A study of the reliability of a solar-wind power supply system

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Abstract. The growing demand of agricultural consumers for autonomous energy generating systems based on renewable energy sources leads to a need for an evaluation of the reliability of electricity supply. In this regard, the present study is devoted to considering approaches for the reliability evaluation of a solar-wind power supply system taking into account the changeability in the power of solar and wind energy flows, as well as methods for calculating the parameters of its reliability. As a result of a theoretical study, a mathematical model was developed to estimate the reliability of a solar-wind power supply system. This paper presents the obtained reliability parameters of the power supply system for a dwelling house on the basis of a solar-wind installation.

1. Introduction

The widespread use of power converters of renewable energy sources (RES) is limited by the presence of a number of obstacles connected with economic, regulatory, technical, and geographical factors. At the same time, technical factors include issues of connection and operation of facilities based on RES [1]. The latter is complicated by the fact that the experience of operating power supply systems for agricultural facilities, including rural residential buildings, in the Russian Federation is still insufficient. For this reason, the evaluation of the reliability of renewable electricity supply systems is problematic. And when deciding on the suitability of converters of renewable energy for power supply systems, the accurate evaluation of the reliability of power supply and the possibility of providing it in accordance with the reliability category are required [2-3]. Thus, a study of the reliability of power supply systems for agricultural facilities based on renewable energy is topical.

The object of this research is a solar-wind system for the power supply of a dwelling house.

The subject of the research is the reliability of a solar-wind power supply system.

The purpose of the work is to conduct a study on the reliability of a solar-wind system for the power supply of a dwelling house.

In order to achieve this goal, it is necessary to solve the following tasks:

- To analyse existing methods for the reliability evaluation.
- To simulate the operation of a solar-wind power supply system.
- To calculate the reliability parameters of a solar-wind power supply system.
2. Materials and methods
Solar-wind installations can be widely used for the power supply of small agricultural facilities, in particular, residential buildings. This is due to the availability of solar and wind energy and the relatively low cost of land to place converters of RES, as well as a wide range of commercially available converters, and, accordingly, the ability to create systems of required power. In addition, the combination of converters of various types of RES has a positive effect on the reliability of power supply systems based on them [4-6]. This is due to the possibility of redistributing the electrical load between the converters of various types of RES when the intensity of the flow of renewable energy of the same kind (solar or wind) is being reduced. Thus, failure can occur with a long-term decrease in the intensity of the solar and wind energy flows at the consistently high consumption level of electrical energy by rural residential buildings. In this case, for the no-break power, batteries of electric energy can be used. Thus, the presented power supply system has a complex structure, for the study of the reliability of which the methods of system analysis can be used.

1. A solar-wind power supply system is characterized by the properties inherent only to the entire power supply system as a whole but not to any of its elements separately;
2. Elements of a solar-wind power supply system are interconnected, which makes it possible to isolate the system in the form of an integral independent object in the study of the reliability.

As a result of analysing the data on the reliability of solar-wind power supply system elements, it was concluded that, in the study, it is preferably to identify elements that have the greatest impact on the reliability of the power supply system, while not taking into account other elements, in order to simplify the reliability model. The design scheme of the solar-wind power supply system is shown in figure 1.

![Design model of a solar-wind power supply system.](image)

Reference designations in figure 1:
A is a rechargeable battery;
I is an inverter;
X, Y, Z are circuit breakers;
F is a unit with photovoltaic modules;
C is a controller;
W is a wind power installation.

The study of the reliability of the solar-wind power supply system was carried out using the logical-probabilistic method by constructing a fault tree. This approach allows taking into account events that may cause a power supply system failure, including failures of its separate element [7-8].

