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Estimating Distributed Generation reliability level

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Abstract. The paper considers the reliability level of different distributed generation units. The world comparative statistics of reliability parameters depending on the unit capacity and other influencing factors are presented. The study includes an analysis of possible approaches to the correction of statistical parameters under the particular conditions. The calculation and analysis of structural reliability parameters for a group of distributed generation units is performed. It is shown that conventional *N*+1 reliability principle is not enough for distributed generation given a great number of operation conditions. A set of *N*+*n* principles is proposed according to the required distributed generation reliability level. Considering the reliability parameters is of great importance for the selection of installed power and the structure of distributed generation for industrial and household facilities under the design and evaluation of its technical and economic efficiency. Gradual growth of the share of distributed generation in power and energy balances of power systems raises the issue of its reliability calculation and regulation. The results obtained in the paper are also important for the maintenance, planning of repairs, and providing necessary logistics solution for the delivery of spare parts and consumables to generating plants.

Key words. Distributed power generation; power system reliability; power distribution; availability; statistical distributions.

1. Introduction

The ongoing development of Distributed Generation (DG) is concerned primarily with the renewables like photovoltaic power plants (PVPPs) and wind power plants (WPP). Distributed generation in the form of combined heat and power (CHP) is used to supply urban buildings and structures, residential households by electricity and thermal energy. In suburban and rural areas both types of sources supply energy for modern industrial enterprises and farmers. The CHP is usually represented by gas piston units (GPUs) or gas turbine units (GTUs), including microturbines.

The issue of power supply reliability, considering DG units as a main source of the energy, is of a great interest. Such conditions correspond to limited grid capacity, microgrids' island modes, or off-grid operation conditions. Obtaining parameters such as the availability factor and the probability of a plant operation makes possible to estimate the balance features during the year. The frequency of a unit shutdown leading to the loss of 100% of its power, affects the assessment of the possibility of power balance.

Although calculations of reliability parameters in the energy sector have been conducted for a long time [1-4], there are relatively few scientific papers devoted particularly to the assessment of the structural and balance reliability of electricity and energy supply by the DG units [5-10]. The publications are aimed primarily at improving the computation techniques and not the reliability factor application itself. A few numerical statistics are mentioned in the existing publications. In addition, there's a lack of its comparative analysis.

The gradual growth of DG share in power and energy balances of power systems raises the issue of their reliability calculation and regulation. The main problem of the DG-containing balances is that the power and energy output is considered mostly from the point of view of the primary energy source forecasting (like solar irradiance or wind speed) and its availability. Reliability consideration can be of the crucial importance when turning to the distributed power supply in terms of Distributed Generation and Smart Grid concepts.

The main goal of the paper is to show that the reliability factor cannot be neglected in terms of DG contribution to power and energy balances. The paper is devoted to the complex comparative analysis of reliability parameters of various DG types depending upon its capacity and different operating conditions. The consideration reveals that DG reliability level doesn't corresponds the reliability level of the conventional power plants. Potentially it may results in a correction of power and energy reserves and service intensity.

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The results obtained in the paper are also important for the maintenance, planning of repairs and providing necessary logistics solution for the delivery of spare parts and consumables to generating plants. Taking into account the reliability parameters is critically important for the selection of installed power and the structure of distributed generation for industrial and household facilities during the design and evaluation of its technical and economic efficiency.

2. World Statistics of DG Units Reliability

The reliability parameters of power supply via DG can be affected both by the parameters of the generation itself and by the reliability of adjacent grid equipment. However, the first ones are the priorities for consideration. DG objects are usually installed in the point of consumption. The length of the distribution power lines is minimal and the lines themselves rarely suffer from faults. Therefore, only the equipment of the distribution switchgear and DG units affects reliability. Reliability parameters of grid equipment are several orders of value higher than for generation units [11]. In modern practice, the calculations assume the absolute reliability of MV small transformers, busbars, and vacuum circuit breakers. A backup energy source in the form of a grid connection may not be available, especially for thermal energy (including the buildings with photovoltaic systems where electric heating and air conditioning is used). In addition, the available grid capacity can be less than the total load power. Thus, if the DG units are disconnected, the operation of a customer load is disrupted. So, DG units reliability is the top priority for the consideration.

