Mathematical modeling of a PV installation for rural electrification

A A Medyakov¹, D M Lastochkin¹, A D Kamenskih¹, I K Garipov² and A P Ostashenkov²

¹ Volga State University of Technology, 3 Lenin square, Yoshkar-Ola, Mari El Republic, Russian Federation
² Mari State University, 1 Lenin square, Yoshkar-Ola, Mari El Republic, Russian Federation

E-mail: MedyakovAA@volgatech.net

Abstract. Since a new Federal Law of the Russian Federation “On Electric Power Industry” has been adopted consumers with microgeneration systems can now sell excess electric energy. Consequently, more agricultural consumers got interested in using renewable energy installations. In this context, the study focuses on mathematical modeling of electricity output by a microgeneration system, in particular with PV panels, to assess the conceivable amount of electric energy that can be eventually sold. The authors built a model of the system tied to a grid for three options: fixed-tilt PV panels, PV panels with a solar tracking system, and concentrator PV systems. The findings analysis confirms that in order to maximize the electricity transmitted to the electric grid, it is rational to use solar energy concentrators with a Sun-tracking system.

1. Introduction

Newly adopted Federal Law of the Russian Federation dated December 27, 2019 No. 471-FZ “On Amendments to the Federal Law “On Electric Power Industry” in a part of the microgeneration development”, gave the right to the owners of microgeneration systems to sell their excess electricity. Microgeneration systems encompass facilities for electricity production operating on (but not limited to) the use of renewable energy sources (RES). In this context, there has been an increased interest among agricultural consumers in renewable energy installations [1, 2] with the following conditions: power receiving devices are tied to 1000-V electric grid systems; the connected capacity of power receiving installations does not exceed 15 kW. All stated above makes the issue of mathematical modeling of the microgeneration systems, in particular with PV panels, crucial in assessing the potential amount of electricity that agricultural consumers can sell.

The object of the study is a PV installation used to electrify rural areas.

The subject of the research is the PV installation efficiency.

The research aims at building a mathematical model for PV installation to bring electrical power to rural areas.

For that purpose, we will focus on:

- Building a mathematical model for electricity output by a PV installation, assuming that produced excess can eventually be sold.
2. Materials and methods
The research employs as an object of microgeneration a PV installation owned by an agricultural consumer. Moreover, the authors considered several options for the PV system:

- fixed-tilt PV panels;
- PV panels with a solar tracking system;
- concentrator PV systems.

PV installations with a grid-tie inverter linked to an electricity grid and to PV panels are used to supply electricity to a rural residential house. The grid-tied solar systems are often employed [3] as they do not require the use of rechargeable batteries, which simplifies the system thus reducing capital and operating expenditures. The grid-tie inverter converts DC electric energy from PV panels into AC energy. If the energy produced by PV panels exceeds the consumption of electricity by an agricultural consumer, in this case, the excess energy is transmitted to the grid. In the case when the consumption exceeds the production of electricity by PV panels, the electricity amount required is consumed from the grid. The power flows are traced with a power meter (power meter measures the amount of electricity in the forward and reverse directions). The framework of a power supply system is given in figure 1.

![Figure 1. Framework of a power supply system.](image_url)

Solar energy modeling techniques described in [4-6]. The methodology for mathematical modeling of electricity output by a PV panel is as follows. The first stage as part of the modeling step assumes evaluating the total power of the PV panel, based on the parameters of the PV panel and insolation data. The next stage assessed the amount of energy that could be sold at the end of a billing period (a month was considered as a billing period). This value was the difference between the amount of electricity produced and electricity consumed by a rural residential house for the monthly period.

The input parameters for the mathematical model of electricity production by a PV installation could be grouped in the following way: constant parameters (remained unchanged) and variables (values changed within the modeling framework). Thus, the constant input parameters were: latitude of the locality; reflection coefficient (albedo), PV panels parameters (efficiency, aperture area), tilt angle of the PV panels receiving surfaces, number of PV models, concentration coefficient of solar radiation. Variable input parameters for the mathematical model were: average clear sky diffuse insolation on a horizontal surface, kWh/m²/day; average insolation incident on a horizontal surface, kWh/m²/day.

