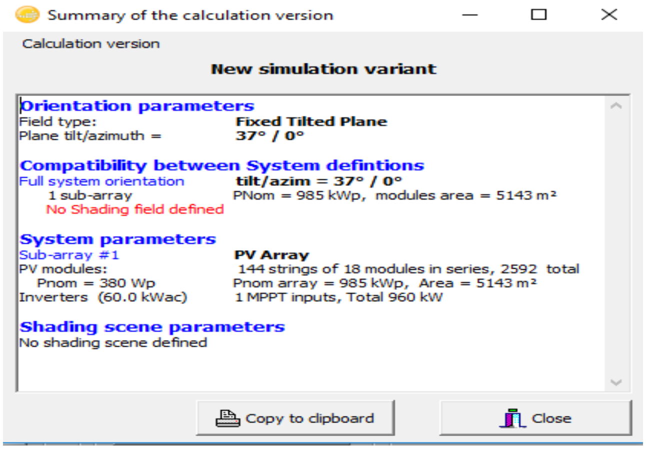


Fig. 7. Calculation variants setting in PVSYST

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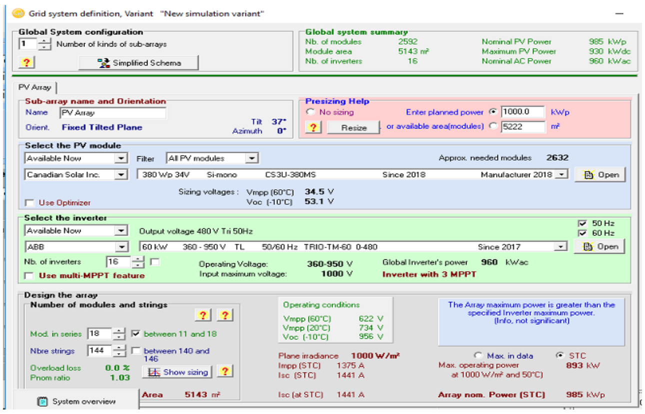

Fig. 8. PV module and inverter information

Running the PVSYST simulation results in the PV system gives us the PV system normalized that is given in figure 9. Another program that can be used for this analysis is PV WATT [9].

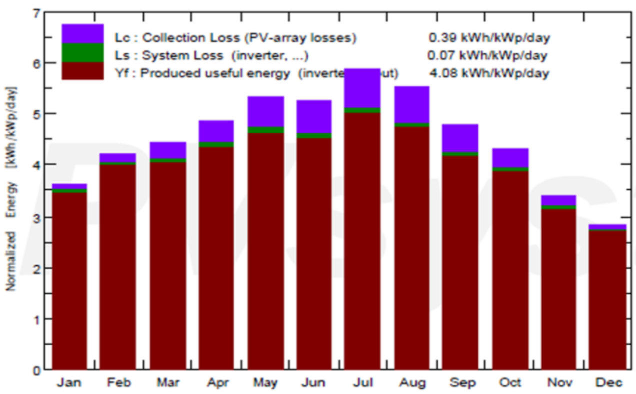


Fig. 9. PV module and inverter information

## 8. Conclusion

This paper presents a road map for the design of large scale photovoltaic systems. A photovoltaic system is a power system designed to supply solar power by means of photovoltaic panels. It presents a detailed design and performance analysis plan of a large-scale grid-connected PV system.

A 1 MW photovoltaic system was designed and then analyzed using PVSYST photovoltaic system performance analysis program. Computer simulations can be used to help with both the design and the analysis of PV systems. As an example MATLLA/SIMILINK was used to analyze a PV system.

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