

Development of Photovoltaic Systems and Application in Smart Grids: Sivas Case

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Abstract - The high solar energy potential in Turkey is an important advantage and the effective utilization of this potential will contribute to the national economy. In this study, the integration of photovoltaic systems (PVs) with smart grids, which are becoming increasingly important in terms of ensuring energy efficiency, is examined. Within the scope of the study, a village with 30 households in Sivas province was designed and the amount of electrical energy that 30 households will need per day was calculated based on the daily energy consumption of each household in the village. Then, a photovoltaic (PV) consisting of 60 panels of 675 Wp (Watt-peak) was designed to meet this need. The PV was integrated into the city grid to meet the electrical energy needs of this village even when the PV was insufficient. For this integration to work without interruption, control technologies were added to the integration and simulated in MATLAB/Simulink environment. With the designed PV, it is seen that the entire electrical energy need of the village can be met between April and September, and a significant part of this need can be met between October and March, and the remaining part can be supplied from the grid thanks to the integration.

Keywords - Photovoltaic system, smart grid, solar energy, energy efficiency.

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1. Introduction

Energy consumption is increasing in the world with population growth and developing industry. Due to the inadequacy of fossil fuels and their negative effects on global warming, renewable energy sources have started to be given more importance in the world. The most important and longest-lasting renewable energy source is solar energy. Countries around the world are constantly working on utilizing the sun, which is an unlimited energy source, and continue their efforts to develop new technologies.

In Turkey, which meets its energy needs from imported sources, the contribution of the use of solar electricity with smart grids is significant. The integration of solar electricity into grids, the storability of this energy, the consumption of stored energy, and the reduction in the amount of loss and leakage provided by smart grids have significant advantages.

Thanks to smart grids, there are many benefits of installing renewable energy sources and energy storage systems together with the advantages of reducing overload and peak load on grids, reducing energy cost, and controlling energy generation and distribution processes [1]. In the model studies created in MATLAB/Simulink environment for renewable energy sources and smart grid integration, energy efficiency increases by providing a bidirectional transition between the grid and buildings [2]. With the integration of renewable energy sources with distribution networks, it is possible to ensure supply quality, energy efficiency, and sustainability of the supply system and reduce losses [3].

The benefits of smart grid integration with PVs have started to be seen more and more in recent years. These integrated systems are becoming widespread due to their advantages in terms of both increasing the utilization rate of renewable energy sources and providing energy efficiency. There are very few MATLAB/Simulink applications of this integration and integration in the literature and these are included in this study.

Within the scope of this study, a sample village was designed for the integration of PVs and smart grids and the process of meeting the electrical energy needs of this village through this integration was simulated in MATLAB/Simulink environment.

2. Photovoltaic Technologies

Solar panels are semiconductor structures that convert the sunlight incident on their surfaces directly into electric current. When solar radiation falls on solar cells, electrical energy is generated by the operation of the solar cell equivalent circuit shown in Figure 1. The energy produced in solar cells is Direct Current (DC).

The equivalent circuit model of a solar cell was described by Lorenzo [4]. The solar cell equivalent circuit consisting of a current source and a diode connected in parallel is shown in Figure 1 and the simplified equivalent circuit is shown in Figure 2.

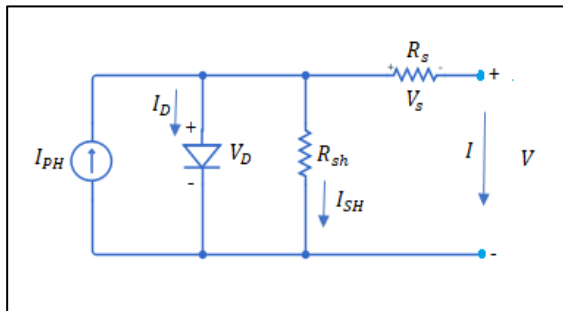


Figure 1. Solar cell equivalent circuit

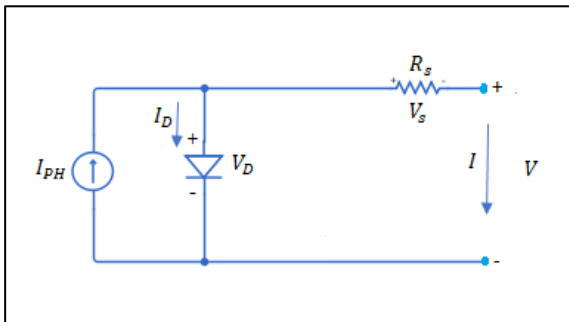


Figure 2. Simplified equivalent circuit

When the simplified equivalent circuit in Figure 2 is examined, the series resistance R_s represents the internal losses of the solar cell due to current and it is preferred to be small for maximum power generation. The resistance R_{sh} is connected to the diode and represents the losses due to current leakage to the ground. Since the value of R_{sh} resistance is very small, it is usually neglected [5].