The following equations were used to evaluate the amount of electricity (kWh) produced by PV panels over a billing period:
• fixed-tilt PV panels

\[ W_{PV,tilt} = S_{PV \Sigma} \cdot \eta_{PV} \cdot W_T \cdot N; \]

• PV panels with a solar tracking system

\[ W_{PV,track} = S_{PV \Sigma} \cdot \eta_{PV} \cdot W_{ST} \cdot N; \]

• concentrator PV system

\[ W_{PV,C} = S_{PV \Sigma} \cdot \eta_{PV} \cdot W_{ST} \cdot k_C \cdot N, \]

where \( S_{PV \Sigma} \) – is the total aperture of the PV panels (the receiving surface area times the number of panels), m\(^2\);
\( \eta_{PV} \) – PV panel efficiency;
\( W_T \) – average value of the energy on a tilted surface at the billing period, kWh/m\(^2\)/day;
\( W_{ST} \) – average value of the energy on a Sun-tracking surface at the billing period, kWh/m\(^2\)/day;
\( N \) – the number of days in the billing period;
\( k_C \) – concentration coefficient of solar radiation.

Insolation on tilted surface, insolation on Sun-tracking surface, and insolation with concentrators were calculated by the methods as described in [7, 8].

Assumptions the authors made for the modeling process:

• within the modeling step, the intensity of the solar power flow is unchanged;
• electrical losses in the elements of the power supply system were not taken into account;
• the shading of PV panels was not taken into account;
• the temperature of PV panels and its influence on their characteristics were not taken into account;
• surface contamination of PV panels was not taken into account;
• the Sun-tracking error was not taken into account;
• solar radiant flux density on each PV panel surface is the same.

3. Results

According to the Federal Law of the Russian Federation dated December 27, 2019 No. 471-FZ “On Electric Power Industry” in a part of the microgeneration development, the linked power of the consumer’s power receiving devices should not exceed 15 kW. In this context, the authors estimated the power load of the consumer (rural residential house), and the sum of nominal rating powers of AC appliances with less than 15 kW. The demand coefficient method was used to measure the estimated capacity. The method assumes that the estimated load of the collector can be measured by:

\[ P_e = P_n \cdot k_d, \]

where \( P_n \) – is the nominal rating power of the AC appliance, kW;
\( k_d \) – is the demand coefficient.

The following formula was used to measure the amount of energy consumed during the billing period:

\[ W_{load} = \sum_{i=1}^{n} (P_{pi} \cdot t_i), \]

where \( P_{pi} \) – is the estimated load of the i-th AC appliance, kW;
\( t_i \) – the number of working hours of the i-th AC appliance during the billing period, hours.

The authors take an even monthly electricity consumption by a rural residential house to simplify the calculations (daily consumption is presumably 14 kWh). Using the above values, monthly values of electricity consumption were estimated taking into account the number of days in a month.
The authors have built a model of PV panel electricity output for the Mari El Republic conditions with the following input parameters [9]:

- lat/Lon – 56.6322° N / 47.7706 E;
- parameters of the PV panel (efficiency – 16%; aperture area – 1.29 m$^2$);
- number of PV models – 30 pcs.;
- concentration coefficient of solar radiation – 2.

The results of modeling of electricity output of PV panel with 30 total aperture $38.7$ m$^2$ modules are given in Table 1.