The failure tree was obtained by sequentially detailing the events related to the failures of the solar-wind power supply system and its elements. When analysing the power supply system, it is advisable to divide the events into two types: those that occur in the presence of the design density of the solar and wind energy flows and those that occur in the presence of the off-design one. With the design density of the solar and wind energy flows, events that lead to the failure of the power supply system were formulated. The latter were also divided into short-term ones, in which to restore the operation of the
power supply system only switching is required, and long-term ones, which included complex events when the failure of one element takes place during test diagnostics or repair of another. The occurrence of the off-design density of the solar and wind energy flows was taken into account by introducing the symbols (F) and (V). In this case, the probabilities of occurrence of the insolation \( q_f \) and the wind speed \( q_v \) at which the power supply of a consumer is not provided, were taken into account. These probabilities were determined on the basis of data on the intensity of the solar radiation and the wind speed at the location of the solar-wind power supply system by determining the time, during which the insolation and the wind speed sufficient for the power supply of a consumer take place.

A tree of failures for the case when there is the sufficient intensity of the solar radiation and the wind speed is presented in figure 2. A tree of failures for the case with the off-design density of the solar and wind energy flows is presented in figure 3.

![Figure 2. A failure tree (the sufficient solar and wind energy intensity).](image1)

![Figure 3. A failure tree (the insufficient solar and wind energy intensity).](image2)
Reference designations in figure 2 and figure 3:
A, I, F, C, W are failed elements in accordance with the scheme in figure 1;
A', I', F', S', W' are elements under repair or exposed to diagnostics;
Xo, Yo, Zo are failures of circuit breakers when a request for the actuation takes place;
X, Y, Z are failures of circuit breakers;
F is a failure of photovoltaic modules with a decrease in the intensity of the solar radiation flux;
V is a failure of a wind power installation when the wind speed decreases.

Based on the analysis of the failure tree, equations were set up to calculate the probability of long shutdowns, $q_{PS}$, and short shutdowns, $q_{STS}$, the probability of a failure due to the decrease in the intensity of the solar radiation flux or the decrease in the wind speed, $q_{PV}$, and the total probability of a failure, $q$.

$$
q_{PS} = q_{o.x} \cdot (\lambda_{f} \cdot \tau_{f} + \lambda_{c} \cdot \tau_{c}) \cdot \lambda_{w} \cdot \tau_{w} + q_{o.x} \cdot (\lambda_{f} + q_{c}) \cdot \lambda_{w} \cdot \tau_{w} + \lambda_{1} \cdot \tau_{i} \cdot \lambda_{w} \cdot \tau_{w} + q_{o.x} \cdot (\lambda_{f} \cdot \tau_{f} + \lambda_{c} \cdot \tau_{c}) \cdot q_{w} + q_{o.x} \cdot \lambda_{y} \cdot \tau_{y} \cdot \lambda_{w} \cdot \tau_{w}. 
$$

$$
q_{STS} = \lambda_{x} \cdot \tau_{x} + \lambda_{y} \cdot \tau_{y} + \lambda_{z} \cdot \tau_{z}.
$$

$$
q_{PV} = (q_{o.x} + \lambda_{1} \cdot \tau_{i}) \cdot (\lambda_{w} \cdot \tau_{w} + q_{z}) \cdot q_{f} + q_{o.x} \cdot (\lambda_{f} \cdot \tau_{f} + \lambda_{c} \cdot \tau_{c}) \cdot q_{V}.
$$

$$
q = q_{PS} + q_{STS} + q_{PV}.
$$

Where, $\lambda_{f}, \lambda_{c}, \lambda_{w}, \lambda_{1}, \lambda_{y}, \lambda_{z}$ are failure rates of system elements;
$q_{o.x}$ is the probability of a failure of an element;
$q_{f}, q_{w}, q_{z}$ is the probability of an outage of system elements;
$\tau_{f}, \tau_{c}, \tau_{w}, \tau_{i}, \tau_{y}, \tau_{z}$ is the average recovery time of system elements;
$q_{f} = q_{f} \cdot k_{f}$;
$q_{f}$ is the conditional probability of the insolation, at which electricity is not provided to consumers;
$k_{f}$ is the idle coefficient of a solar-wind power supply system due to the decrease in the intensity of the solar radiation flux determined according to the following equation:

$$
k_{f} = \frac{\lambda_{f}}{\lambda_{f} + \mu_{f}} (1 - e^{-(\lambda_{f} + \mu_{f})t}),
$$

