The multi-state reliability model of a wind turbine

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Abstract. In coming years it is expected the gradual decarbonisation of the electricity generation sector and its diversification – also in terms of renewable energy sources (RES). One of the aspects of the RES integration is the issue of availability and reliability of their work. Each distributed generation technology has its own specificity of work, which should be reflected in reliability models. In the article, the calculation example concerning the multi-state reliability model of a renewable energy generation unit is presented.

1 The reliability in power engineering

Reliability is the property of an object that characterizes its ability to perform specific tasks, under specific conditions and within a certain time interval. In the case of electricity generating units, failure and availability indicators are determined [1].

The availability indicator of a single element, understood as the probability of operation state, is expressed by the following formula:

$$p = \frac{MTTF}{MTTF + MTTR} = \frac{MTTF}{T} = \frac{\mu}{\mu + \lambda}, \tag{1}$$

and the failure indicator, understood as the probability of failure state, is expressed by the following formula:

$$q = \frac{MTTR}{MTTF + MTTR} = \frac{MTTR}{T} = \frac{\lambda}{\mu + \lambda}, \tag{2}$$

where: $MTTR$ – Mean Time To Repair, $MTTF$ – Mean Time To Failure, $T = MTTF + MTTR$, $\mu = \frac{1}{MTTR}$ – intensity of repairs, $\lambda = \frac{1}{MTTF}$ – intensity of failures [1].

The reliability of electricity generation (generation adequacy) is assessed by determining the probability of a state in which the power demand exceeds the system's generating capacity. On the basis of this probability, the reliability indices of electricity generation (adequacy) are determined, such as Loss of Load Probability (LOLP) [1].

To assess future reliability of electricity generation of the system, the distribution function of available power in this system is required. It is calculated on the basis of assumed reliability models of generating units constituting the power system. There are basically distinguished two types of generation units reliability models - two- and multi-state model [1].

The availability of RES is influenced by the structural (technological) reliability of individual elements or devices, associated with the occurrence of damage and breakdowns, and the availability related to the access to primary energy (production reliability). In contrast to conventional power plants, the output power of the RES is limited by the availability of primary energy and changes over time [2].

2 The reliability model of a wind turbine

The following example of the multi-state reliability model for a wind turbine takes into account structural and production reliability. The analytical method was used.

A wind turbine can be considered as a series connection of elements (devices). The result of their simultaneous operation is wind energy conversion into electricity. The failure of one of the components, e.g. generator or gearbox, causes the failure of whole wind turbine.

For the sake of clarity, in considered example three components of structural reliability are distinguished: electrical system, mechanical system, and control system.

The systems above can be developed, expanding their reliability structure in the process of decomposition.

The production reliability is implemented in the model as additional element representing the availability of primary energy. The structure of the model is presented on Fig. 1.

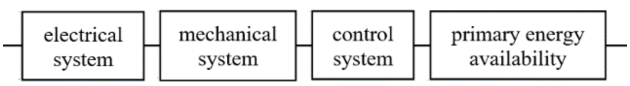

Fig. 1. Considered reliability model of the wind turbine.

The availability of primary energy, affecting the variability of the output power generated by wind turbine, is determined on the basis of statistical climatic date [3] for the city of Poznan.

The wind speed values are adjusted according to the height of nacelle's installation [2]:

$$v(h_2) = v(h_1) \cdot \left(\frac{h_2}{h_1}\right)^{\alpha}, \tag{3}$$

where: h_1=10 m, h_2=80 m – height, $v(h_1)$ – wind speed at a height of h_1, $v(h_2)$ - wind speed at a height of h_2, $\alpha = 1/7$ - parameter depending on the terrain roughness.

For each hour of the year, based on the adjusted statistical values of wind speed, the available output power of the turbine set is calculated. For this purpose, the power curve, corresponding to the Leitwind LTW77

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turbine with a rated output power of 1000 kW [4], is used. The power curve is analytically estimated in order to obtain the mathematical formula of the turbine output power as a function of wind speed:

$$P(v) = \begin{cases} 0 & \text{for} \quad 0 \leq v < v_{CI} \\ P_x & \text{for} \quad v_{CI} \leq v < v_R \\ P_R & \text{for} \quad v_R \leq v < v_{CO} \\ 0 & \text{for} \quad v \geq v_{CO} \end{cases} \tag{4}$$

$$P_x = 0{,}0229v^6 - 0{,}9067v^5 + 13{,}665v^4 + \\ -100{,}55v^3 + 397{,}22v^2 - 767{,}76v + \\ +560{,}57 \tag{5}$$

where: v_{CI} – cut-in wind speed [m/s], v_R – rated wind speed [m/s], v_{CO} – cut-out wind speed [m/s], P_R – rated power [kW]

The calculation of available power according to (4) and (5) for each hour in a year allowed to prepare the ordered graph of power generated by a wind turbine. On its basis, the nine-state reliability model of the availability of primary energy is assumed. Its parameters are summarized in Table 1. The probability of occurrence of a given state is calculated analogously to Eq. (1) and (2).

