Improving a no-failure operation of a PV systems with grid inverters for agricultural regions

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Abstract. The growing interest to the use of power generating complexes based on renewable energy sources has been witnessed recently. It necessitates the need to improve the no-failure operation of such complexes. The highest failure rate is typical for the string inverter in grid-connected PV systems. The failure of the string inverter induces supply termination of electrical energy to the grid. The paper explores an approach to improve the no-failure operation of the process of electrical energy distribution by a PV system to the grid driven by the use of micro inverters. The authors used the logical-probabilistic method to assess the no-failure operation of the PV system. Thus, the authors obtained the expressions to calculate the probability of failure for PV systems, enclosing a string inverter, and micro inverters.

1 Introduction

Electrical energy produced at micro generation facilities, including PV systems, that is not consumed by the owners can be employed as according to the adopted law No. 471-FZ dated December 27, 2019 'On Amendments to the Federal Law 'On the Electric Power Industry' in the part regarding the amplification of micro generation'. A number of factors can specify the amount of electricity to be sold [1], as for instance the duration of PV systems downtime due to elements failures. Therefore, researching the aspects to improve the no-failure operation of PV systems seem to be relevant.

The object of study is a PV system connected to the power grid.

The subject of the study is the no-failure operation of a PV system connected to the power grid.

The purpose of the study is to measure the no-failure operation of a PV system with a string inverter and micro inverters.

The aims were to:
- Analyze two options of structural patterns of PV systems: with a string and a micro inverter;
- Build a fault tree for each of the options analyzed for structural patterns of PV systems;

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- Make up expressions to calculate the probability of PV systems failure;
- Do mathematical modelling of the reliability of a PV system using the data on the reliability of its elements.

2 Materials and methods

The paper deals with a PV system connected to the power grid, enclosing PV modules and a grid inverter. There are no batteries in the PV system under study that reduces capital and operating costs [2]. Figure 1 shows the PV system structural pattern.
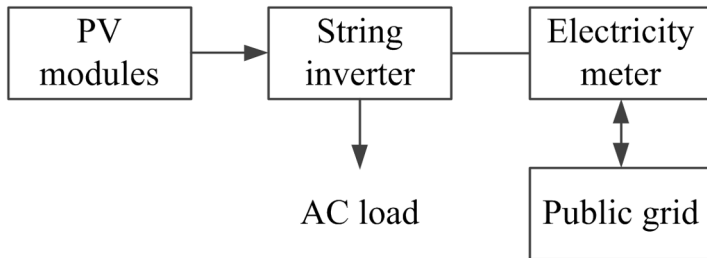

Fig. 1. PV system with string inverter structural pattern.

The reliability of PV system elements and its structure determine the no-failure operation of the latter. A PV system contains elements with different failure rates. The highest value of failure rate is typical for the string inverter in the system under study (Figure 1) [3, 4]. Failure of the string inverter may lead to disconnecting of PV panels from the grid. Therefore, one of the options to improve the reliability of a PV system is to use a micro inverter instead of a string inverter (Figure 2). In such a case, an individual micro inverter is mounted on each PV module (there are micro inverters to connect two or four PV modules). This ensures that a micro inverter failure will not lead to all PV modules disconnecting from the grid. Moreover, when we use micro inverters, the system is easy to expand, as it is enough to install the desired number of micro inverters when we add several PV modules, which is typical for small power consumers. Hence, substituting micro inverters for a string inverter facilitates increase for electricity produced by PV modules at different capacities (due to shading, different installation angles, etc.).
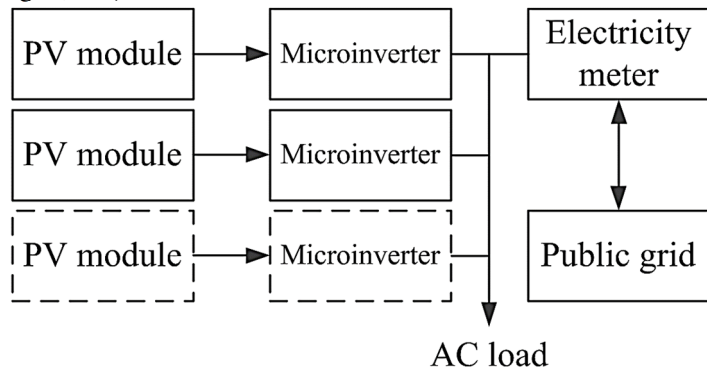

Fig. 2. Scheme of a PV system with micro inverters.