The collected statistics of reliability parameters of DG units are based on reviews and meta-reviews of their reliability [12-19]. The data in the sources are represented in form of duration t_i of operation, maintenance, idle, reserve and outage. The standard data processing methods are used [4]. The collected data are reduced to the following two parameters.

1. To assess the reliability impact of the DG on the energy balance, the availability factor *AF* is used. It shows a share of time within a unit is ready to generate electricity:

$$AF = \frac{t - t_{SOH} - t_{FOH}}{t} \cdot 100\% = \frac{t_{op} + t_{res}}{t} \cdot 100\%, \quad (1)$$

where t is the considered period of time, t_{SOH} is the duration of scheduled outage, t_{FOH} is the duration of forced outage. The numerator of a fraction can also be summed up from the time of operation t_{op} and the idle time as the reserve or backup t_{res}. The last value for DG units designed for the continuous generation of electricity, can be taken as zero. Then, in the context of the year:

$$AF = \frac{t_{op}}{8760} \cdot 100\% \quad (2)$$

2. To assess the effect of the reliability of the DG on the power balance, the mean time between forced outages *MTBFO* is used. This is the time between the forced outages of a unit that occurs for any internal (failure, unscheduled repair, trip by technological protection) or external (trip by relay protection) reasons:

$$MTBFO = \frac{t_{op}}{N}, \quad (3)$$

where *N* is the quantity of outages. Forced disconnection leads to the loss of 100% of the DG unit power. At the best case, it leads to the necessity for automatic resynchronization after a few dozens of seconds, at the worst - to the necessity of service by operational personnel. *MTBFO* is also close to the *MTBI* parameter - Mean time between incidents, used in reports by some utilities. *MTBFO* can be obtained by dispatch reports as well as by reports of automatic control system of non-dispatchable DG.

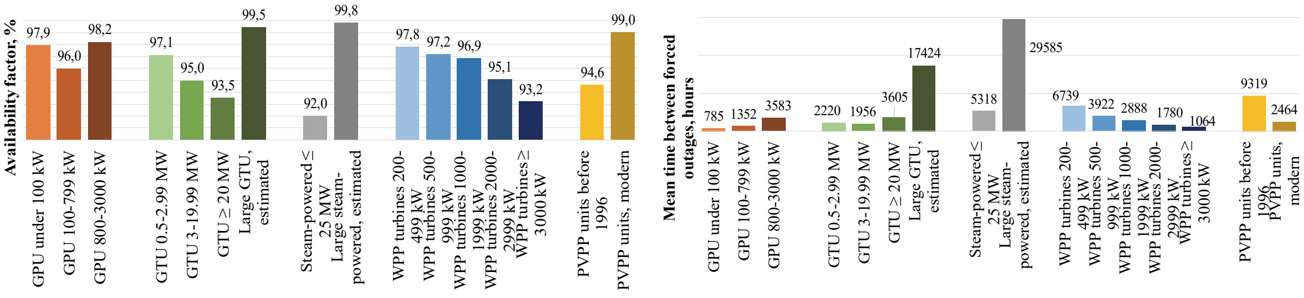
The results of the statistics collection are shown in Fig. 1. To compare the reliability level of the DG and the reliability level of large-scale power plants, the parameters of equipment corresponding to modern combined-cycle plants are given. Based on the results of the analysis, the following conclusions can be made.

1. All the DG types, except the PVPPs, have an evident dependence of reliability parameters on power. For PVPPs, the decisive role is played by the degree of technology development, i.e. PV modules technical generation as well as the development of their protection and interconnection schemes, and the availability of stand-by (reserve) modules.

2. Large steam-powered and gas turbine equipment have the number of forced outages 5-8 times lower and *AF* at 2-7% higher. This is caused either by the design of such equipment or by the electrical distance from the load and disturbance points in the grid. The equipment of power stations at high voltage classes is protected by relatively advanced Relay Protection and Automation (RPA) devices Also the higher qualification of the operating personnel, and smoother load schedule contributes to the result. Relatively frequent, but short-term outages of DG units caused by disturbances in the external grid and internal power supply system, RPA imperfections, etc.