Table 1. The parameters of the nine-state reliability model of the availability of primary energy.

state number	output power [kW]	frequency [h/yr]	probability
8	1000	89	0,0102
7	963	227	0,0259
6	874	381	0,0435
5	638	622	0,0710
4	378	819	0,0935
3	187	1311	0,1497
2	76	1598	0,1824
1	9	1754	0,2002
0	0	1959	0,2236

For elements related to structural reliability the two-state model is implemented. This means that the element can be usable or not. The probabilities of these states are arbitrarily adopted ($p = 0{,}95,\ q = 0{,}05$), taking into account previous research [5].

Therefore, the considered wind turbine model consists of 3 two-state elements and one nine-state element. This means that $2^3 \cdot 9^1 = 72$ combinations of possible system operating states can be obtained. The probabilities of particular states are determined by the elements of the equation (6) transformed into a non-renumbered form:

$$(p_E + q_E) \cdot (p_M + q_M) \cdot (p_C + q_C) \cdot \\ \cdot (p_{W1} + \ldots + p_{W8} + q_W) = 1\,, \tag{6}$$

where: p_E, p_M, p_C – probabilities of availability of structural elements (correspondingly: electrical, mechanical and control system), q_E, q_M, q_C - probabilities of unavailability of structural elements, $p_{W1} \div p_{W8}$ – probabilities of wind turbine operation in 1-8 states of wind energy availability, q_W – probability of wind turbine inability for operation due to the lack of appropriate wind conditions.

For example, after the Eq. (6) transformation the element $p_E \cdot p_M \cdot p_C \cdot p_{w1}$ is equal to the probability of the state, in which all structural elements are operational and wind conditions allow the turbine to operate with 9 kW of output power. If at least one of the structural element is unserviceable, then the output power is zero, even if the primary energy is available. Hence, combinations of passible operating states, resulting in the same value of output power, can be combined into one state by summing up their probabilities.

Fig. 2. presents the probability distribution and cumulative distribution function of available output power for the considered wind turbine and for the assumed location.

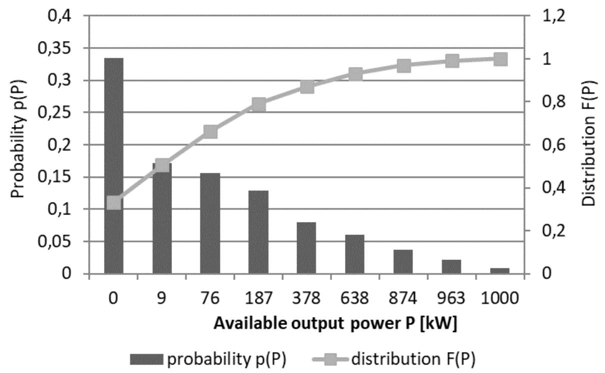

Fig. 2. The probability distribution and cumulative distribution function of available output power for the considered wind turbine and for the assumed location.

3 Conclusions

The obtained reliability model of wind turbine can serve as a starting point for further reliability analyses. It can be implemented in considerations related to generation adequacy of power system.

The obtained results strongly depend on parameters of a given wind turbine and location. Therefore, each case should be considered individually. The disadvantage of an analytical method is a large number of combinations to consider.

References

1. Paska J., *Niezawodność systemów elektroenergetycznych* (Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa, 2005)
2. Paska J., *Rozproszone źródła energii* (Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa, 2017)
3. Ministry of Investment and Development, Typical meteorological and statistical climatic data for energy calculations of buildings (2019) https://www.gov.pl/web/inwestycje-rozwoj/dane-do-obliczen-energetycznych-budynkow [Access: 16.01.2019]
4. Technical specifications of the Leitwind LTW77 1000 turbine set (2019) https://en.wind-turbine-models.com/turbines/1649-leitwind-ltw77-1000 [Access: 16.01.2019]
5. Paska J., Surma T., Przegląd elektrotechniczny **4a** 150-156 (2012)