A logical-probabilistic method was used to assess the probability of a PV system failure. A fault tree was built for each of the two PV system options (Figure 3), that encompassed 16 PV modules. The elements with the highest impact on the PV system no-failure operation

were taken into account. Figure 3b shows the fault tree for the system option with micro inverters (4 PV modules are connected to each micro inverter).
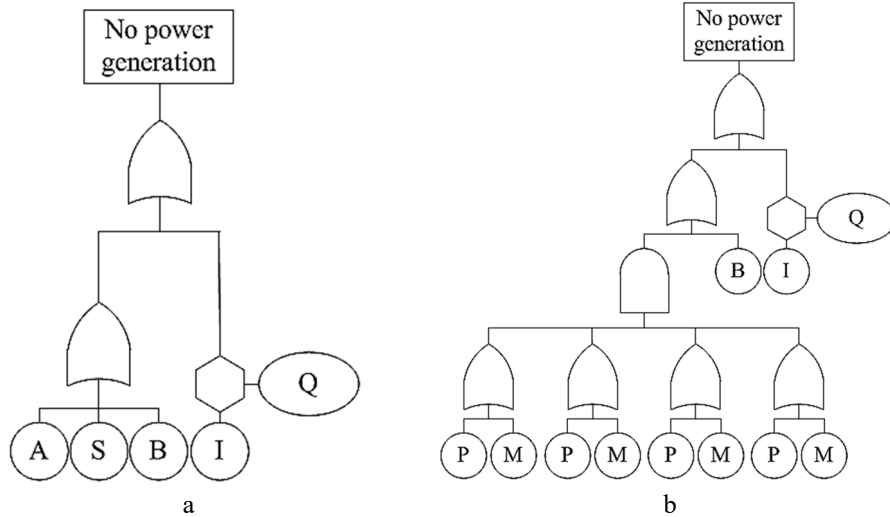

Fig. 3. Fault trees. a) system option with string inverter; b) system option with micro inverter.

Symbols in the Figure 3: A – PV array; S – string inverter; B – AC circuit breaker; P – PV modules; M – micro inverter; I – PV system failure due to reduced insolation; Q – restrictive condition, characterized by the magnitude of the probability of insufficient insolation.

The techniques used to draw the fault trees described in [5-7]. The algorithm for fault tree was the following. The top-level event was defined - the lack of supply of electrical energy to the grid. Then, intermediate failures and combinations of minimal, immediate, required, and sufficient for top-level event failures were identified and linked with logical symbols. Additionally, each failure event was setup through successive detailed levels of a PV system design with determination of the failures initial causes.

Two groups of events were taken into account while building the fault tree: those happening when insufficient insolation occurs, in terms of the possibility of electrical energy supply to the grid, and sufficient insolation. The latter included events associated with failures of switching devices, inverters, and PV modules.