3. For hydrocarbon-based DG plants, the increase in unit capacity leads to a positive effect of increasing the mean time between forced outages. Within the range of effective capacities, this value is about 750 h per MW for gas piston units and 100 h per MW for gas turbines proportionally to their power. This is caused both by a more sophisticated design of powerful units and by more stable operating conditions.

4. The *AF* is stable at the level of ~97.5±1 % for gas piston units, and for gas turbines it decreases by 0.2% per MW, due to the inaccessibility of such units repair wherever excepting the manufacturer plant.



a) b)

Fig. 1. The bar charts of DG units reliability parameters: a) availability factor *AF*; b) mean time between forced outages *MTBFO*

5. Due to the complexity of the design and the remote location of modern wind turbines from consumption centers a step up of unit capacity leads to the reduction in *MTBFO* and *AF* of 1000 h per MW and 0.4% per MW, correspondingly.

6. The mean time between forced outages for PVPP units falls by a factor of 5 in a retrospective mainly due to faults and excessive protection trips of modern power converters. However, the development of the technologies for the PVPPs and their mass production provided the availability of such stations up to 99%, which corresponds to the level of large power plants.

It should be noted, in terms of the probabilistic approach, the *AF* can be interpreted with some assumption as the probability of DG unit operation $AF \approx p$ [%] or $AF \approx P$ [%], that is, *AF* is often considered as a general statistical parameter, while p and P associated with the calculated value of the particular unit or power plant, correspondingly. To calculate the combinations of operation and outage probabilities for several units during a year using the described above statistics, a binomial distribution is used:

$$q(n,k) = C_n^k q^k p^{n-k}, \qquad (4)$$

where $q(n,k)$ is the probability of a state when k of n units are disconnected; C_n^k is the number of combinations of n elements over k; q and p is the probability of outage time and operation of a single unit, correspondingly. The value q can be easily found using $q=1-p$. The cumulative probability defines the probability that the number of units under maintenance will not exceed the quantity necessary for a load operation, taking into account the available power:

$$Q(n,k) = \sum_{j=1}^{k} q(n,j) \qquad (5)$$

The corresponding values of the total power can be obtained by multiplying the unit power by the number of operating or disconnected units. The issues of the statistics applicability for specific operation conditions are discussed below.

3. Correction of the Collected Statistics

An important factor affecting the actual reliability parameters is a technical generation of equipment. Technical generation assumes homogeneous equipment at a certain stage of its development, significantly differing in technical and economic indicators, reliability, functionality, and others from the previously produced equipment. New generation of power plants may differ in a level of reliability, both positively and negatively. In the case of maintaining the level of technical complexity, the unit of new generations have larger service intervals and improved reliability parameters.

The states like Repair and Failure for distributed generation units are often difficult to separate. In their design, there are the parts and devices that require routine maintenance and replacement. In difficult conditions, they become weak links. It leads to an intermediate state such as Repair Due to Accelerated Wear and the need for an unscheduled stop of the generating unit. Since it is difficult to distinguish Failure and Repair states, a change in the service interval indirectly indicates a corresponding change in the reliability level of the unit. For example, if the manufacturer increases the service interval, this will lead to the corresponding increase in *MTBFO* in the event that the causes of forced outages are dominated by failures associated with malfunction of such weak links. Therefore, a simple linear correction of AF^{corr} can be performed using statistics on the causes of failures:

$$AF^{corr} = \frac{t - t_{SOH}^{corr} - t_{FOH}^{corr}}{t} \cdot 100\% = \frac{t - t_{SOH}^{corr} - \left(\alpha \cdot \dfrac{t_{SOH}^{corr}}{t_{SOH}} + \beta \right)}{t} \cdot 100\%, \qquad (6)$$

where t_{SOH}^{corr} is the value of the service interval, different from the base one, α is the share coefficient of internal causes of forced outages, β is the share coefficient of external causes of forced outages. When changing the service interval, *MTBFO* is ambiguously changed:

$$MTBFO^{corr} \approx MTBFO \cdot \left(\alpha \cdot \frac{t_{SOH}^{corr}}{t_{SOH}} + \beta \right) \qquad (7)$$

In case if the causes of failure are internal causes associated with accelerated wear, then the increase in *MTBFO* can be approximated in proportion to the growth of the service interval with the corresponding weighting factor (0.5). The component of *MTBFO* determined by other (external) causes with a weighting factor of 1-0.5 = 0.5, does not change. For example, with an average time between forced outages of 2000 h for units with a planned service interval of 2000 h and a percentage of accelerated wear of 50% in the causes of forced outages, an increase in the service interval for new generation units of up to 4000 h will lead to an increase in the expected *MTBFO* up to 2000 * (0.5 * 4000/2000 + 0.5 * 1) = 3000 h. For the units discussed in Section 1, the service interval was 2000-4000 h, while the current DG plants operate at 4000-8000 h intervals [11].