By applying Kirchhoff's law of currents to the circuit in Figure 1, the current in Equation 1 is found.

$$I = I_{PH} - I_D - I_{SH} \quad (1)$$

Equation 2 shows the diode current equation I_D

$$I_D = I_0 \left(e^{\frac{qV}{nkT}} - 1 \right) \quad (2)$$

Diode current I_D varies as a function of the absolute temperature of the diode, the voltage, and the current drawn by the load.

In Equation 2;

- q : Electron charge 1.602×10^{-19} C
- V_D : Potential difference between the terminals of the diode,
- n : Ideality factor,
- k : Boltzmann constant 1.381×10^{-23} J/K
- T : Represents absolute temperature in Kelvin [6].

By applying Kirchhoff's law of voltages to the solar cell equivalent circuit in Figure 1, the source current expression in Equation 3 is obtained.

Here, series resistance (R_s), parallel resistance (R_{sh}), and coil L are parameters that vary according to the characteristics of the solar cell.

$$I_D = I_0 \left(e^{\frac{qV_D}{nkT}} - 1 \right) = I_0 \left(e^{\frac{q(V_S + L.R_{SH})}{nkT}} - 1 \right) \quad (3)$$

$$I_{SH} = \frac{V_D}{R_{SH}} = \frac{(V_S + L.R_{SH})}{R_{SH}} \quad (4)$$

Since $I = I_{PH} - I_D - I_{SH}$ in Equation 1, Equation 5 is obtained.

$$I = I_{PH} - I_0 \left(e^{\frac{q(V_S + L.R_{SH})}{nkT}} - 1 \right) - \frac{(V_S + L.R_{SH})}{R_{SH}} \quad (5)$$

The power transferred to the load depends only on the resistance. The point where the power transferred to the load is maximum is called the maximum power point. The maximum power (P_{max}) can be written as in Equation 6 [5].

$$P_{max} = V_{opt} \cdot I_{opt} \quad (6)$$

The power generated in PV depends on the voltage and current values. The power transferred in PV varies depending on the illumination intensity (G) and the area of the cell (A). Figure 3 shows the characteristics of the power generated in the PV voltage graph.

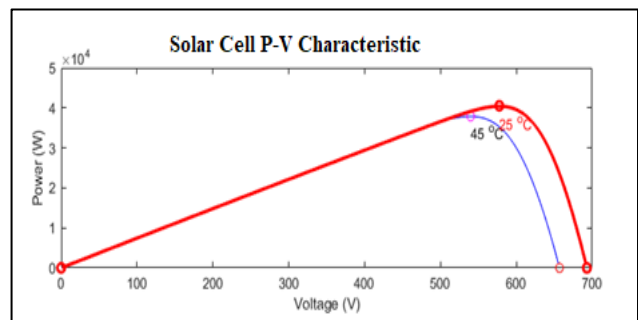


Figure 3. P-V characteristic of CWT 675W solar cell

Solar cell efficiency, which depends on the ratio between the power transferred to the battery and the absorbed solar radiation, is shown in Equation 7.

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{opt} \cdot I_{opt}}{G \cdot A} \quad (7)$$

The charging factor in Equation 8, which indicates the cell performance, is obtained by dividing the maximum power (P_{max}) by the product of the short circuit current (I_{sc}) and the open circuit voltage (V_{oc}) [8].

$$FF \text{ (Filling Factor)} = \frac{P_{max}}{V_{oc} \cdot I_{sc}} = \frac{V_{opt} \cdot I_{opt}}{V_{oc} \cdot I_{sc}} \quad (8)$$

For an ideal solar cell, a fill factor greater than 0.7 is appropriate [4].

3. Materials and Methods

Due to its geographical location, Turkey is worthy of consideration for PVs in terms of sunshine duration and efficiency. The most effective utilization of such an important energy source and potential will make a great contribution to the national economy [9]. Solar energy is utilized through PVs. PVs are used in two different ways: grid-connected on-grid and off-grid systems. In grid-connected systems, the electrical energy produced is sent directly to the consumer, while in off-grid systems, the energy produced is stored and used when necessary.

3.1. Solar Energy Potential of Sivas Province

When the solar energy potential map of the world is examined, it is seen that Turkey is in an advantageous position in terms of solar radiation amount and sunshine duration.

Table 1 shows the amount of solar radiation and sunshine duration according to the geographical regions of Turkey taken from the Solar Energy Potential Atlas (GEPA) study.

When the table is examined, it is seen that the sunshine duration and solar radiation values of the southern and central parts of Turkey are high [10].

Table 1. Irradiance and sunshine hours according to geographical regions of Turkey

| Regions | Total Solar Energy (kWh/m ² -year) | Sunbathing Duration (hour/year) |
|-------------------------|---|---------------------------------|
| Southeast Region | 1.460 | 2.993 |
| Mediterranean Region | 1.390 | 2.956 |
| Eastern Anatolia Region | 1.365 | 2.664 |
| Central Anatolia Region | 1.314 | 2.628 |
| Aegean Region | 1.304 | 2.738 |
| Marmara Region | 1.168 | 2.409 |
| Black Sea Region | 1.120 | 1.971 |

Sivas province is located in the Central Anatolia Region and the total sunshine duration is 2.628 hours per year and the amount of solar energy per m² per year is 1.314 kWh. Monthly irradiation values and sunshine duration values of Sivas province are shown in Figure 4. When the figure is analyzed, it is seen that the irradiance values of Sivas province are high especially in summer months in accordance with the GEPA data [8], [11].