| Month | $W_{PV,tilt}$ | $W_{PV,track}$ | $W_{PV,C}$ | $W_{PV} - W_{load}$ | Sold, kWh |
|-------|---------------|----------------|------------|---------------------|-----------|
| Jan   | 141.4         | 147.6          | 292.3      | -294.4              | 0         |
| Feb   | 215.8         | 249.4          | 493.8      | -177.9              | 0         |
| Mar   | 553.9         | 586.0          | 1160.3     | 118.1               | 118.1     |
| Apr   | 906.7         | 974.2          | 1928.9     | 484.9               | 484.9     |
| May   | 1342.6        | 1443.4         | 2858.1     | 906.8               | 906.8     |
| Jun   | 1540.7        | 1673.8         | 3314.2     | 970.8               | 970.8     |
| Jul   | 1091.4        | 1673.8         | 3314.2     | 970.8               | 970.8     |
| Aug   | 1409.4        | 1501.4         | 2972.9     | 973.6               | 973.6     |
| Sep   | 766.3         | 1084.1         | 2146.7     | 344.5               | 344.5     |
| Oct   | 668.4         | 723.2          | 1326.2     | 232.6               | 232.6     |
| Nov   | 331.5         | 352.6          | 698.1      | -90.2               | 0         |
| Dec   | 104.5         | 162.0          | 320.7      | -331.3              | 0         |

Negative values in the column lines ($W_{PV} - W_{load}$, kWh) mean that in those months the amount of electricity produced by the PV panel did not exceed the electricity consumed by the AC appliance of the rural residential house. However, the electricity produced by the PV panels partially covered the needs, thus, in November, the electricity consumed from the grid was 90.2 kWh for the option with PV panels set at a fixed tilt angle, and it was 69.2 kWh for the option with a solar tracking system.

On the basis of the data analysis given in Table 1, we conclude that:

- the excessive electricity production over consumption is possible for the months with a high flux rate of solar radiation;
- the use of a solar tracking system can increase the annual output of a PV installation by 19.8%;
- the most effective in terms of the electricity produced are concentrator PV systems. The yearly amount of electricity transmitted to the electric grid when using concentrators is three times higher than the same indicator for a system with PV panels set at a fixed tilt angle.

4. Conclusions

It is rational to use a grid-tied solar system from the perspective of selling the excess energy produced by PV panels by agricultural consumers. Such systems do not require to exploit rechargeable batteries,
which results in the system simplification and reduction of capital and operating expenditures. Modeling was built for such a system using the example of a rural residential house in the Mari El Republic. The findings analysis confirms that in order to maximize the electricity transmitted to the electric grid, it is rational to use solar energy concentrators with a Sun-tracking system. As for the option with the fixed-tilt PV panels, this gives a more than three times increase in the amount of electricity transmitted to the electric grid. A similar indicator equals 19.8% for the option of an installation with a tracking system (without concentrators).

References

[1] Ghaith A F, Epplin F M and Frazier R S 2017 Economics of grid-tied household solar panel systems versus grid-only electricity Renew. Sust. Energ. Rev. 76 407-24
[2] Volkov S V, Garipov I K, Lastochkin D M, Medyakov A A, Onuchin E M and Ostashenkov A P 2019 Study of the reliability of the power supply system based on the solar power plant J. Espacios 40 29
[3] Kouro S, Leon J I, Vinnikov D and Franquelo L G 2015 Grid-connected photovoltaic systems: an overview of recent research and emerging pv converter technology IEEE Ind. Electron. Mag. 9 47-61
[4] Khatib T, Mohamed A and Sopian K 2012 A review of solar energy modeling techniques Renew. Sustain. Energy Rev. 16 2864-9
[5] Ampratwum D B and Dorvlo A S S 1999 Estimation of solar radiation from the number of sunshine hours Appl. Energy 63 161-7
[6] Chen Z 2017 Modeling and Simulation for an 8 kW Three-Phase Grid-Connected Photo-Voltaic Power System Open Physics 15 603-12
[7] Da Rosa A V 2013 Fundamentals of Renewable Energy Processes (Burlington: Academic Press) p 475-88
[8] Duffie J A and Beckman W A 2013 Solar Engineering of Thermal Processes (Hoboken: John Wiley & Sons) p 352-72
[9] Notton G, Lazarov V and Stoyanov L 2010 Optimal sizing of a grid-connected PV system for various PV module technologies and inclinations, inverter efficiency characteristics and locations Renewable Energy 35 541-54