The next influencing factor is the electrical state conditions. They are taken into account in the paper by the fractional coefficient β of forced outages for external reasons. Frequent trips of the GPU from RPA devices with external short-circuits occur due to the low ride-through settings for the over/under voltage and frequency devices. The corresponding average U and f are typically ± 10% and ± 1 Hz, respectively. The first stage of protection trips a generator with a time delay of 0-200 ms, the second stage trips with a delay of 0.5-1 s, although Grid Code requirements often are much tolerant. The mentioned settings lead to excessive protection trips and frequent shutdown of a DG unit. The mean time between forced outages is inversely proportional to the occurrence of the states beyond the limits of the settings. The duration of the t_{FOH} determining the *AF* can be calculated based on the probable duration of such states. Calculation of the relevant parameters to be made in accordance with the theory of reliability [4].

However, the main factor leading to a deviation from global statistics is specific local operating conditions. DG operates both in the zone of centralized power supply and in islanded microgrids located in the remote areas in a wide variety of climatic conditions and electric states. This results in more frequent repairs and decreased availability of spare parts and qualified service for DG units. Relative classification of operating conditions (OCs) of DG units is given in Table I. To match the particular operating conditions with the defined in Table I a simple method of expert evaluations was used. Easy or hard OCs score if the real parameters match the corresponding group of OCs. If two groups correspond to the easy OCs and two correspond to the hard OCs, the OCs classified as medium. Easy OCs correspond to the number of scheduled outage hours t_{SOH} in the absence of forced outages. Hard OCs correspond to the maximum duration of forced outage hours t_{FOH}. Some improvement in the statistics is that the maintenance can be combined with the repair without adding additional scheduled outage hours.

Statistics of CHP DG units at the heavy industry taking into account the defined OCs is presented in Table II. Corresponding capacity ranges of the samples vary from 1000 kW to 2000 kW for GPUs and from the 4000 kW to 9000 kW for GTUs. For comparison, typical parameters are given for the MV overhead line of 10 kV and of 5 km length. It is typical for the power supply of consumers in rural areas.

Table I. - The Criteria for DG Operation Conditions Ranking

Easy OCs close to the ideal	**Hard OCs**
General	
Correct design solutions for main and auxiliary equipment	Fit the operation plan for equipment already purchased
Electric	
Baseload	Peaking
No frequent starts / stops	Daily starts / stops, incl. cold ones
Absence of disturbances in the external grid	Frequent faults, phase breaks, voltage dips
Only grid-connected operation	Periodic operation as an island
Smooth load curve	Sufficient load steps
Symmetric values of currents and voltages in phases	Unbalanced values of currents and voltages in phases
Operation	
Fuel of a nominal calorific value without mechanical and chemical impurities	Deviation of a calorific value of fuel from the calculated, fuel preparation issues
Quality consumables and lubricants	Costs priority for consumable and lubricating materials
Service and maintenance	
Manufactirer's personnel	Own personnel
Closeness of warehouses of spare parts and advanced logistics	Supply of spare parts and consumables on demand and on request
The service contract and the manufacturer's telemetry on the units	The on-site diagnostics on demand
The first 3 years of operation of the unit (before repairs)	Statistics for the period of operation taking into account repairs (from 3 years)
Experience in the maintenance of power plants	Experience in maintenance primarily for a grid equipment or an electric motors
Proper maintenance standards	-

Mean time between forced outages varies from 1338 hours for GPUs to 2517 hours for GTUs. The average *MTBFO* is 2030 hours. Calculated on the basis of the statistics share ratio of internal causes for forced outages α is 32.5%, the share ratio β of external causes during forced outages is 67.5%. The following features are noted.