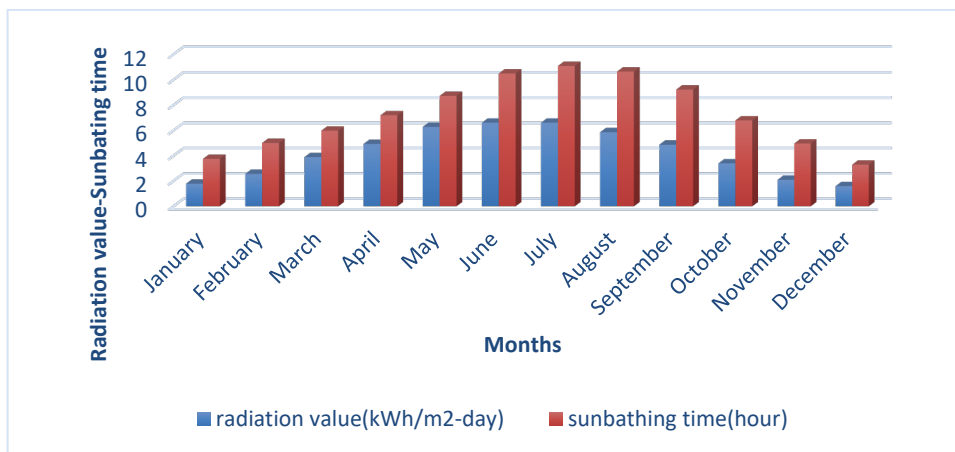


Figure 4. Global irradiance values and sunshine hours of Sivas province

3.2. Sivas Province Village Example

In this study, a solar power plant (SPP) has been designed for a village with 30 households in the

center of Sivas province in order to meet the electrical energy needs of this village. Then, this solar power plant is integrated with the smart grid and simulated in MATLAB/Simulink environment.

Panel Number Calculation

1. The electrical energy requirement per household is taken as 8 kWh per day [12]. This corresponds to 240 kWh per month. The Chamber of Electrical Engineers calculated this consumption as approximately 230 kWh [13]. This corresponds to 7,66 kWh per day. In this study, daily consumption is taken as 8 kWh.
2. Daily electricity needs of 30 households in the village; 8 kWh×30 = 240 kWh equals.
3. Number of panels needed for the village,

SCN = TPR/(SCP×SD×0,85)[14], is calculated with the formula. In the formula;
 SCN : Solar Cell Number
 TPR : Total Power Required (kWh)
 SCP : Solar Cell Power (W)
 SD : Sunbathing Duration (h)
 0,85 : PV module efficiency coefficient.

In the selection of PV to be used in the SPP plant designed to meet the energy needs of the village, calculations based on the power of the panels between the same brand PV panels showed that more panels were required for panels with low power and fewer panels were required for panels with high power.

3.3. Simulation of Photovoltaic Module in MATLAB-Simulink Environment

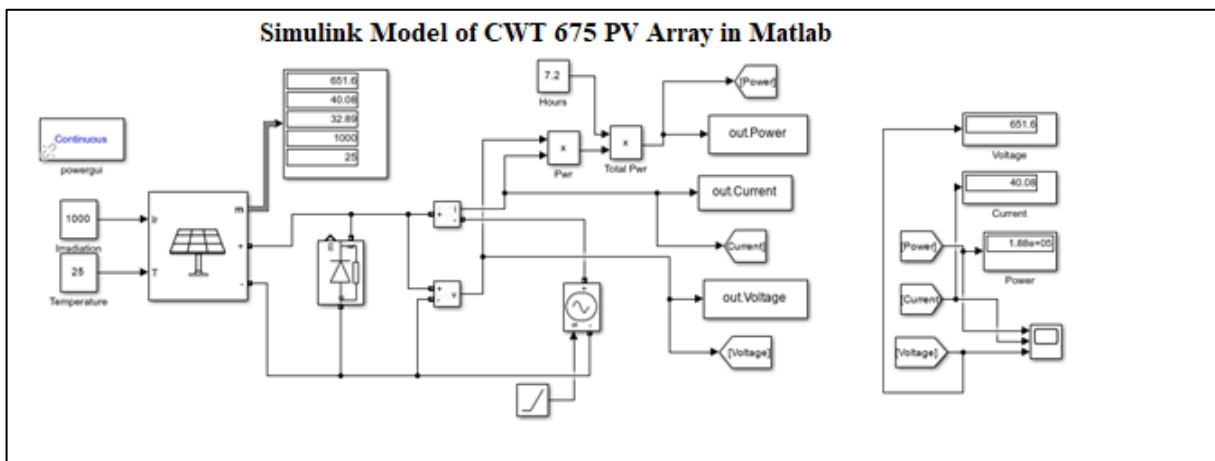


Figure 5. Solar panel model

Based on the solar cell equivalent circuit, a PV system was obtained by solar panel modeling in MATLAB/Simulink application. In the Simulink study, it was observed that the voltage, current and power values of the solar panel changed as the solar irradiation value changed. Using the CWT 675 panel module of the PV model, Simulink calculation was made from MATLAB parameters.