Resulting from a fault tree construction, the authors obtained expressions to calculate the probabilities of failures of systems with a string inverter q_{SI}, and with micro inverters q_{MI}:

$$q_{SI} = q_A + q_S + q_B + q_I;$$
$$q_{MI} = (q_P + q_M)^n + q_B + q_I,$$

where $q_A = (1 - (1 - q_{P'})^m)^x$ – failure probability for PV array;

$q_{P'}$ – failure probability of a PV module;

m – number of PV modules in the grid;

x – number of circuits in PV array;

q_S – failure probability for the string inverter;

q_B – failure probability for a AC circuit breaker;

$q_I = q_{II} \cdot \frac{\lambda_I}{\lambda_I + \mu_I} \left(1 - e^{-(\lambda_I + \mu_I)t}\right)$ – failure probability due to insufficient insolation;

q_{II} – conditional probability of insufficient insolation;

λ_I – intensity of insufficient insolation occurrence, h^{-1};

μ_I – intensity of sufficient insolation restoration, h^{-1}.

$q_P = q_{P'}^{\ k}$ – failure probability of PV modules connected to a micro inverter;

k – number of PV modules connected to a micro inverter (k = 4 for micro inverters, designed to connect four PV modules);

q_M – failure probability of a micro inverter designed to connect k PV modules;

n – number of micro inverters.

For the micro inverter system option, when an individual micro inverter is mounted on each PV module:

$$q_{MI'} = (q_{P'} + q_{M'})^{n'} + q_B + q_I,$$

where $q_{M'}$ – failure probability of a micro inverter designed to connect one PV module;

n' – number of micro inverters.

3 Results

The above expressions were used for mathematical modeling of the reliability of a PV system with 16 PV modules in the climatic conditions of the central part of the Republic of Mari El. Table 1 gives the values of the reliability indicators of the elements of the PV system [8]. An exponential law of distribution of the operating time to failure was employed for all elements of the PV system. Assumptions used in mathematical modeling:

– No aging and wear of the elements of the PV system (the failure rates of all elements do not depend on time);
– All elements of the same type are equally reliable (the failure rates for alike elements are the same);
– All elements operate in the nominal (normal) mode provided for by the technical specifications;
– Element failures are random and independent events.

Table 1. Indicators values of system elements reliability.

Elements	Failure rate 10^{-6} failures/hour
PV module	0.0152
Inverter	27
AC circuit breaker	5.712

Table 2 shows the results of mathematical modeling for the following system options:

– PV system (2 series of 8 PV modules) with string inverter;
– PV system with micro inverters (4 PV modules for each micro inverter);
– PV system with micro inverters (1 photovoltaic module for each micro inverter).

Table 2. Results of mathematical modeling of the PV systems reliability.

	q_{SI}	q_{MI}	$q_{MI'}$
Failure probability (in %, 1 year)	0.066	0.056	0.056
Failure probability (in %, 10 years)	0.970	0.515	0.279

Resulting from the analysis of the data given in table 2, the following can be concluded:

– The probability of a complete termination of the electrical energy supply to the grid with an increase in the duration of a period of PV system operation both with a string inverter and micro inverters increases; however, for the latter version of the system, the failure probability remains less possible than the corresponding probability for a system with a string inverter;

- The use of micro inverters that can be connected with only one PV module provides the best reliability of the PV system as to electrical energy supply to the grid;
- The use of micro inverters that can be connected with several PV modules allows for reducing the possibility of a complete cessation of electrical energy supply to the grid compared to the option of a PV system with a string inverter; meanwhile, the reliability of the PV system does not differ much from the corresponding indicator for a system with micro inverters designed to connect only one PV module, while assessing the reliability within a period equal to the warranty period of a standard inverter (approximately 10 years).

4 Conclusions

The authors built a fault tree (complete cessation of electrical energy supply) for various options of PV systems: with a string inverter, and with micro inverters. They obtained expressions to calculate the failure probability for the options studied of PV systems, taking into account the number of PV modules that can be connected to one micro inverter, as well as the number of circuits of PV modules and their number in the circuit.

The authors have performed mathematical modeling of the PV system reliability with 16 PV modules for the climatic conditions of the central part of Mari El Republic. Thus, they obtained the values for the PV systems failure probability for the periods of 1 year and 10 years. The analysis of the results obtained proved that the use of micro inverters facilitates the reduction of probability of a complete cessation of electrical energy supply to the grid.

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