Table II. - The Statistics of DG Outages

Equipment	**Probability**			
	%		**Hours per year**	
	Operates	**Down**	**Operates**	**Down**
10 kV overhead	99.18	0.82	8688	72
GTU, hard OCs	91.58	8.42	8022	738
GTU, med OCs	94.95	5.05	8318	443
GTU, easy OCs	98.32	1.68	8613	147
GPU, hard OCs	56.93	43.07	4987	3773
GPU, med OCs	91.32	8.68	8000	760
GPU, easy OCs	97.72	2.28	8560	200

1. Equipment availability factors in case of the most hard OCs are reduced by 30%. The reason is primarily the service availability and quality of service equipment not always providing the quick elimination of the malfunction. In addition, the statistics do not contain data on gas turbine units meeting the scheduled 60-hours maintenance time (*AF* = 99.3%) declared by many manufacturers.

2. The average *MTBFO* generally corresponds to the global one. Given the high proportion of forced outages due to external causes, β = 67.5%, it can be assumed that the main reason for the forced outages of DG units worldwide is the excessive trips of generator by protections aimed at equipment security.

In addition, it can be concluded that the reliability of the power supply by the DG units can be significantly worsened with unsatisfactory operation statistics. The corresponding calculations are presented below.

4. Case Study

The case study based on the statistics presented above. Different types of DG units are considered: GTUs, GPUs and WPPs. The case of PVPP including 2500 modules with a total area of 2500 m^2 is calculated. The numerical series calculations were carried out using (5), (6).

For GTUs and GPUs the corrected statistics data is used (Table II) and the rated power: 6000 kW for GTU and 2000 for GPU, correspondingly. The reliability parameters of q are taken from the third column of Table II (see above). For the renewables the world statistics from Table I was taken. The q value was obtained as $q=1-p$ with the respect of the discussed above assumption of $AF \approx p$ [%]. The calculations use the most urgent wind turbine capacity of 2000-2999 kW, q=4.9%. In addition, the performance of a PVPP with an installed capacity of 500 kW is estimated, q=1.0 %. For hydrocarbon-based and WPP the results for the most typical case of power plant including four units are presented. The results of the calculations are shown in Fig. 2. For comparison, the results of rural 10 kV overhead line [20] are presented. According to the results of the calculations, the following conclusions can be made.

The standard for electric power industry principle *N*+1, is not truly correct to the DG units. The principle assumes that for any power system equipment unit there is another one unit providing backup or reserve enough to ensure generation, transmission or distribution. Historically, it has been applied to grid equipment (transmission lines, transformers, busbars), that have a failure rate of 103-106 times less than the failure rate of generator units (i.e. the probability of events such as failure of the first unit plus failure of the second unit is minimal).

Generators strictly require periodic maintenance instead the repair on demand (the probability of events such as scheduled outage of the first plus failure of the second raises). Taking into account the real reliability parameters of the grid equipment, the *N*+1 principle allows to ensure the absence of a power deficit with a probability of at least 95.4%, more often 99.7% (engineering criteria for two and three standard deviations σ for normal distribution, respectively). The probability of the 10 kV overhead line operation is 96.76%, and the probability that the number of switched off power lines does not exceed single line is 99.96 %.

The application of the *N*+1 principle to generation units leads to incomplete accounting of the probability of outage time of two or more generating units simultaneously. The *N*+1 principle ensures operation without power deficit with a probability of not less than 99.7% only with the most easy (i.e., ideal - unattainable) OCs for both GTUs (99.83%) and GPUs (99.70%). For the average OC, the *N*+1 principle ensures an operation without power deficit only with a probability of not less than 95.4%, that is, 98.57% for GTU and 95.99% for GPU. To obtain the probability of an operation without power deficit not less than 99.7% and medium OCs, the use of the *N*+2 principle is necessary. Similar conditions are for wind turbines with 98.65 % and 99.95%, respectively (regardless of the availability of wind as a primary energy source).

In order to achieve an acceptable balance reliability of power supply from the GPUs in the hardest OCs, it is necessary to use the *N*+3 (96.56%) principle to obtain a probability of an operation without power deficit not less than 95.4% and the *N*+4 (~100%) principle for obtaining a probability of an operation without power deficit at least 99.7%. It should be noted that the measures presented do not solve the issue of the reliability of the fuel transportation system. Essentially the conclusions about the necessary *N*+*n* reserves to be based on the economic principle and backup costs analysis.