The panel with the least number and the highest capacity to meet the need was preferred because it occupies less space and has lower installation costs. CWT 675 W panel was used in the study.

The number of panels needed for the village is $240 \text{ kWh}/(675 \text{ W} \times 7,2\text{h} \times 0,85) = 58,09$ panels.

Sivas province has an annual sunshine duration of 2.628 hours. Since the aim of the study is the integration of PV system and smart grid, the system feeds the grid with the excess energy produced in the summer months, and in case the village cannot meet the amount needed (in winter or when the irradiation is low), it is fed from the grid. For this reason, the average sunshine duration of Sivas province, which is 7,2 hours and corresponds to the sunshine duration of April, was used in the calculations [14].

The SPP plant consists of 60 CV brand 675 W panels (58,09 panels in the calculation were taken into account as 60 to create order in serial-parallel connections in the plant design).Electricity energy to be produced by the PV plant in one day is equal to

$$7,2\text{h} \times 60 \text{ panel} \times 675\text{W} = 291.600 \text{ Wh.}$$

The solar power plant is designed by integrating a total of 60 CWT 675 W panels, 4 panels in N_p (parallel connection) and 15 panels in N_s (series connection).

The elements of the system circuit were installed and the solar panel model developed in MATLAB/Simulink with the CWT 675 panel was designed. Figure 5 shows the designed solar panel model.

In the PV system model, current-voltage magnitudes change nonlinearly according to environmental and weather factors.

In this direction, PV systems are created and put into use by combining the PV array in series or parallel according to the amount of demand, ground, and sunshine position. Based on the calculations of the Sivas province village example, a system was designed in Simulink using 60 CWT 675 panels. I-V and P-V graph of the Ns:15, Np:4 model of the CWT 675 PM panel is shown in Figure 6. CWT 675 panel specifications are given in Table 2.

Table 2. CWT 675PM panel specifications [15]

| Model Type | CWT675-144PM |
|--|--------------|
| Maximum Power (Pmax) | 675 Wp |
| Number of Cells (quantity) | 132 (6 x 22) |
| Open Circuit Voltage (V _{oc}) | 46,20 V |
| Short Circuit Current (I _{sc}) | 18,56 A |
| Maximum Power Voltage (V _{mp}) | 38,50 V |
| Maximum Power Current (I _{mp}) | 17,54 A |
| Temperature Coefficient (I _{sc}) | 0,040% / °C |
| Temperature Coefficient (V _{oc}) | -0,260% / °C |
| Ns | 15 |
| Np | 4 |

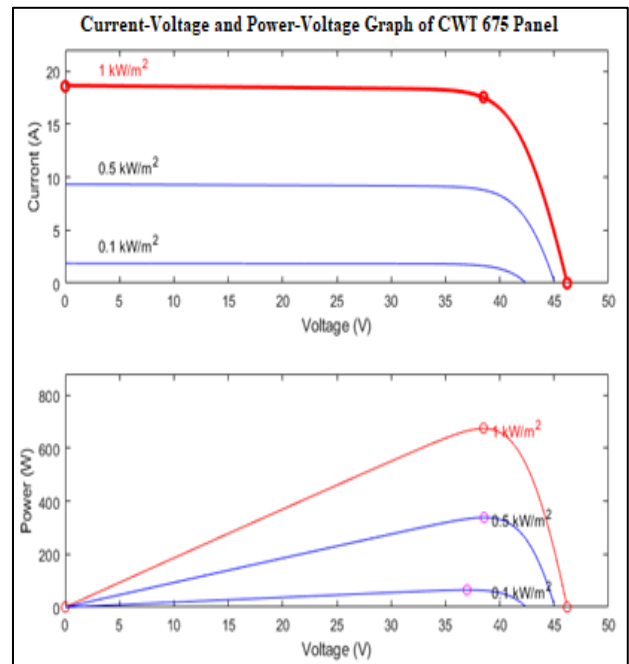


Figure 6. I-V and P-V graph of CWT 675 W Panel

3.4. MATLAB/Simulink Integration

Figure 7 shows the I-V and P-V graphs obtained by entering the electrical properties of the CWT 675 Wp panel into the MATLAB Simulink application. As the solar panel light intensity increases, the power also increases. The maximum power that the cell or module can produce is called peak power (Wp).

The simulation studies of the grid-connected PV system installed in the designed village and its integration with MPPT (Maximum Power Point Tracking) and battery were carried out in MATLAB/Simulink environment on the structure in Figure 7. The integration was created using the ready-made toolbars in the MATLAB/Simulink library.