Where, $\lambda_{f} = T_{0f}^{-1}$ is the intensity of occurrence of the off-design insolation, year-1;
$\mu_{f} = T_{f}^{-1}$ is the recovery rate of the design insolation, year-1;
$T_{0f}$ is the duration of the period with the insufficient insolation;
$T_{f}$ is the duration of the period with the sufficient insolation.

$$
q_{V} = q_{V} \cdot k_{V};
$$

$q_{o}$ is the conditional probability of occurrence of the wind speed, at which no power supply is provided to consumers;
$k_{o}$ is the idle rate of a solar-wind power supply system due to the decrease in the intensity of the wind flow determined according to the following equation:

$$
k_{o} = \frac{\lambda_{o}}{\lambda_{o} + \mu_{o}} (1 - e^{-(\lambda_{o} + \mu_{o})t}),
$$

Where, $\lambda_{o} = T_{0o}^{-1}$ is the intensity of occurrence of the off-design wind speed, year-1;
$\mu_{o} = T_{o}^{-1}$ is the recovery rate of the design wind speed, year-1;
$T_{0o}$ is the duration of the period with an insufficient value of the wind speed;
$T_{o}$ is the duration of the period with a sufficient value of the wind speed.

3. Results

To obtain the values of the reliability indicators of the solar-wind power supply system, the input data presented in Table 1 were substituted in the equations. To take into account the effect of the wind speed
and the intensity of the solar radiation, the following values were taken (for the climatic conditions of the Republic of Mari El):

- the duration of the period with the insufficient insolation, \( T_{0f} = 0.44 \);
- the duration of the period with the design insolation, \( T_f = 0.56 \);
- the conditional probability of occurrence of the insufficient insolation, \( q_f = 0.1 \);
- the duration of the period with the insufficient wind speed, \( T_{0v} = 0.38 \);
- the duration of the period with the sufficient wind speed, \( T_v = 0.62 \);
- the conditional probability of occurrence of the insufficient wind speed, \( q_v = 0.2 \).

Table 1. Input data for estimating the reliability.

| System Element         | Parameter | Value       |
|------------------------|-----------|-------------|
| Wind power installation| \( \lambda_W \), 1/year | 0.4         |
|                        | \( q_W \)  | 0.0036      |
|                        | \( \tau_W \), year | 0.0032      |
| Photovoltaic modules   | \( \lambda_F \), 1/year | 0.2         |
|                        | \( q_F \)  | 0.002       |
|                        | \( \tau_F \), year | 0.0002      |
| Controller             | \( \lambda_C \), 1/year | 0.05        |
|                        | \( q_C \)  | 0.0002      |
|                        | \( \tau_C \), year | 0.0002      |
| Inverter               | \( \lambda_I \), 1/year | 0.05        |
|                        | \( \tau_I \), year | 0.0002      |
|                        | \( \lambda_X = \lambda_Y = \lambda_Z \), 1/year | 0.001       |
| Circuit breakers       | \( q_{0,X} \) | 0.001       |
|                        | \( q_Z \)  | 0.0000002   |
|                        | \( \tau_X = \tau_Y = \tau_Z \), year | 0.0002      |

The results of the calculation of the reliability values of the solar-wind power supply system using the above input data are the following:

\[
q_{PS} = 1.59 \cdot 10^{-8};
q_{STS} = 60 \cdot 10^{-8};
q_{FV} = 7.73 \cdot 10^{-8};
q = 69.32 \cdot 10^{-8}.
\]

4. Conclusions

1) It is preferably to conduct a study of the reliability of a solar-wind power supply system using a logical-probabilistic method by constructing a fault tree. This approach allows taking into account events that may cause a power supply system failure, including failures of its individual elements. The fault tree was obtained by sequential detailing the events related to the failures of the power supply system and its elements.

2) A study of the reliability of the power supply system of a residential house for the climatic conditions of the Republic of Mari El was conducted. The probability of failures was 69.32 \cdot 10^{-8}.

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