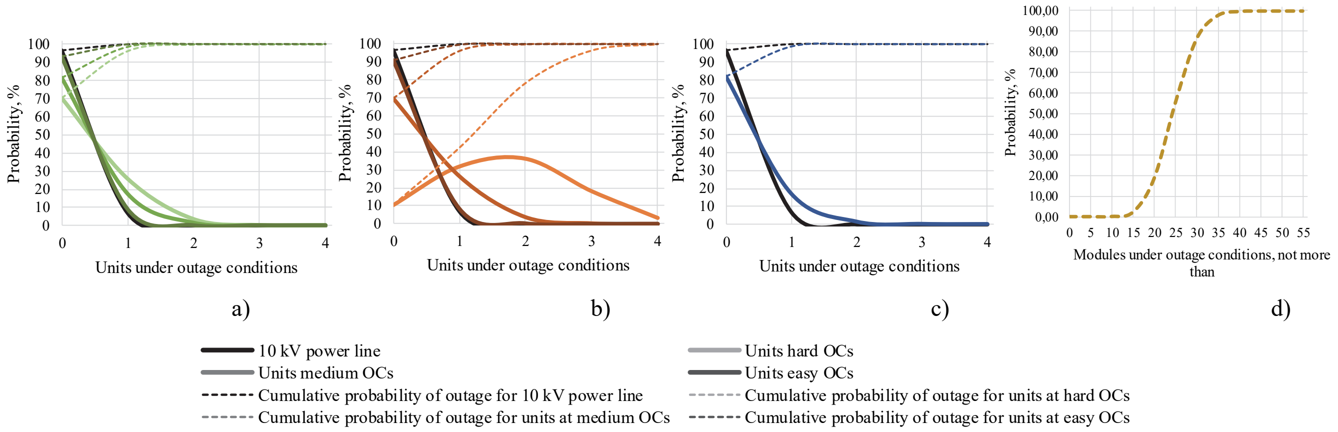


Fig. 2. Probability and cumulative probability of outage for: a) GTUs; b) GPUs; c) WPPs; d) PVPP modules

For the photovoltaic station, the cumulative probability for the annual interval shows the need for an average of 1% of spare photovoltaic modules, which is 25 out of 2500. Such a large number of reserve modules correlates with world statistics showing that the failure of one of the modules leads to a deterioration of conditions for the remaining modules of the entire string of the PVPP [16].

5. Conclusions

1. For hydrocarbon-based DG units, the increase in unit capacity within its range of effective capacities leads to an increase in reliability. For units based on renewables, an inversed relationship is observed, which is caused by the limiting capabilities of power semiconductor electronics.

2. Powerful modern wind turbines in general are inferior in reliability to units based on hydrocarbon fuel (even without regard to the availability of wind as a primary energy source). For photovoltaic plants, the novelty of the technical generation of photovoltaic modules plays a decisive role.

3. The DG units have 2-5% lower equipment availability factor in comparison with the units of large power plants. Nevertheless, DG units are subject to forced short-term outages 5-8 times often than the large generation units.

4. When calculating the reliability parameters of DG units, it is desirable to perform the statistics correction depending on the technical generation of units, the impact of internal and external causes of outages, and the expected electrical states.

5. The statistics described in the paper show that in the hardest operating conditions, the availability factor and the probability of operation deviate down from the mean ones by more than 40%. Nevertheless, the mean time between forced outages during operation corresponds to the global one at 1300-2000 h. For most DG units in the world, it is due to the short electrical distance to the disturbance point in the grid and the excessive operation of imperfect relay protection devices.

6. The N+1 principle is limitedly applicable to the selection of the capacity and structure of the DG equipment. It provides a probability of an operation without power deficit of at least 99.7% (which is comparable to the grid's one) only for unattainable ideal operating conditions. Under medium and hard operation conditions depending upon the required probability of power deficit absence it is necessary to use up to N+4 principle for the modern DG units. Essentially the conclusions about the necessary N+n reserves to be based on the economic principle and cost analysis.

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