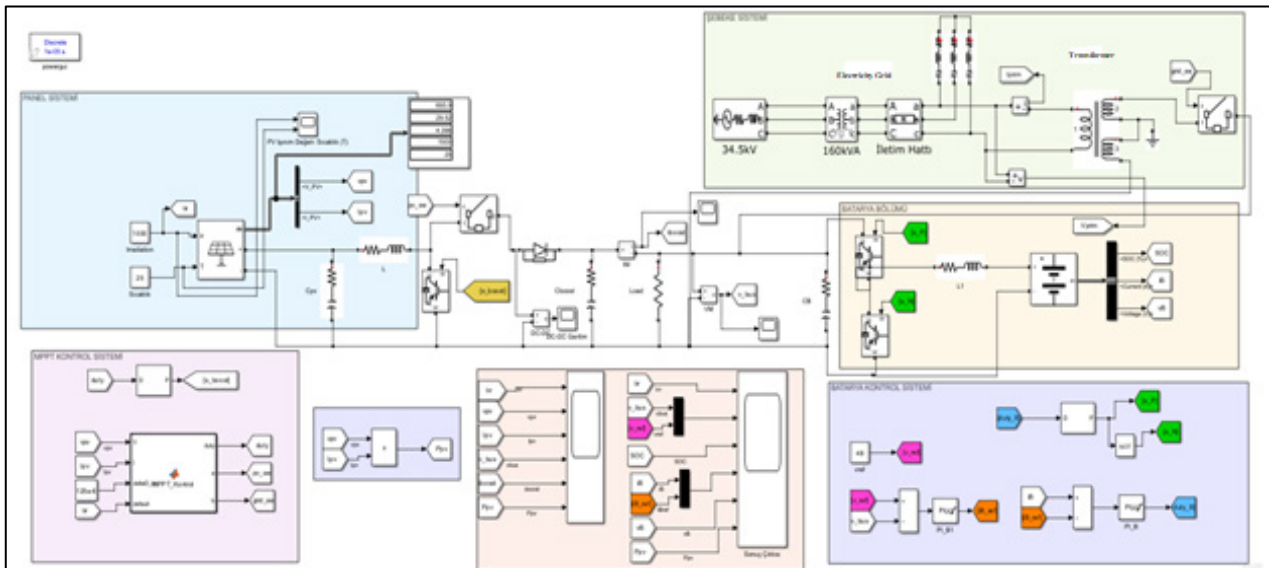


Figure 7. PV System and smart grid integration

In the MATLAB/Simulink model, a module for the input of different values of irradiance and temperature data, a module for the PV panel electrical characteristics, a module for the inverter, a module for the MPPT, a module for the battery and a

module for the simulation of the grid integration of the power plant were created. Standard test conditions (1.000 W/m² for radiation and 25 °C for temperature) were assumed.

These data can be changed manually by the model operator according to the desired irradiance and temperature values. All of the temperature and irradiance data are used in the module titled PV Panel, which contains 15 series connected and 4 parallel connected CWT 675 model PV modules.

PVs have an increasing importance in modern smart grid systems. Typically maximum power point tracking (MPPT) to maximize the energy output of the PV arrays algorithm is used [7]. The voltage and current of PV panels are time-variable as they depend on the amount of radiation and ambient temperature. It is very important to monitor the maximum power point and operate PV modules at this level.

In the designed system, the grid is not needed as long as the electricity needed by the village is met by the solar power plant. The electrical energy generated from the solar power plant is converted into AC voltage to be used in the load through the inverter. In cases where the village's electrical energy needs are not met by the solar power plant, the electrical energy is met from the grid thanks to the MPPT. MPPT stands for maximum power point tracking. MPPT is the logical and mathematical infrastructure that ensures that the energy obtained from solar panels is delivered at the highest level in proportion to the internal resistance of the load. MPPT also manages the charging status of the battery. In other words, if the electrical energy generated from the solar power plant is more than the load, the code written in MPPT directs the excess electrical energy to the battery. Even with MPPT maximizing solar power collection, if the batteries are not fully charged and there is not enough sunlight to generate enough power, the system will automatically draw electricity from the grid to meet the need.

4. Findings and Discussion

In the case of the designed village in the center of Sivas province, the daily electrical energy requirement is calculated as 240 kWh. The solar power plant installed in the village consists of 60 CWT 675 model solar panels, 4 parallel and 15 series. The designed solar power plant generates 291.600 Wh of electricity per day. The daily electrical energy requirement of the village is represented as load in MATLAB/Simulink model. According to the standard test conditions used in MATLAB/Simulink, the irradiation value is entered as 1.000 W/m^2 .

The panel output voltage time plot of the solar power plant model simulated in MATLAB/Simulink environment is shown in Figure 8.

As seen in Figure 8, the output voltage value of the solar power plant in MATLAB/Simulink environment was measured at approximately 600 V. The panel output power value graph of the simulated solar power plant model is shown in Figure 9.

As seen in Figure 9, the output power value of the solar power plant in MATLAB/Simulink environment was measured as approximately 40.000 W.

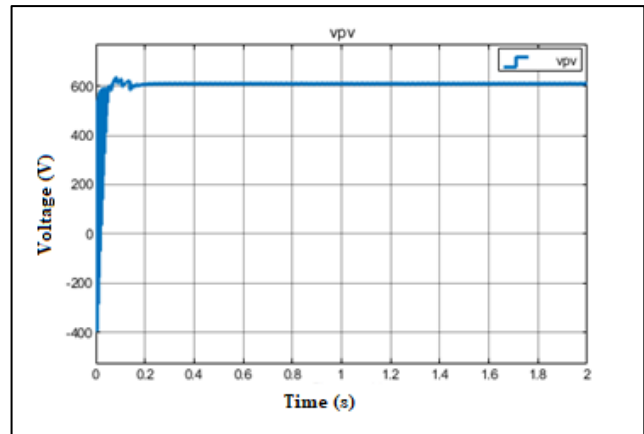


Figure 8. Output voltage time graph of the panel

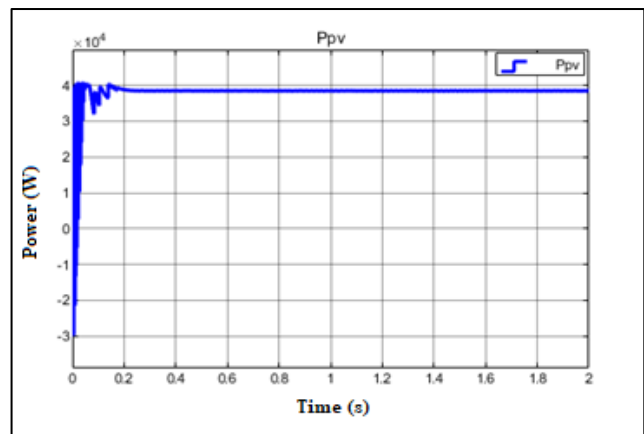


Figure 9. Power time graph of the panel

The electrical energy produced in the solar power plant is output from the power plant as DC voltage and then sent to the converter, the DC voltage that enters the converter as low is raised and output from the converter. The output voltage of the panel is the input voltage of the converter and the converter input was measured at approximately 600 V. Through the converter, the voltage is increased and the output voltage of the converter is approximately 760 V.

When the irradiance value of 1.000 W/m^2 is entered into the system in a MATLAB/Simulink environment, the MPPT reference voltage value is approximately 760 V. In the MATLAB/Simulink environment, as the irradiance value changes, the voltage on the load line also varies.

The DC voltage amplified in the converter is sent to the inverter to be converted into AC voltage used in the load. As long as the electrical energy converted to AC in the inverter meets the needs of the load, the load continues to be fed from the solar power plant. The electrical energy consumed in the load is supplied from the solar power plant or the grid through the MPPT system. As long as the solar radiation value is sufficient, the electrical energy to be consumed by the load is supplied from the solar power plant. When the solar radiation value is insufficient, the electrical energy to be consumed by the load is provided by the grid. In cases where the grid and the solar power plant are insufficient, the source of electrical energy to be consumed by the load is the battery.

State of charge (SOC) is a relative measure of the amount of energy stored in a battery and is defined as the ratio between the amount of charge that can be removed from the cell at a given time and the total capacity. The estimation of the amount of energy stored in the battery with the help of the battery state of charge (SOC) in the MATLAB Simulink program is shown in Figure 10, and the relative size of the battery to be used in MATLAB Simulink is shown in Figure 11. The battery used in the system is Mexxsun brand, Lithium battery model, 30 units, 24V/100Ah nominal power.

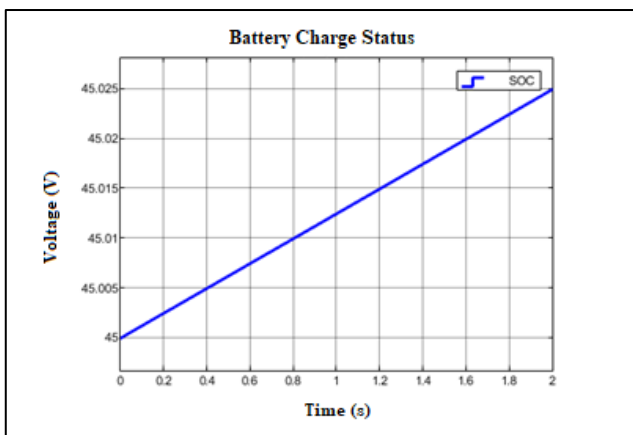


Figure 10. Battery charging state voltage graph

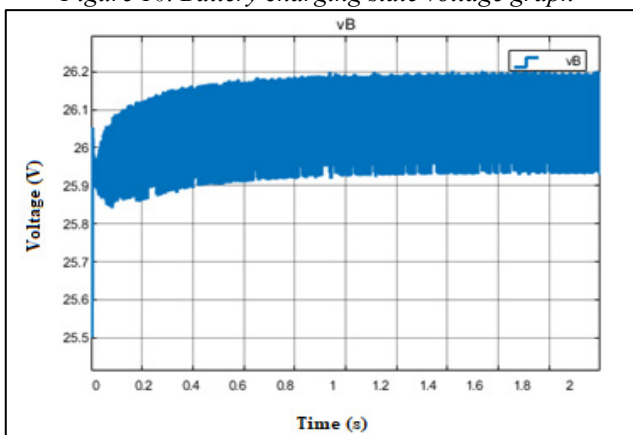


Figure 11. Battery voltage graph

The voltage graph of the reference line and the line at load used in MPPT is shown in Figure 12. (vbus; voltage at load, vref; reference voltage).

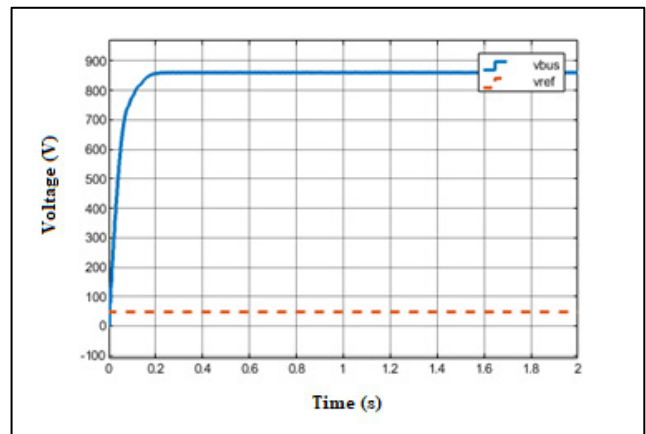


Figure 12. Voltage graph of the reference and loaded line used in MPPT

The electrical energy generated from the system is stored in the battery by means of a battery management system and MPPT when it is more than the load needs. In this system, the electricity demand of the load is met in three cases.

1. With the electrical energy generated from the solar energy system
2. From the grid
3. From the battery

While the load is fed from the solar power plant and the grid, the battery system is also charged. In the system, load supply and battery charge control are done through a smart grid scenario with an algorithm prepared using an MPPT. According to the scenario, the load supply, solar power system, grid or battery is selected by using the reference voltage and irradiance value comparison.

According to the algorithm written on the MPPT used in the scenario, there are 3 main cases:

1. Feeding the load and battery from the solar energy system
2. Feeding the load and battery from the grid
3. Feeding the load only from the battery

MATLAB MPPT code was used for these three scenarios. According to this scenario, in the first case, if the average irradiance value falling on the solar panel is above 500 W/m^2 , the PV panel breaker is made passive by MPPT, the electrical energy generated by the power plant is supplied to the system, the grid becomes passive. The load and battery are fed from the power plant. At the same time, the plant output voltage given as input to the MPPT is compared with the reference voltage simulating the minimum requirement of the load. If the panel output voltage is above the reference voltage, the battery is also fed.

If the panel output voltage is below the reference voltage, no battery supply is realized and only load supply is realized. This scenario is a precautionary measure against possible adverse environmental factors in case of low power plant output voltage despite sufficient irradiance.

For the first case, the battery charge rate for feeding the battery with panel energy is given in Figure 13.

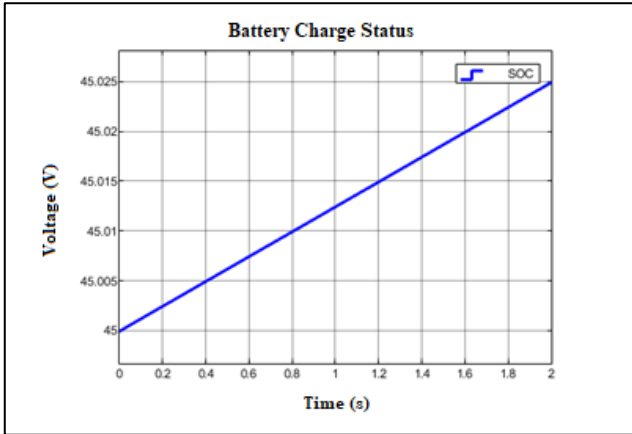


Figure 13. Voltage graph of battery charging state at irradiance of 500 W/m^2

In the second case, if the coefficient of the average irradiance value falling on the solar panel is below 500 W/m^2 , the PV panel breaker is activated by MPPT. The grid breaker is made passive. The load and battery are fed from the grid.

For the second case, the battery charge rate graph for feeding the battery with grid energy is given in Figure 14.

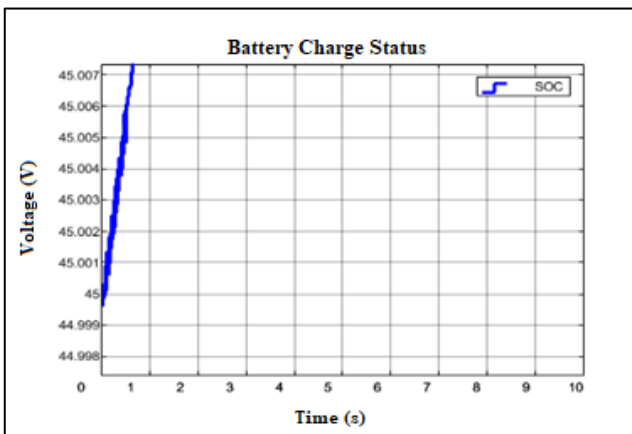


Figure 14. MATLAB/Simulink voltage graph of battery charging state under irradiance of 500 W/m^2

In the third case, if the irradiance falling on the panel is below 500 W/m^2 and the grid is also interrupted, the load is fed only from the battery.

For the third case, the battery charge rate graph of the system fed with battery energy is given in Figure 15.

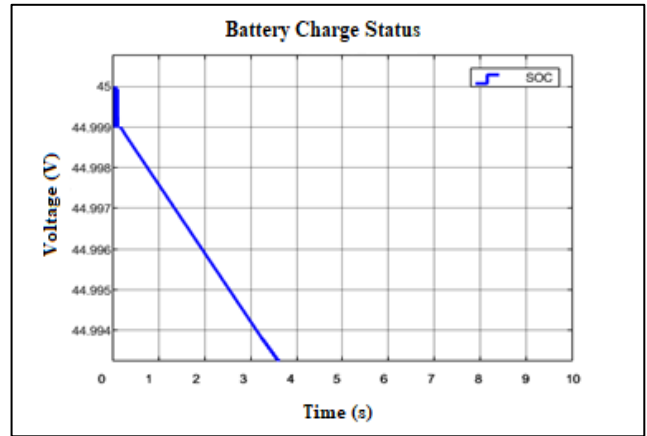


Figure 15. MATLAB/Simulink voltage graph of battery charging state under irradiance of 500 W/m^2 and grid outage

The rate of meeting the need according to the months of the electricity energy planned to be obtained from the solar power plant by taking into account the losses is given in Table 3. When the table is analyzed, it is seen that the electricity to be produced from the power plant between April and September will meet the entire need of the village, while the need cannot be completely met between October and March. Thanks to the smart grid and PV integration, it will be possible to meet the load from the grid or battery with MPPT control between October and March.

Table 3. Ratio of the solar power plant to meet the need

| Months | Sunbathing Time (hour) | Power Generated (Wh) | 0,85 with efficiency coefficient (Wh) | Rate of meeting the need (%) |
|-----------|------------------------|----------------------|---------------------------------------|------------------------------|
| January | 3,76 | 152.280 | 129.438 | 53,93 |
| February | 5,02 | 203.310 | 172.814 | 72 |
| March | 5,99 | 242.595 | 206.206 | 85,91 |
| April | 7,20 | 291.600 | 247.860 | 103,27 |
| May | 8,73 | 353.565 | 300.530 | 125,22 |
| June | 10,50 | 425.250 | 361.463 | 150,6 |
| July | 11,09 | 449.145 | 381.773 | 159,07 |
| August | 10,65 | 431.325 | 366.626 | 152,76 |
| September | 9,23 | 373.815 | 317.743 | 132,39 |
| October | 6,80 | 275.400 | 234.090 | 97,53 |
| November | 4,97 | 201.285 | 171.092 | 71,28 |
| December | 3,30 | 133.650 | 113.603 | 47,33 |

5. Conclusion

Smart grids are systems that provide energy efficiency and have become widespread in Turkey as in the rest of the world.

Thanks to developing electronic and communication technologies, the integration of renewable energy sources and smart grid integration means less energy need for Turkey, which imports more than half of its energy? Reducing energy imports is a critical contribution to energy supply security. It is important to increase the opportunities to utilize solar energy in Turkey, which has a high sunshine duration. In this context, the integration of PVs with smart grids will contribute to the utilization of renewable energy resources in Turkey.

The solar power plant designed within the scope of this study is integrated into the city grid together with the MPPT and battery system to meet the needs of the city grid when the energy produced by the solar power plant is not sufficient. When the energy produced by the solar power plant does not meet the needs of the village, the energy needed is met from the grid thanks to the MPPT and from the battery when necessary. With such applications, it is possible to significantly reduce the amount of electricity supplied from the main grid.

The solar power plant designed within the scope of the study consists of 60 CWT 675 panels and is intended to meet the electrical energy needs of a village with a daily electrical energy need of 240 kWh. In the calculations made, it is seen that the power plant will meet the entire electrical energy need of the village between April and September. Between October and March, some of the village's energy needs will be met from the solar power plant, while a significant portion will be met from the grid.

Utilization of renewable energy sources through grid-connected systems is both important for the effective utilization of renewable energy sources and contributes significantly to reducing the amount of electricity supplied from fossil-based power generation plants such as natural gas and coal.

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